

## Fracture Resistance of Unsplit Pistachio (*Pistacia vera* L.) Nuts against Splitting Force, under Compressive Loading

H. Maghsoudi<sup>1</sup>, M. H. Khoshtaghaza<sup>1\*</sup>, S. Minaei<sup>1</sup>, and H. Zaki Dizaji<sup>2</sup>

### ABSTRACT

Mechanical properties of non-split pistachio nuts are among the lada required for the design of equipment needed for processing of the nut. Unsplit pistachio nut samples were uniaxially loaded to determine the nut's needed splitting force and energy, as well as Poisson's ratio and Young's modulus of elasticity. The tests were carried out at four moisture contents (5, 10, 15 and 20% wb), under four loading rates (10, 20, 30 and 40 mm min<sup>-1</sup>), and on two varieties (O'hadi and Badami) of the nut. The highest splitting forces for the varieties (281.9 N for Badami and 102.4 N for O'hadi) were obtained at a moisture content of 5% wb and loading rate of 40 mm min<sup>-1</sup>, while the lowest forces, 97.0 N for Badami and 16.8 for the case of O'hadi, occurred at moisture contents of 20% wb along with loading rate of 10 mm min<sup>-1</sup>. Different trends were observed between O'hadi and Badami varieties for the required energy to split nuts with increasing moisture content and loading rates. By increasing moisture content, Poisson's ratio for unsplit pistachio nuts increased from 0.374 to 0.388 and from 0.326 to 0.337 for O'hadi and Badami varieties, respectively. Young's modulus exhibited an indirect relationship with moisture content while a direct relationship with loading rate, in either of the varieties. Increase in moisture content from 5 to 20% wb led to a decrease in Young's modulus, from 322.59 to 223.23 MPa and from 816.25 to 719.28 MPa, for O'hadi and Badami variety nuts, respectively.

**Keywords:** Fracture resistance, Loading rate, Moisture content, Non-split pistachio nut.

### INTRODUCTION

Pistachio nut (*Pistacia vera* L.) is cultivated in the Middle East, United States and in Mediterranean countries. Iran produces about 229,660 tonnes of pistachio nuts annually, 60% of which is exported (FAO, 2005). A considerable portion of harvested pistachio nuts remain non-cracked even after being processed. The value of non-opened shell pistachio nut is significantly less than that of the split nuts (Maghsoudi *et al.*, 2008). Also it occurs that some unsplit pistachio kernels are of a

desirable deep green color, so that it is preferred to crack the shell and remove the kernel safe for use in the confectionery and pastry industries (Woodroof, 1979). It is important that pistachio opening process be quick and efficient splitting large numbers of nuts at a time, while the crack also occurring along the suture of the nut's shell. Hence, a knowledge of the fracture characteristics of unsplit pistachio nuts, under compressive loading, becomes imperative for the rational design of an efficient nut splitting system.

There are some authors reporting on physical properties of split pistachio nut and

<sup>1</sup> Department of Agricultural Machinery Engineering, Tarbiat Modares University, P. O. Box: 14115-336, Tehran, Islamic Republic of Iran.

\* Corresponding author, e-mail: khoshtagh@modares.ac.ir

<sup>2</sup> Department of Agricultural Machinery Engineering, Shahid Chamran University, P. O. Box: 135, Ahvaz, Islamic Republic of Iran.



kernel (Hsu *et al.*, 1991; Pearson *et al.*, 1994; Kashaninejad *et al.*, 2005; Ozden and Alayunt, 2006; Razavi *et al.*, 2007a, b, c; Maghsoudi *et al.*, 2010). Other researchers have studied moisture-dependent mechanical properties for various other biological materials. Oloso and Clarke (1993) found that failure energy absorption for cashew nuts increased with an increase in the moisture content while the failure force decreased. Similarly, both Braga *et al.* (1999) and Aydin and Ozcan (2002) found that the maximum force required to crack terebinth fruits and macadamia nuts was obtained when nuts were positioned at right angles to the longitudinal axis, whereas the minimum force required to crack samples occurred when the force was applied along the longitudinal axis. Olaniyan and Oje (2002) reported some aspects of the mechanical properties of shea nut. They found that rupture force decreased with increasing moisture content in either horizontal or vertical loading positions. Guner *et al.* (2003) investigated rupture force, specific deformation and rupture energy required for the initial failure of some varieties of hazelnuts under compressive loading as a function of moisture content and compression loading position. The experiments showed that the highest deformation, rupture force and energy were obtained for nuts loaded along the thickness at a deformation rate of  $0.522 \text{ mm s}^{-1}$ . Afkari and Minaei (2004) studied the behavior of wheat kernels under quasi-static loading and reported its relation with grain hardness. Also, according to Vursavus and Ozguven (2005), the conditioning of pine nut kernel at higher moisture content reduced the force required to rupture the nut. There are various research reports on the Young's modulus and Poisson's ratio of some such biological materials as wheat (Arnold and Roberts, 1969), rough rice (Shitanda *et al.*, 2001), Golden Delicious apple (Grotte *et al.*, 2002), chickpea (Khazaei and Mann, 2005), and African

nutmeg (Burubai *et al.*, 2008). For the design of such pistachio nut's processing equipments and apparatus as splitting or shelling machines, it is necessary to determine the response of the unsplit nut to the applied compression load under various conditions. Literature review indicates that investigation on the fracture characteristics of unsplit pistachio nuts is rare. Therefore, the objective of this study was set to determine the average splitting force, splitting energy, Poisson's ratio and Young's modulus of the unsplit pistachio nuts under quasi-static compression over a range of moisture contents and loading rates.

## MATERIALS AND METHODS

Unsplit dried pistachio nuts were randomly selected out of two pistachio varieties of Badami and O'hadi, widely cultivated in Iran (five kilograms from each variety). To measure the initial moisture content of the nuts, a certain predetermined weight of the sample (3 to 5 grams) was dried in an oven at  $103 \pm 2^\circ\text{C}$  until the changes between two successive weighings of the samples became negligible (Razavi and Taghizadeh, 2007). Initial moisture contents of O'hadi and Badami pistachios were found to be 4.87% and 4.63% (wet basis), respectively. Mechanical properties of nut samples were determined at four moisture levels of 5, 10, 15 and 20 (% wb) and in three replications. This range of moisture content was selected, because pistachio processing operations as well as its storage occur in moisture contents from 5 to 20% wb. In each replication, twenty pistachio nuts were taken as sample. To prepare samples with higher moisture contents, the required amount of distilled water was calculated from the following equation and added to the unsplit pistachio nuts (Kashaninejad *et al.*, 2005):

$$W_2 = W_1 \times \left[ \frac{M_1 - M_2}{100 - M_1} \right] \quad (1)$$

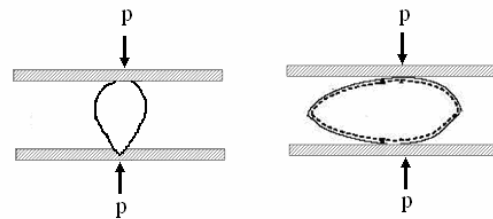
where,  $W_1$  and  $W_2$  represent masses of the sample and distilled water (g), while  $M_1$  and  $M_2$  are the initial and the desired moisture contents (% wb), respectively. The sample was kept at 5°C in a refrigerator for 10 days to let the moisture to homogeneously diffuse throughout the product. The diffusion throughout the samples was controlled through kernel splitting. Before start of a test, the required quantities of samples were allowed to warm up to room temperature (Aydin and Ozcan, 2002).

A material testing machine (H50 K-S, Hounsfield, England) was employed quasi-static compression tests. The sample was placed between two parallel plates (Figure 1), and due to the desired goal which was splitting (not cracking) the samples, compression force was exerted just along the thickness (perpendicular to suture line) of the sample to split the shell as shown in Figure 2. The experiments were carried out at four loading rates (10, 20, 30 and 40 mm min<sup>-1</sup>), for all moisture content levels (Vursavus and Ozguven, 2005).

The mechanical characteristics of unsplit pistachio nuts were expressed in terms of maximum splitting force and energy, as well as Poisson's ratio and Young's modulus of elasticity. During the experiments, the material testing machine's software program recorded force diagram as a function of deformation. Force exertion stopped when initial crack detected through software as a sharp reduction in the value of force. The area under the force-deformation curve, at the maximum force, was taken as the required energy for splitting. Young's modulus for a whole nut, when it is compressed through parallel plates, was determined according to ASAE standards for compression test of food materials of convex shape (ASAE, 2004):



**Figure 1.** Direction of loading in quasi-static compression test of unsplit pistachio nut using parallel plates.



**Figure 2.** Force exertion along practical directions for splitting.

where,  $E_m$  is apparent modulus of elasticity (Pa),  $D_c$  is deformation (m),  $\mu$  represents Poisson's ratio (dimensionless),  $F$  is force (N),  $R_U$ ,  $R'_U$  are maximum and minimum radii of curvature of the convex surface of the sample at the point of contact with the upper plate (m),  $R_L$ ,  $R'_L$  are maximum and minimum radii of curvature of the convex surface of the sample at the point of contact with the lower plate (m). The constants  $K_U$  and  $K_L$  are dimensionless parameters related to geometrical characteristics of the bodies in contact with each other.

For calculating the Young's modulus based on this method, Poisson's ratio of unsplit pistachio nut was needed. Poisson's ratio was calculated directly from the ratio of lateral to longitudinal strains of each unsplit pistachio nut, when the sample subjected to axial compression load

$$E_m = \frac{0.338F(1-\mu^2)}{D_c^{\frac{3}{2}}} \left[ K_U \left( \frac{1}{R_U} + \frac{1}{R'_U} \right)^{\frac{1}{3}} + K_L \left( \frac{1}{R_L} + \frac{1}{R'_L} \right)^{\frac{1}{3}} \right]^{\frac{3}{2}} \quad (2)$$



(Equation (3)). This term is defined mathematically below (Figure and Teixeira, 2007):

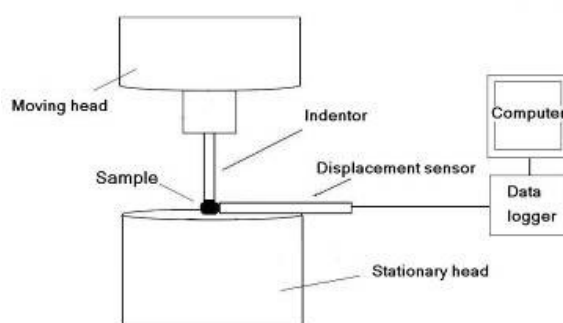
$$\mu = \frac{d/D}{e/L} \quad (3)$$

where,  $\mu$  is the Poisson's ratio (dimensionless),  $d$  is the transverse deformation (mm),  $D$  is the sample width (mm),  $e$  is the axial deformation (mm) while  $L$  representing the length of sample (mm). Axial displacement (strain) for unsplit nuts was measured and recorded using the material testing machine (Figures 3 and 4). Horizontal displacement, perpendicular to the loading axis, was determined through a bending beam (CE-10, Tokyo Sokki Kenkyujo, Japan) which contacted the sample. At the end of the beam, there were four strain gages installed and set as a complete bridge circuit. Beam displacement causes resistance change of strain gages, which is converted into voltage change and recorded by a data logger (TC-31K, Tokyo Sokki Kenkyujo, Japan). The material testing

machine was used to calibrate the displacement meter. Through a comparison of the displacement shown by material testing machine and voltage changes as shown by data logger, the correction coefficient was found to be 1.341. The data logger reflected the real displacement on its screen by applying this coefficient in calculations.

### Experimental Design

A factorial experiment in a randomized complete block design was employed to study the effects of four moisture contents, four loading rates and two variety levels on splitting force and energy, Poisson's ratio and Young's modulus of unsplit pistachio nuts under the applied compression load. SPSS 14 statistical software (SPSS Inc. US, 2005) was employed to analyse data through one-way Analysis of Variance (ANOVA). The differences among means were compared through Duncan's Multiple Test



**Figure 3.** Schematic diagram of the set-up for measuring Poisson's ratio.



**Figure 4.** Instruments employed to measure Poisson's ratio for unsplit pistachio nuts.

(95% significance level).

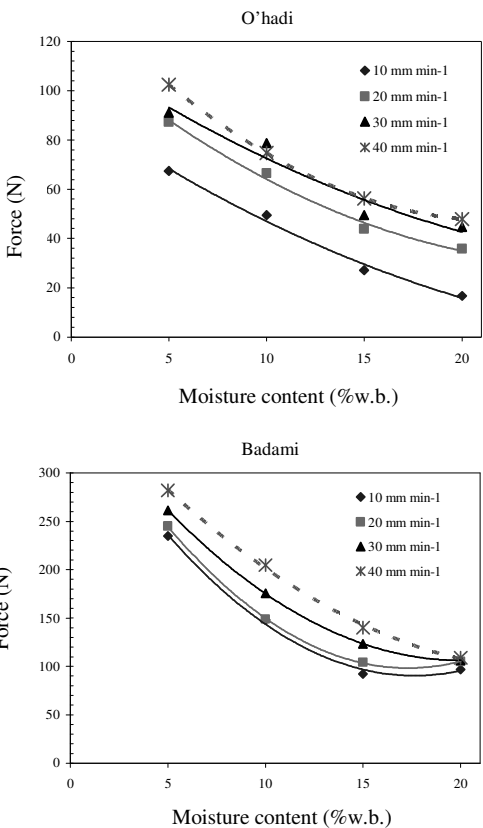
RESULTS AND DISCUSSION

Physical Property

Table 1 shows some physical properties of unsplit pistachio nuts at various moisture contents for O’hadi and Badami varieties. In general, results of physical study showed that by increasing the moisture content from 5 to 20% (wet basis), the average length, width, thickness, geometric mean diameter, sphericity and unit mass of unsplit pistachio nuts increased linearly.

Splitting Force

The splitting force of the nut as a function of moisture content and loading rate are presented in Figure 5 for both O’hadi and Badami varieties. Statistical analysis showed that the effect of variety, moisture content and loading rate on splitting force were significant ( $P < 0.01$ ) while the interaction effect of these parameters not significant. Splitting force of the shell for all the loading rates, in general, decreased as moisture content increased. Within each moisture content level, the splitting force increased by increase in loading rate from 10 to 40 mm min<sup>-1</sup>. The higher needed force might be due to shorter time needed for reaction to loading at higher rates. For both varieties the



**Figure 5.** Effect of moisture content and loading rate on mean values of splitting force for either one of the two varieties of unsplit pistachio nuts.

maximum force, 281,9 N for Badami and 102.4 N for O’hadi, were obtained at the moisture content of 5% wb and loading rate of 40 mm min<sup>-1</sup>, while the lowest force, 97.0 N for Badami and 16.8 for O’hadi, occurred at a moisture content of 20% wb and loading

**Table 1.** Some physical properties of unsplit pistachio nuts at various moisture contents, two varieties.

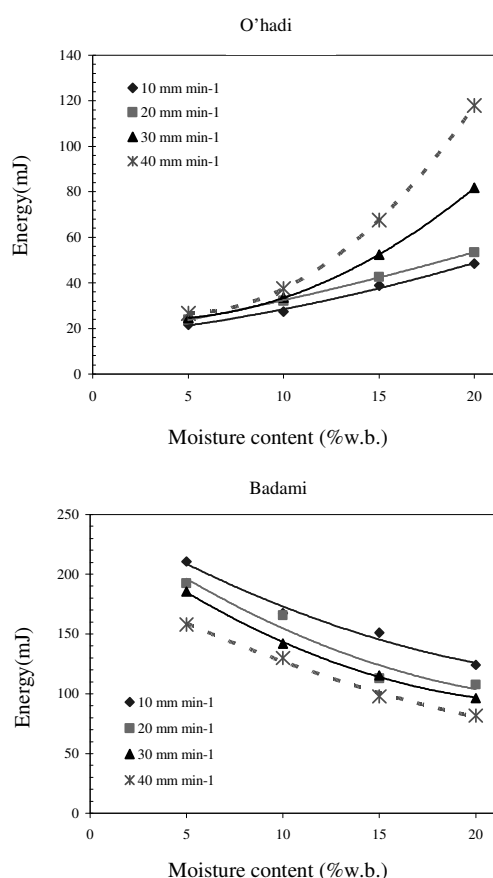
Variety	Moisture content (% wb)	Length (mm)	Width (mm)	Thickness (mm)	Geometric mean diameter (mm)	Sphericity (%)	Mass (g)
O’hadi	5	18.82±0.89	12.05±0.49	11.56±0.67	12.26±0.55	73.79±1.96	1.145±0.203
	10	18.99±0.95	12.06±0.77	11.64±0.79	13.43±0.88	73.80±2.36	1.179±0.221
	15	19.38±0.82	12.56±0.51	12.07±0.64	14.28±0.56	73.95±1.86	1.244±0.157
	20	19.86±1.01	12.83±0.64	12.36±0.59	14.75±0.60	74.75±2.18	1.376±0.161
Badami	5	21.84±1.09	11.28±0.60	12.59±0.54	14.78±0.43	67.70±1.56	1.320±0.163
	10	21.98±0.68	11.59±0.50	12.97±0.71	15.06±0.65	68.09±1.78	1.361±0.196
	15	22.50±1.08	11.81±0.68	13.49±0.68	15.15±0.71	68.12±2.43	1.478±0.168
	20	23.34±1.06	12.35±0.59	14.06±0.52	15.95±0.59	68.43±2.50	1.584±0.219



rate of  $10 \text{ mm min}^{-1}$ . The reason for this trend can be attributed to the fact that at higher moisture contents, shell became soft and weak, this being responsible for the reduction in splitting force. Therefore, for the design of cracking machines, the moisture content and loading rates should be taken into consideration. Previous works have also demonstrated that rupture force decreases with increase in moisture content (Olaniyan and Oje, 2002; Aydin, 2003; Guner *et al.*, 2003; Ozden and Alayunt, 2006; Zaki Dizaji and Minaei, 2008; Altuntas and Erkol, 2009).

### Splitting Energy

Figure 6 shows the splitting energy needed for O'hadi and Badami varieties. Rupture



**Figure 6.** Effect of moisture content and loading rate on splitting energy for the two pistachio varieties.

energy increased with increase in moisture content for O'hadi variety. This is probably due to softening of the shell that results in further deformation, and more area under the force-deformation curve up to the splitting point. Similar relationships have been reported by Gupta and Das (2000) for both in vertical and in horizontal position loadings of sunflower seed and its kernel, Altuntas and Yildiz (2007) for faba bean, and by Guner *et al.* (2003) for hazelnuts. But, as for Badami variety, a reverse trend between splitting energy and moisture content was discerned. It can be seen that at all loading rates, and at a moisture level of 5% wb, the sample requires more energy for being splitted than at the other moisture contents with the energy coming down for samples at higher moisture contents. Previous works, by Vursavus and Ozguven (2005) for pine nut, Singh and Goswami (1998) for cumin seed, Zhang *et al.* (2005) for the case of rice as well as Khazaei *et al.* (2001) for almond nut as well as for its kernel, have demonstrated similar descending results. Braga *et al.* (1999) investigated the required energy for cracking of macadamia nut under compression loading at different compression positions. They showed an inverse relationship between initial rupture energy and moisture content along the suture line and as well in the direction perpendicular to the suture line. Koyuncu *et al.* (2004) found that energy decreased linearly with increase in shell thickness. The authors, as well implied that as the shells get thinner, the energy required for cracking of nuts increases. This contrasting behavior between O'hadi and Badami varieties for the required energy might be due to the differences in structure of their shells and the nature of deformation before the advent of the splitting point. Mechanical properties of the unsplit pistachio nuts indicate that the nuts of different cultivars differ in their shell hardness, being differently under loading. Observations indicate that Badami variety nut is longer and has a harder shell tissue than O'hadi variety. In this connection,

Khazaei (2003) reported that the larger size chickpea kernels show more resistance to rupture. Also Zaki Dizaji and Minaei (2008) noted that there is a direct relationship between mean geometrical diameter and the needed splitting energy as observed among several chickpea varieties.

The following regression models (Equations (4) and (5)) were developed to express splitting force and energy of unsplit pistachio nuts as a function of moisture content and loading rates:

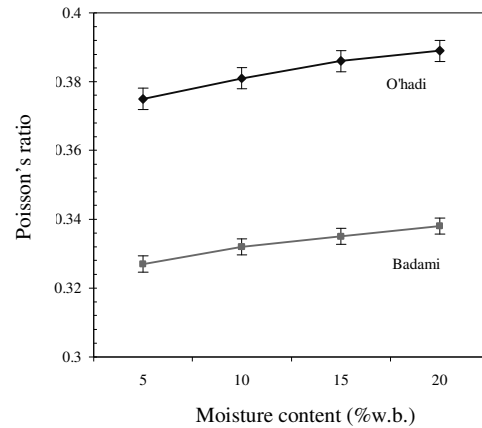
$$F = f_1 M_c^2 + f_2 M_c + f_3 \quad (4)$$

$$E = e_1 M_c^2 + e_2 M_c + e_3 \quad (5)$$

where,  $F$  is the splitting force (N),  $E$  the splitting energy (mJ),  $M_c$  representing moisture content (% wb), and  $f_1, f_2, f_3, e_1, e_2$  as well as  $e_3$  the coefficients as given in Table 2. These equations can be employed in the design of such processing equipment as, nut sheller, splitter or cracker.

### Poisson's Ratio

Figure 7 shows the variation of Poisson's ratio ( $\mu$ ) of unsplit pistachio nuts (O'hadi and Badami varieties) as against the nut's moisture content. These results indicate that there is a trend of increase in Poisson's ratio with increasing moisture content, and this might be due to decrease in the air gap between shell and its kernel in the unsplit nut (Sitkei, 1986). Results of the Analysis of Variance (ANOVA) showed that variety and moisture content exerted significant effects



**Figure 7.** Poisson's ratio of unsplit pistachio nuts.

on Poisson's ratio ( $P < 0.01$ ), but no conspicuous interaction effect was observed. The average Poisson's ratio in unsplit pistachio nut was found to be 0.383 for O'hadi variety which was higher than that for the Badami variety with an average of 0.333. This may have originated from differences in shell texture in these varieties showing Badami to have a more porous shell texture than O'hadi variety, and due to the fact that more porous materials possess a lower Poisson's ratio (Mohsenin, 1986). Decrease in moisture content led to an increase in pore space of the samples, therefore, the Poisson's ratio at 5% moisture, (rather a dry sample), showed its lowest value, significantly different from that in samples at other levels of moisture content. The linear relationship (Eqs. 6 and 7) between Poisson's ratio ( $\mu$ ), and moisture

**Table 2.** Coefficients obtained for regression equations of splitting force and energy (Equations (2) and (3)) for unsplit pistachio nuts.

Variety	Loading rate (mm min <sup>-1</sup> )	$f_1$	$f_2$	$f_3$	$R^2$	$e_1$	$e_2$	$e_3$	$R^2$
O'hadi	10	0.19	-8.46	139.93	0.91	0.04	0.84	16.08	0.99
	20	0.07	-5.29	117.75	0.98	0.02	1.37	16.24	0.99
	30	0.13	-6.68	118.35	0.99	0.21	-1.31	26.07	0.96
	40	0.08	-5.41	93.38	0.98	0.39	-3.79	35.79	0.97
Badami	10	0.46	-23.23	387.57	0.98	0.16	-9.53	252.33	0.98
	20	0.69	-27.7	382.23	0.98	0.21	-11.50	248.38	0.95
	30	0.97	-33.46	387.82	0.99	0.24	-11.95	238.53	0.98
	40	0.91	-32.16	374.06	0.99	0.12	-8.18	196.90	0.97



content ( $M_C$ , % wb) was formulated as follows:

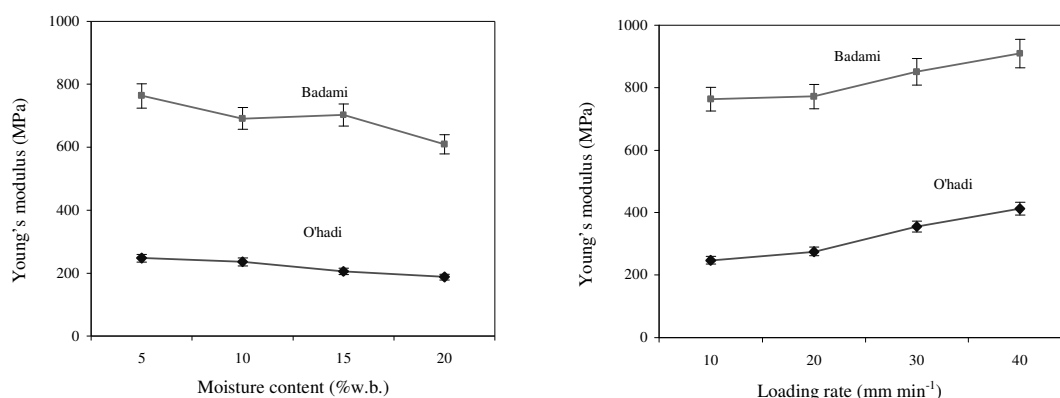
$$\mu = 0.001M_C + 0.37; R^2 = 0.97, \text{O'hadi} \quad (6)$$

$$\mu = 0.001M_C + 0.32; R^2 = 0.98, \text{Badami} \quad (7)$$

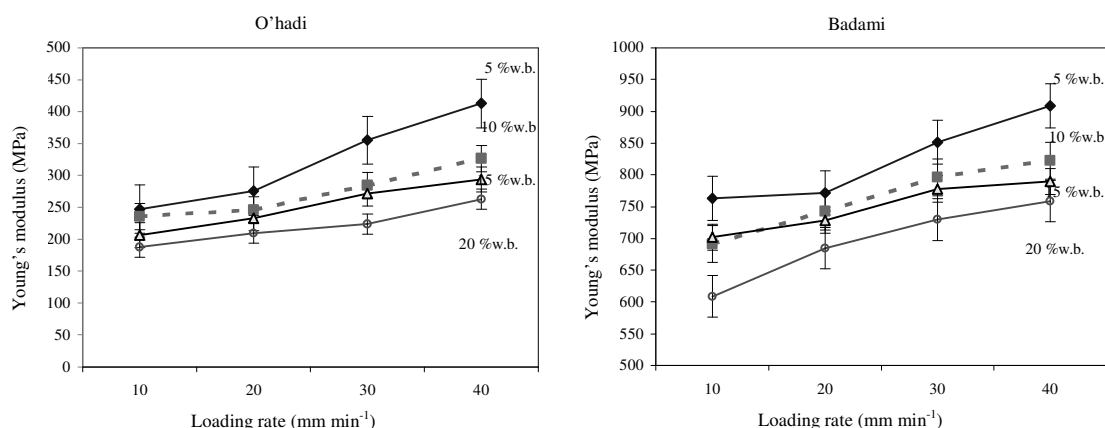
### Young's Modulus

Results of Analysis of Variance demonstrated that all the independent parameters (variety, loading rate and moisture content) exerted high significant effects ( $P < 0.01$ ) on Young's modulus. Increasing moisture content from 5 to 20% wb (at  $10 \text{ mm min}^{-1}$  of loading rate) decreased Young's modulus in nuts from 247.18 to 187.82 MPa and from 763.36 to 608.91 MPa, in O'hadi and Badami varieties, respectively (Figures 8 and 9).

This shows that nuts by absorbing water, gradually lose their elastic properties and become of a great tendency to act as viscoelastic materials. This might be due to the reason that splitting force of the shell for all loading rates, generally decreases as moisture content is increased. Zaki Dizaji and Minaei (2008), and also Khazaei and Mann (2005) determined the modulus of elasticity for chickpea kernels at three moisture content levels and they also reported the same decreasing trend in fracture force in response to increase in moisture content. Also Young's modulus of unsplit pistachio nut increased with increase in loading rate from 10 to  $40 \text{ mm min}^{-1}$ , in both O'hadi and Badami varieties (Figures 8 and 9). When loading rate increases, samples need more splitting



**Figure 8.** Effect of moisture content (5% wb), and loading rate ( $10 \text{ mm min}^{-1}$ ) on Young's modulus.



**Figure 9.** Interaction effect of moisture content and loading rate on Young's modulus of elasticity.



**Table 3.** Coefficients of Equation (6) for different loading rates.

Variety	Loading rate (mm min <sup>-1</sup> )	<i>a</i>	<i>b</i>	<i>R</i> <sup>2</sup>
O'hadi	10	-4.15	271.01	0.97
	20	-4.24	303.86	0.98
	30	-7.56	380.55	0.92
	40	-9.67	444.59	0.93
Badami	10	-9.05	804.59	0.85
	20	-5.46	800.18	0.96
	30	-7.67	884.59	0.97
	40	-9.68	940.82	0.93

force for a less extent of deformation, so that the slope of force-deformation curve increases resulting in Young's modulus to exhibits higher value. Burubai *et al.* (2008) investigated the elastic modulus in African nutmeg as a function of moisture content and of loading rate. They reported that elastic modulus decreased with increasing moisture. However, they observed a negative trend with as loading rate.

Average value of Young's modulus was determined to be 269.94 and 765.93 MPa for O'hadi and Badami varieties, respectively. In a comparison with other kernels, elastic moduli in pistachio nuts were found to be higher than those in barley kernels (Bargale and Irudayaraj 1995), African nutmeg (Burubai *et al.*, 2008), Avocado pear (Baryeh, 2000) and than rice kernels (Zhang *et al.*, 2005). This might be due to the more brittle texture nature of unsplit pistachio nut's shell. The linear regression equation (Equation (8)) between Young's modulus and moisture content at different loading rates was established as follows:

$$E_m = aM_c + b \quad (8)$$

where,  $E_m$  is the Young's modulus (MPa),  $a$  and  $b$  the constant coefficients and  $M_c$  standing for moisture content (% wb). These equations can be employed to design and establishment of the splitting processes for the split opening of unsplit pistachio nuts. The values of the needed coefficients in Equation (8) for various loading rates are presented in Table 3.

## CONCLUSIONS

Splitting force of pistachio shells decreased, regardless of nut variety and loading rate, as moisture content increased from 5 to 20% wb. Also this force increased with increase in loading rate for both varieties and within the moisture content in which the experiments were carried out.

Splitting energy for all the loading rates was highly dependent on moisture content, but with increase in moisture, different trends were observed for O'hadi and Badami varieties.

By increasing moisture content from 5 to 20%, Poisson's ratio of unsplit pistachio nuts increased linearly for O'hadi variety from 0.375 to 0.389 and for Badami variety from 0.327 to 0.338.

Young's modulus for unsplit pistachio nut decreased with increase in moisture content from 5 to 20% wb, while it increased with increase in the loading rate from 10 to 40 mm min<sup>-1</sup>, in both O'hadi and Badami varieties.

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## Nomenclature

$a, b$	Constant coefficients
$d$	The transverse deformation, (mm)
$D$	Sample width, (mm)
$D_c$	Deformation, (m)
$e$	Axial deformation, (mm)
$E_m$	Young's modulus, (MPa)
$E$	Splitting energy, (mJ)
$f_1, f_2, f_3, e_1, e_2, e_3$	Constant coefficients
$F$	Splitting force, (N)
$M_1$	Initial moisture content, (% wb)
$M_2$	Desired moisture content, (% wb)
$M_c$	Moisture content, (% wb)
$L$	Length of sample, (mm)
$K_U, K_L$	Geometrical constants, (Dimensionless)
$R_U, R'_U$	Maximum and minimum radii of curvature of the convex surface of the sample at the point of contact with the upper plate, (m)
$R_L, R'_L$	Maximum and minimum radii of curvature of the convex surface of the sample at the point of contact with the lower plate, (m)
$W_1$	Mass of the sample, (g)
$W_2$	Mass of distilled water, (g)
$\mu$	Poisson's ratio (Dimensionless)

## REFERENCES

- Afkari Sayyah, A. H. and Minaei, S. 2004. Behavior of Wheat Kernels under Quasi-static Loading and Its Relation to Grain Hardness. *J. Agric. Sci. Technol.*, **6**: 11-19.
- Altuntas, E. and Erkol, M. 2009. The Effects of Moisture Content, Compression Speeds and Axes on Mechanical Properties of Walnut Cultivars. *J. Food Bioprocess Technol.*, **4**(7): 1288-1295.
- Altuntaş, E. and Yildiz, M. 2007. Effect of Moisture Content on Some Physical and Mechanical Properties of Faba Bean (*Vicia faba* L.) Grains. *J. Food Eng.*, **78**(1): 174-183.
- Arnold, P. C. and Roberts, A. W. 1969. Fundamental Aspects of Load-deformation Behavior of Wheat Grains. *Trans. ASAE*, **12**(1): 104-108.
- ASAE. 2004. *ASAE Standard: S368.4*. Compression Test of Food Materials of Convex Shape. *Trans. ASAE*, PP. 585-592.
- Aydin, C. 2003. Physical Properties of Almond Nut and Kernel. *J. Food Eng.*, **60**: 315-320.
- Aydin, C. and Ozcan, M.M. 2002. Some Physico-mechanic Properties of Terebinth Fruits. *J. Food Eng.*, **53**: 97-10.
- Bargale, P. C. and Irudayaraj, J. 1995. Mechanical Strength and Rheological Behavior of Barley Kernels. *J. Food Sci. Technol.*, **30**: 609-623.
- Baryeh, E. 2000. Strength Properties of Avocado Pear. *J. Agric. Eng. Res.*, **76**: 389-397.
- Braga, G. C., Couto, S. M., Hara, T. and Neto, J. T. P. A. 1999. Mechanical Behaviour of Macadamia Nut under Compression Loading. *J. Agric. Eng. Res.*, **72**: 239-245.
- Burubai, W., Amula, E., Davies, R. M., Etekpe, G. W. W. and Daworiye, S. P. 2008. Determination of Poisson's Ratio and Elastic Modulus of African Nutmeg (*Monodora myristica*). *J. Int. Agrophysics*, **22**(2): 99-102.
- FAO. 2005. *Food and Agricultural Organization*. Available from <http://faostat.fao.org/>.
- Figura, L. O. and Teixeira, A. A. 2007. *Food Physics: Physical Properties Measurement and Application*. Springer-Verlag, Heidelberg, Berlin, PP. 550.
- Grotte, M., Duprat, F., Pitri, E. and Loonis, D. 2002. Young's Modulus, Poisson's Ratio, and Lamé's Coefficient of Golden Delicious Apple. *Int. J. Food Properties*, **5**(2): 333-349.
- Guner, M., Dursun, E. and Dursun, I. G. 2003. Mechanical Behaviour of Hazelnut under Compression Loading. *J. Biosys. Eng.*, **85**(4): 485-491.
- Gupta, R. K. and Das, S. K. 2000. Fracture Resistance of Sunflower Seed and Kernel to Compressive Loading. *J. Food Eng.*, **46**: 1-8.
- Hsu, M. H., Mannapperuma, J. D. and Singh, R. P. 1991. Physical and Thermal

- Properties of Pistachios. *J. Agric. Eng. Res.*, **49**: 311–321.
18. Kashaninejad, M., Mortazavi, A., Safekordi, A. and Tabil, L. G. 2005. Some Physical Properties of Pistachio (*Pistacia vera* L.) Nut and Its Kernel. *J. Food Eng.*, **72**(1): 30–38.
  19. Khazaei, J. and Mann, D. D. 2005. Determining the Modulus of Elasticity of Chickpea Kernels Using the Elasticity Methods. *International Conference on Agrophysics*, 28-31 August, Lublin, Poland, PP. 259.
  20. Khazaei, J. 2003. Force Requirement for Pulling off Chickpea Pods as Well as Fracture Resistance of Chickpea Pods and Grains. Unpublished Ph.D. Dissertation. Department of Agricultural Machinery Engineering, Tehran University, Tehran, Iran.
  21. Khazaei, J., Rasekh M. and Borghei, A. M. 2001. Physical and Mechanical Properties of Almond and Its Kernel Related to Cracking and Peeling. *J. Agric. Sci.*, **7**(2): 63-71. (in Persian)
  22. Koyuncu, M. A., Ekinici, K. and Savran, E. 2004. Cracking Characteristics of Walnut. *J. Biosys. Eng.*, **87**(3): 305-311.
  23. Maghsoudi, H., Khoshtaghaza, M. H. and Minaei, S. 2008. Some Phsico-mechanic Properties of Unsplit Pistachio Nut. *International Conference of Agricultural Engineering and Industry Exhibition*, 23-25 June, Hersonissos, Crete, Greece, PP. 108.
  24. Maghsoudi, H., Khoshtaghaza M. H. and Minaei, S. 2010. Selected Geometric Characteristics, Density, and Mechanical Properties of Unsplit Pistachio Nut. *Int. J. Food Properties*, **13**: 394–403
  25. Mohsenin, N. N. 1986. *Physical Properties of Plants and Animal Materials*. Gordon and Breach Science Publishers, New York, NW, 742 PP.
  26. Olaniyan, A. M. and Oje, K. 2002. Some Aspects of the Mechanical Properties of Shea Nut. *J. Biosys. Eng.*, **81**(4): 413–420.
  27. Oloso, A. O. and Clarke, B. 1993. Some Aspects of Strength Properties of Cashew Nuts. *J. Agric. Eng. Res.*, **55**: 27–43.
  28. Ozden, K. and Alayunt, F. N. 2006. The Determination of Some Physical Properties of *Pistachio vera* L. *Pakistan J. Biologic. Sci.*, **9**(14): 2612-2617.
  29. Pearson, T. C., Slaughter, D. C. and Studer, H. E. 1994. Physical Properties of Pistachio Nuts. *Trans. ASAE*, **37**(3): 913-918.
  30. Razavi, S. M. A., Emadzadeh, B., Rafe, A. and Mohammad Amini, A. 2007a. The Physical Properties of Pistachio Nut and Its Kernel as a Function of Moisture Content and Variety. Part I. Geometrical Properties. *J. Food Eng.*, **81**: 209–217.
  31. Razavi, S. M. A., Rafe, A., Mohammadi Moghaddam, T. and Mohammad Amini, A. 2007b. The Physical Properties of Pistachio Nut and Its Kernel as a Function of Moisture Content and Variety. Part II. Gravimetric Properties. *J. Food Eng.*, **81**: 218–225.
  32. Razavi, S. M. A., Mohammad Amini, A., Rafe, A., and Emadzadeh, B. 2007c. The Physical Properties of Pistachio Nut and Its Kernel as a Function of Moisture Content and Variety. Part III. Frictional Properties. *J. Food Eng.*, **81**: 226–235.
  33. Razavi, S. M. A. and Taghizadeh, M. 2007. The Specific Heat of Pistachio Nuts as Affected by Moisture Content, Temperature, and Variety. *J. Food Eng.*, **79**: 158–167.
  34. Shitanda, D., Nishiyama, Y. and Koide, S. 2001. Compressive Strength Properties of Rough Rice Considering Variation of Contact area. *J. Agric. Eng.*, **53**: 53-58.
  35. Singh K. K. and Goswami, T. K. 1998. Mechanical Properties of Cumin Seed (*Cuminum cyminum* Linn.) under Compressive Loading. *J. Food Eng.*, **36**: 311-321.
  36. Sitkei, G. 1986. *Mechanics of Agricultural Materials*. Elsevier Science Publishers, Budapest, Hungary, PP.483.
  37. Vursavus, K. and Ozguven F. 2005. Fracture Resistance of Pine Nut to Compressive Loading. *J. Biosys. Eng.*, **90**(2): 185–191.
  38. Woodroof, J. G. 1979. *Tree Nuts: Production, Processing, Products*. 2<sup>nd</sup> Edition, AVI Publishing Company, Westport, Conn, PP. 588.
  39. Zaki Dizaji, H. and Minaei, S. 2008. Determination of Some Chickpea Physical and Mechanical Properties in Relation to Quantitative Losses. *Iranian J. Food Sci. Technol.*, **4**(2): 57-66.
  40. Zhang Q., Yang W. and Sun Z. 2005. Mechanical Properties of Sound and Fissured Rice Kernels and Their Implications for Rice Breakage. *J. Food Eng.*, **68**: 65–72.



## مقاومت شکست پسته دهان بسته (*Pistacia vera* L.) به منظور خندان کردن تحت بارگذاری فشاری

ح. مقصودی، م. ح. خوش تقاضا، س. مینائی و ح. ذکی دیزجی

### چکیده

خواص مکانیکی پسته دهان بسته برای طراحی تجهیزات فرآوری مورد نیاز است. در این تحقیق به منظور تعیین نیرو و انرژی خندان کردن، ضریب پواسون و همچنین ضریب کشسانی نمونه های پسته دهان بسته را به صورت محوری تحت بارگذاری قرار گرفتند. تمامی آزمایش ها در چهار رطوبت (۵، ۱۰، ۱۵ و ۲۰% w.b.)، چهار سرعت بارگذاری (۱۰، ۲۰، ۳۰ و  $40 \text{ mm min}^{-1}$ ) و برای دو رقم (اوحدی و بادامی) انجام گرفت. بالاترین مقدار نیروی خندان کردن برای هر دو رقم،  $281/9 \text{ N}$  برای بادامی و  $102/4 \text{ N}$  برای اوحدی، در رطوبت ۵% w.b. و سرعت بارگذاری  $40 \text{ mm/min}$  حاصل شد، در حالیکه کمترین مقدار نیرو  $97 \text{ N}$  برای بادامی و  $16/8 \text{ N}$  برای اوحدی در رطوبت ۲۰% w.b. و سرعت  $10 \text{ mm/min}$  به دست آمد. برای مقدار انرژی مورد نیاز برای خندان کردن پسته های دهان بسته در بین دو رقم اوحدی و بادامی رفتار متفاوتی در مقابل افزایش مقدار رطوبت و سرعت بارگذاری مشاهده شد. با افزایش مقدار رطوبت ضریب پواسون به ترتیب از  $0/374$  تا  $0/388$  و  $0/326$  تا  $0/337$  برای رقم اوحدی و بادامی افزایش پیدا کرد. ضریب کشسانی در هر دو رقم با مقدار رطوبت رابطه عکس و با سرعت بارگذاری رابطه مستقیم نشان داد. افزایش مقدار رطوبت از ۵ تا ۲۰% باعث کاهش ضریب کشسانی دانه ها از  $322/59 \text{ MPa}$  تا  $223/23 \text{ MPa}$  و از  $816/25$  تا  $719/28 \text{ MPa}$  به ترتیب برای رقم اوحدی و بادامی شد.