Quality Assurance and Safety of Crops & Foods, June 2013; 5 (2): 145-156

Wageningen Academic Publishers

Engineering characterization of Persian walnut and its kernel (*Juglans regia* L.) for obtaining high quality produce

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Received: 27 December 2011 / Accepted: 27 February 2012

RESEARCH PAPER

Abstract

Knowledge of walnut fruits properties as a function of moisture content is crucial for the efficient processing of the product and optimizing oil extraction. Several engineering properties such as average geometric diameter, unit mass, surface area, volume and sphericity were evaluated in Persian walnut and its kernel. All the parameters increased as the moisture content increased from 3.41 to 17.65% dry basis. For the bulk density, true density, porosity and repose angle of nuts, the moisture dependent changing ranges were 315.51-300.12 kg/m^3, 688.05-664.83 kg/m^3, 54.11-54.85%, 38.05-39.1°, respectively, while the corresponding values for kernels were 377-364 kg/m^3, 1,043.6-1,028.7 kg/m^3, 63.87%-64.61%, and 40.6-41.5°, respectively. The static coefficients of friction range on glass, steel, galvanized iron sheet and plywood were 0.284-0.293, 0.276-0.301, 0.307-0.321 and 0.404-0.426 for nuts and 0.322-0.332, 0.312-0.323, 0.348-0.360 and 0.443-0.451 for kernels, respectively. The force required for initiating nut rupture at a loading rate of 50 mm/min decreased from 534.2 to 406.7 N, 69.6 to 26.92 N and 195.2 to 133.3 N, by increasing moisture content for x-, y-, and z-axis orientations, respectively. With an increase in the moisture content, the absorbed energy for fracture of walnut and its kernel increased. Kernel fracture was more resistant in the z-axis orientation of loading for all moisture content levels.

Keywords: compression loading, mechanical properties, moisture content, Persian walnut, physical properties

1. Introduction

Walnut is one of the oldest cultivated fruits in the world. Walnut belongs to the *Juglandaceae* family, *Juglans* variety *Juglans regia* L. World production of walnuts exceeds almost 1,500,000 metric tons (Gharibzahedi *et al.,* 2011b). China, the United States and Iran were the major producers, with about 25%, 20% and 11% of total global production, respectively. The production in these countries has increased rapidly in recent years (FAO, 2002). Walnut fruit has a high nutritional value and high-quality wood. Walnut has a high calorie level and rich nutrient composition. When it is consumed in sufficient quantity, it can significantly contribute to daily diet and has medical importance because of presence of specific compounds like polyunsaturated fatty acids (Gharibzahedi *et al.,* 2011b; Martinez *et al.*, 2008).

Engineering properties of biological materials including shape, size, mass, bulk density, true density, porosity, static friction coefficient against various surfaces and rupture characteristics are important to design an equipment for processing, transportation, sorting, separation and storing of such material (Balasubramanian, 2001; Braga *et al.,* 1999; Gharibzahedi *et al.,* 2010b).

The information of the morphology and size distribution of walnuts is essential for the accurate design of the equipment for cleaning, grading and separation. Gravimetric properties are important in design of equipment related to aeration, drying, storage and transport. Bulk density determines the capacity of storage and transport systems, while true density is useful for separation equipment. Porosity of the mass of nuts and kernels determines the resistance to air flow during their aeration and drying (Gharibzahedi *et al.,* 2012a). The frictional properties such as the angle of repose and the coefficient of external friction are recognized by engineers as important properties concerned with rational design of nut/kernel bins and other storage structures including the compressibility and flow behaviour of materials (Baryeh, 2002; Baryeh *et al.,* 2001). Moreover, the information of fracture characteristics of nut and kernel is imperative for a rational design of efficient grinding systems, as well as the optimization of the process and product parameters. In addition, physical and mechanical characteristics vary extensively with seed moisture content and are important to the process/product designer because post-harvest operations like blanching, steeping/soaking, cooking and washing of seeds involve hydration (Pliestic *et al.,* 2006; Vursavus and Ozguven, 2004).

Physical and mechanical properties have recently been studied for various nut crops such as macadamia nut (Braga *et al.,* 1999), raw cashew nut (Balasubramanian, 2001), hazelnuts (Aydin, 2002; Güner *et al.,* 2003), arecanut kernel (Kaleemullah and Gunasekar, 2002), groundnut kernel (Olajide and Igbeka, 2003), almond nut and kernel (Aydin, 2003), shea nut (Olaniyan and Oje, 2002) and pine nuts (Gharibzahedi *et al.,* 2010a).

Therefore, the objective of this study was to determine physical and mechanical properties of the Persian walnut (*Juglans regia* L.) and the kernel as well as the effect of moisture content on these properties. The range of moisture content selected was 3.41% to 17.65% dry basis (d.b.) since all processing operation and storage are performed in this moisture range.

2. Materials and methods

Material and sample preparation

Dried walnut (cv. Toyserkan) seeds were used for all experiments in this study. The crop was collected from Hamedan province located in the western region of Iran during the summer of 2008. The nuts were cleaned in a clean air screen to remove impurities, and after being cracked, the kernels were separated from the shell by hand. Samples were kept in a refrigerator until analyses were performed.

Measurements of physical properties

The moisture content of the samples (nut and kernel) was determined by using the AOAC official method 925.40 (AOAC, 2002). To obtain higher moisture contents than initial, the samples were prepared by adding a pre-determined quantity of distilled water and sealing in separate polyethylene bags. The samples were kept at 5 °C in a refrigerator for 1 week to enable the moisture to distribute uniformly. Before starting the experiment, the samples were kept at room temperature for 2 h. All the physical properties of the samples were assessed at moisture levels of 3.41%, 6.35%, 9.75%, 15.5% and 17.65% d.b. with five replications at each level.

To determine the average size of the seed, 100 seeds were randomly picked and their three linear dimensions, namely length (L), width (W) and thickness (T), were measured using a digital versnier caliper with an accuracy of 0.01 mm. The geometric mean diameter (D_g), sphericity (Φ), surface area (S) and volume (V) of walnuts were calculated by the following relationships (Mohsenin, 1986):

$$D_g = (LWT)^{1/3} \quad (1)$$

$$\Phi = \frac{(LWT)^{1/3}}{L} \quad (2)$$

$$S = \pi D_g^2 \quad (3)$$

$$V = \frac{\pi}{6}(LWT) \quad (4)$$

Sample unit mass was determined by means of an electronic balance reading to 0.001 g (B310P, Sartorius, Göttingen, Germany). The bulk density (ρ_b), the ratio of the nuts and kernel mass to a certain volume was determined with a weight per hectolitre tester, which was calibrated in kg/m^3 (Gharibzahedi *et al.,* 2010a). Volume of kernels and true density (ρ_t) were measured by the liquid displacement method. Toluene (C_7H_8) was used, rather than water, because it was not absorbed by the seeds and its surface tension is less than that of water, therefore it fills even shallow dips in a seed and its dissolution power is low (Gharibzahedi *et al.,* 2011a). According to Mohsenin (1986) the porosity (ε) can be expressed as follows:

$$\varepsilon = 1 - \left(\frac{\rho_b}{\rho_t}\right) \quad (5)$$

Where: ε is the porosity (%); ρ_b is the bulk density (kg/m^3); and ρ_t is the true density (kg/m^3).

The angle of repose (α) was determined by the method applied by Gharibzahedi *et al.* (2010a). The static coefficients of friction of the samples against four different surfaces, namely plywood, glass, steel and galvanized iron sheet were determined according to the technique introduced by Pliestic *et al.* (2006). A fiberglass box of 150 mm length, 100 mm width and 40 mm height without base and lid was filled with a sample and placed on an adjustable tilting plate, faced with the test surface. The sample container was raised slightly (5-10 mm) so as not to touch the surface. The inclination of the test surface was increased gradually with a screw device until the box just started to slide down and the angle of tilt (θ) was read from a graduated scale. For each replication, the sample in the container was emptied and refilled with a new sample. The coefficient of friction (μ) was calculated from the following relationship:

$\mu = \tan(\theta)$ (6)

Measurements of mechanical properties

Mechanical properties of walnut and kernel were measured by an Instron Universal Testing Machine (Model SMT-5, SANTAM Company, Tehran, Iran) equipped with a 50 N load cell and integrator (Gupta and Das, 2000). The measurement accuracy was ±0.001 N in force and 0.001 mm in deformation. The individual nut and kernel was loaded between two parallel plates of the machine and compressed along the three orthogonal axes: x-axis, y-axis and z-axis (as explained by Koyuncu *et al.* 2004) until rupture occurred as denoted by a rupture point in the force-deformation curve. The rupture point is a point on the force-deformation curve at which the loaded specimen shows a visible or invisible failure in the form of breaks or cracks. This point is detected by a continuous decrease of the load in the force-deformation diagram (Gharibzahedi *et al.,* 2012b). While the rupture point was detected, the loading was stopped. In the moisture range from 3.41 to 17.65% d.b., these tests were carried out at the loading rate of 50 and 10 mm/min for walnut and its kernel, respectively. The selected loading rate for nuts and kernels were determined after primary experiments based on the best kernel extraction quality and time and energy saving items. Energy absorbed by the sample at rupture was determined by calculating the area under the force-deformation curve by means of a digital planimeter (Model 1250-1, Numonics Corp., Lansdale, PA, USA) (Altuntas and Erkol, 2011).

Statistical analysis

The results obtained from the physical and mechanical tests were subjected to analysis of variance (ANOVA) and Duncan's test using SPSS 13 software (SPSS Inc., Armonk, NY, USA).

3. Results and discussion

Physical properties

Dimensions, size distribution and unit mass of walnut and kernel

A summary of the results of determined physical dimensions of walnut and its kernel is presented in Table 1. These results explain the average value, maximum, minimum and standard deviation of each measurement at a moisture content of 3.41% d.b. The frequency distribution curves of walnuts showed that about 88% of the nuts had a length in the range of 32-38 mm, about 83% had a width in the range of 29-33 mm and about 76% had a thickness in the range of 29-33 mm. Also, about 94% of the kernels had a length in the range of 24-28 mm, about 77% had a width in the range of 23-26 mm and about 81% had a thickness in the range of 8-11 mm. The mean values of 100 measurements were: 35.43 mm for length, 32.10 mm for width, 31.57 mm for thickness and 5.09 g for unit mass of raw walnut at a moisture level of 3.41% d.b. The corresponding values of the kernel were 25.76 mm, 25.69 mm, 9.85 mm and 5.90 g, respectively. The values of dimensions and mass of walnuts are found to be higher than that of hazelnut (Aydin, 2002) and filbert nuts (Pliestic *et al.,* 2006), but lower than that of cashew nut (Balasubramanian, 2001). The walnut kernels are longer and wider than hazelnut kernels (Aydin, 2002), but hazelnut kernels are thicker. Unit mass value for raw walnut and its kernel were 11.56 and 5.90 g at a moisture level of 3.41% d.b., respectively.

The geometric mean diameter of the walnuts was found to be 32.87 mm. This value is much higher than the corresponding walnut kernel value of 18.08 mm. The geometric mean diameter for nut and kernel was higher than for pistachio nut (12.97 and 10.65 mm, respectively),

Table 1. Dimensions and unit mass of the studied walnut and its kernel at 3.41% dry basis.

Parameter	No. of observations	Minimum	Mean	Maximum	Standard deviation
Nut					
Length (mm)	100	29.51	35.43	40.71	2.33
Width (mm)	100	27.54	32.10	37.71	1.92
Thickness (mm)	100	24.44	31.57	36.24	2.14
Geometric mean diameter (mm)	100	26.99	32.87	38.03	2.10
Mass (g)	100	9.62	11.56	14.17	1.52
Kernel					
Length (mm)	100	23.89	25.76	28.44	1.42
Width (mm)	100	23.08	25.69	28.28	1.33
Thickness (mm)	100	7.44	9.85	12.80	1.57
Geometric mean diameter (mm)	100	16.00	18.59	21.75	1.08
Mass (g)	100	62.33	72.16	77.97	5.07

pine nut (11.23 and 7.10 mm, respectively) and hazelnut varieties (16.52-18.56 and 12.20-14.17 mm, respectively) (Güner *et al.,* 2003; Kashaninejad *et al.,* 2006; Ozguven and Vursavus, 2005).

The regression relationship and coefficient of determination (R^2) values obtained by fitting the experimental data of between length, width, thickness, unit mass and moisture content of walnut and its kernel are presented in Table 2. These equations can be used specifically in the design of harvesting, threshing and separating processes. The three axial dimensions increased by an increase in moisture content from 3.41 to 17.65% d.b. The dimensional increases in nut length, width and thickness were 0.67, 0.46 and 0.38%, respectively, whereas the corresponding values for kernels were 0.31, 0.23 and 1.11%. Differences between the values were statistically significant ($P<0.05$). The average geometric diameter increased with the increase in moisture content like axial dimensions. The geometric mean range diameter for walnut and its kernel changed from 32.87 to 33.04 and 18.59 to 18.72 mm as the moisture content increased from 3.41 to 17.65% d.b., respectively ($P<0.05$). In addition, unit mass of walnut and kernel varied from 11.56 to 11.66 and 5.09 to 5.16 g as the moisture content increased from 3.41 to 17.65% d.b., respectively ($P<0.05$). Therefore, the increase of unit mass for walnut and its kernel was 0.86 and 0.98%, respectively. Similar trends have been reported by Visvanathan *et al.* (1996) and Baryeh (2001) in the case of neem nuts and bambara groundnuts, respectively. The general relationship between the unit mass of walnut and kernel and moisture content is given in Table 2.

Volume

The volume of nut increased linearly with the moisture content from 18,790.1 mm^3 at 3.41% d.b. to 19,078.3 mm^3 at 17.65% d.b., while the volume of kernel increased from 3,410.3 to 3,468.2 mm^3. Aviara *et al.* (1999) and Baryeh (2002) have reported a linear increase in seed volume with increasing moisture content for guna seeds and millet seeds, respectively. The reason for this increase was probably due to swelling of the plant tissue. This indicated that drying of nuts and kernels of higher moisture contents may result in their shrinkage due to a decrease in the dimensions. Altuntas and Ozkan (2008) found the mean values of volume to be 10.68 cm^3 at 5.1% d.b. for walnut, which is lower compared to the value for the same moisture content in this study due to the lower linear dimension of variety they used. The relationship between volume (V) (w: walnut; k: kernel) and moisture content (Mc) can be represented by the following regression equations:

$$V_w = 18{,}679 - 21.704\ Mc \qquad R^2 = 0.985 \qquad (7)$$

$$V_k = 3{,}396.8 + 3.956\ Mc \qquad R^2 = 0.993 \qquad (8)$$

The relationship between volume of walnut and kernel, and moisture content was found to be significant at $P<0.05$.

Surface area

Variation of the surface area with moisture content showed that the surface area of walnut and kernel increases linearly by increasing in moisture content. Similar trends have been reported for other nuts and kernels such as neem nut (Viswanathan *et al.,* 1996), bambara groundnuts (Baryeh, 2001), almond and kernel (Aydin, 2003) and pistachio nut and kernel (Kashaninejad *et al.,* 2006). These changes had significant effects on surface area ($P<0.05$). This fact can be attributed to the increase in the dimensions with expansion or swelling as the result of moisture uptake in the intracellular spaces within the nuts and kernels. The ratio between volume and surface area is generally described as the characteristic length. As this ratio increases, the heat and mass transfer rates from nuts/kernels increases, facilitating heating, drying and cooling operations and thus indicating the enhancement of the product quality (Baryeh *et al.,* 2001). The relationship between moisture content and surface area of walnut and kernel can be expressed in the following equations:

$$S_w = 3383 - 2.441\ Mc \qquad R^2 = 0.988 \qquad (9)$$

$$S_k = 1081.5 + 1.057\ Mc \qquad R^2 = 0.998 \qquad (10)$$

Table 2. The relationships between dimensions and unit mass of Persian walnut and its kernel and moisture content (Mc).

Parameter	Nut		Kernel	
	Equation	R^2	Equation	R^2
Length	L = 35.36 + 0.017 Mc	0.998	L = 25.74 + 0.005 Mc	0.982
Width	W = 32.06 + 0.009 Mc	0.912	W = 25.69 + 0.0041 Mc	0.976
Thickness	T = 31.53 + 0.008 Mc	0.993	T = 9.83 + 0.007 Mc	0.984
Geometric mean diameter	D_g = 32.83 + 0.011 Mc	0.995	D_g = 18.57 + 0.008 Mc	0.939
Mass	M = 11.54 + 0.006 Mc	0.986	M = 5.077 + 0.004 Mc	0.972

Sphericity

The values of sphericity were calculated individually with Equation 2, by using the data on geometric mean diameter and the length of the walnut and kernel. The results are presented in Figure 1. The sphericity is the shape character of the solid relative to that of a sphere of the same volume. The suitable product shape can be determined in terms of its sphericity which affects the flow ability characteristics. The sphericity of walnut insignificantly decreased from 92.77 to 92.63% and that of kernel increased from 72.16 to 72.47% due to an increase in moisture content from 3.41% to 17.65% d.b. The variations in sphericity with moisture content of walnut and kernel can be represented by the following relationships:

$$\Phi_w = 92.8 - 0.0082\ Mc \qquad R^2 = 0.983 \qquad (11)$$

$$\Phi_k = 72.10 + 0.0198\ Mc \qquad R^2 = 0.983 \qquad (12)$$

Density

The bulk density of nuts and kernels decreased significantly ($P<0.05$) as the moisture content increased (Figure 2). Viswanathan *et al.* (1996), Aydin (2003) and Pliestic *et al.* (2006) also observed such negative linear relationship between bulk density and moisture content for neem nut, almond nut and filbert nut, respectively. This could be due to the fact that an increase in mass owing to the moisture gain in nut and kernel was lower than accompanying volumetric expansion (Pliestic *et al.,* 2006). The reduction in the bulk density could also be associated to the reduction in sphericity at higher moisture content which could cause loose packing patterns of nuts and increased bulk volume (Balasubramanian, 2001). However, Hsu *et al.* (1991) observed opposite results for the pistachio nuts. This discrepancy could be due to the cell structure and the volume and mass increase characteristics of the grains, seeds and nuts and their kernels as moisture content increases. The bulk densities of nut and kernel were found to bear the following relationships with their corresponding moisture contents:

$$\rho_{bw} = 319.1 - 1.043\ Mc \qquad R^2 = 0.983 \qquad (13)$$

$$\rho_{bk} = 380.5 - 0.901\ Mc \qquad R^2 = 0.944 \qquad (14)$$

Effect of moisture content on the true density for both walnut and kernel is shown in Figure 2. The true density of walnut and kernel was found to decrease significantly ($P<0.05$) as moisture content increases. Similar results are reported by Aviara *et al.* (1999) for guna seeds, Baryeh (2001) for bambara groundnuts, Kaleemullah and Gunasekar (2002) for arecanut kernels and Pliestic *et al.* (2006) for filbert nut in the moisture range of 4-39.3% d.b. The decrease in true density values by increasing in moisture content may be due to a lower weight increase of nut/kernel in comparison with its volume expansion on moisture gain. However, in contrast, some reports reveal an increase in the true density by increasing moisture content (Baryeh, 2002; Gharibzahedi *et al.,* 2010a,b; Kashaninejad *et al.,* 2006; Pliestic *et al.,* 2006). The grain mass increase in comparison to its volume increase as its moisture content increases, in the crops that were subjects of research of the mentioned authors, is the main reason for this observation.

This decrease trend will affect the flow ability and aerodynamic characteristics such as terminal velocity of nuts and kernels (Gharibzahedi *et al.,* 2010a). These properties are useful for air conveying or pneumatic

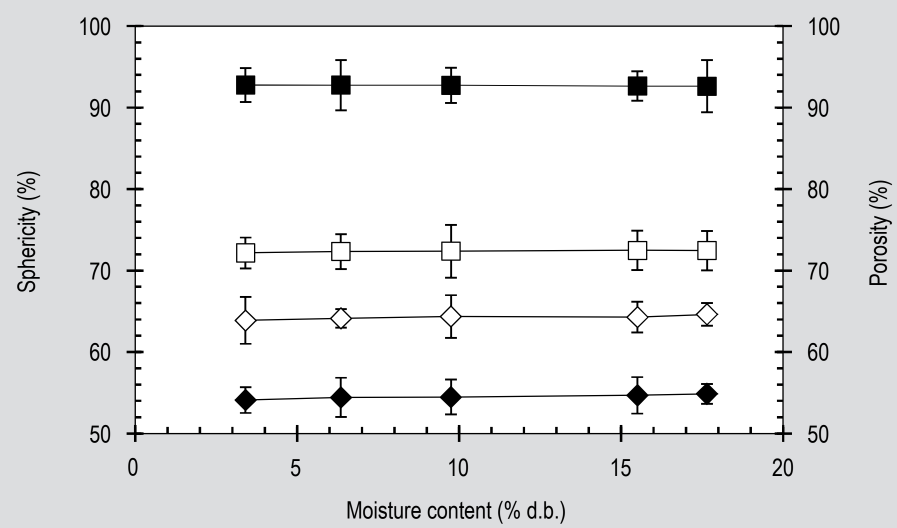

Figure 1. Effect of moisture content on sphericity (black squares = nut; white squares = kernel) and porosity (black diamonds = nut; white diamonds = kernel) of Persian walnut.

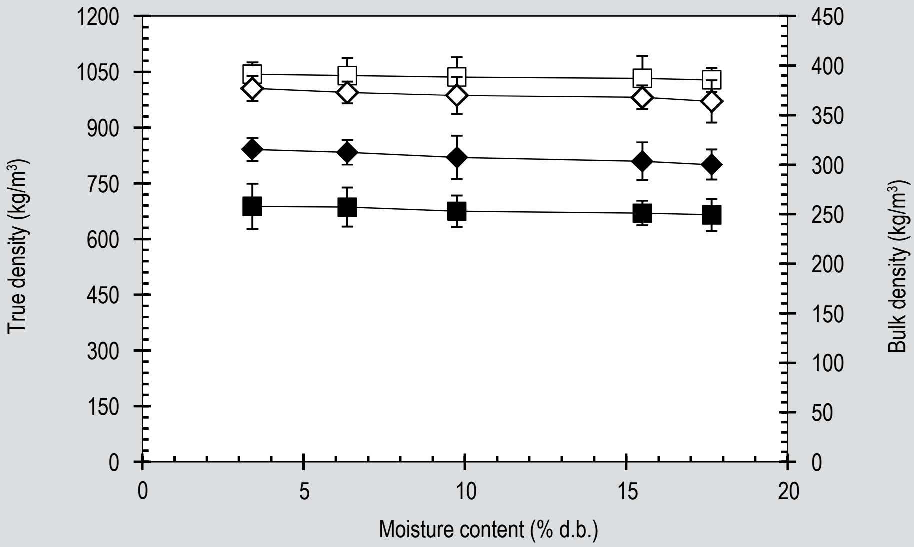

Figure 2. Effect of moisture content on true density (black squares = nut; white squares = kernel) and bulk density (black diamonds = nut; white diamonds = kernel) of Persian walnut.

separation of materials in such a way that when the air velocity is greater than the terminal velocity, it lifts the particles. The air velocity at which the nut/kernel remains in suspension is considered as terminal velocity (Gharibzahedi *et al.,* 2010a, 2011a). Therefore, the rate of air transfer in cleaners and driers, and subsequently maintenance of product quality can improve by application of the regression relationship between the values of the true density and moisture content. The true densities of nut and kernel were found to fit the following relationships with their corresponding moisture contents:

$$\rho_{tw} = 692.3 - 1.558\ Mc \qquad R^2 = 0.991 \qquad (15)$$

$$\rho_{tk} = 1{,}046.4 - 1.038\ Mc \qquad R^2 = 0.980 \qquad (16)$$

Porosity

The experimental results of the porosity for walnut and its kernel at different moisture contents are also presented in Figure 1. The porosity of both nut and kernel of walnut was found to increase slightly by increasing moisture from 3.41 to 17.65% d.b. The porosity of nut increased from 54.11 to 54.85%, while porosity of kernel increased from 63.87 to 64.61%. Changes in the porosity of nut and kernel against moisture content were not significant. Since the porosity depends on bulk and true densities, the magnitude of variation in porosity depends only on these factors. Therefore, the dependency of porosity on these densities is definitely different for each seed or nut by increasing moisture content. Higher porosity values provide better aeration and water vapour diffusion during deep bed drying, and the data may be utilized for design of aeration systems. The relationship between the porosity of walnut and its kernel, and moisture content can be represented by the following regression equation:

$$\varepsilon_w = 0.0039\ Mc^2 + 0.0346\ Mc + 54.223 \qquad R^2 = 0.948 \qquad (17)$$

$$\varepsilon_k = 0.0032\ Mc^2 + 0.0164\ Mc + 63.903 \qquad R^2 = 0.918 \qquad (18)$$

Angle of repose

Experimental values of repose angle of walnut and its kernel increased significantly ($P<0.05$) by increasing moisture. It seems that at a higher moisture content nut and kernel might tend to stick together due to the plasticity effect (stickiness) over the surface of the nut and kernel resulting in the increase of the angle of repose (Gharibzahedi *et al.,* 2011a). Also, a linear increase in angle of repose as the seed moisture content increases has been noted by Visvanathan *et al.* (1996) for neem nuts. However, Baryeh *et al.* (2001) and Aviara *et al.* (1999) found the increase in moisture content to be nonlinear for guna seeds and bambara groundnuts, respectively. These contradictions might be due to differences in the surface roughness of grains or seeds as they were wet (Baryeh, 2001). The relationship between moisture content and angle of repose can be represented by the following equation:

$$\alpha_w = 38.35 + 0.0417\ Mc \qquad R^2 = 0.998 \qquad (19)$$

$$\alpha_k = 38.61 + 0.1606\ Mc \qquad R^2 = 0.994 \qquad (20)$$

The repose angle, as other engineering parameters, is expressed in the form of regression equations as a function of the moisture content. Once the moisture content is known, the parameters can be obtained from these equations. As the moisture content depends on weather conditions, these equations can be used for other environmental conditions than those of Iran. The data would be useful for suitable design of hoppers and storage bins, thus enhancing process and quality control of the nut and kernel of walnuts in Iran as well as other countries.

Static coefficient of friction

The static and dynamic coefficients of friction for walnut and kernel determined with respect to glass, plywood, steel and galvanized sheet surfaces are presented in Figure 3. It was observed that the static coefficient of friction increased by increasing in moisture content for all the surfaces ($P<0.05$). It seems that at higher moisture contents the nut and kernel became rougher and its sliding characteristics were diminished, therefore the coefficient of static friction increased. Also due to increasing the stickiness and adhesion between nuts or kernels and material surfaces at higher moisture contents, the resulting adhesive force plays an important role in increasing the value for the coefficient of static friction.

The design of hoppers, bunker silos and other bulk solid storage and handling structures should ensure non-arching (that is, avoiding stoppage of flow of bulk solids). The coefficient of mobility, which represents the freedom of motion of a substance, is inversely related to the coefficient of friction (tangent of angle of internal friction). The higher the coefficient of friction, the lower the mobility coefficient, and hence the larger the hopper opening and hopper side wall slope and the steeper angle of inclination is required in inclined grain transporting equipment. Optimum design will avoid immature flow (where some depth of granular particles remains stationary) and the arching phenomena to ensure a fully developed sliding flow (Gharibzahedi *et al.*, 2011a).

Similar results were published by other authors (Gharibzahedi *et al.,* 2010a; Kashaninejad *et al.,* 2006; Pliestic *et al.,* 2006). At all moisture contents, the static coefficient of friction for nut was greatest against plywood (0.404-0.426), followed by galvanized iron sheet (0.307-0.321), steel (0.276-0.301) and least for glass (0.284-0.293), while for kernel, the static coefficient of friction was greatest on plywood (0.443-0.451), followed by galvanized iron sheet (0.348-0.360), glass (0.322-0.332) and least for steel (0.312-0.323). The coefficient of friction has also been found to be higher on plywood than on galvanized iron for millet seeds (Baryeh, 2002) and black cumin seeds (Gharibzahedi *et al.,* 2010b). This may be attributed to smoother and more polished surface of galvanized iron compared to plywood. The regression equations and their R^2 values obtained by fitting the experimental data of coefficient of static friction as a function of moisture content are listed in Table 3. It can be noted that the coefficient of static friction of walnut and its kernel has a linear relationship with moisture content in all friction surfaces.

Mechanical properties

Rupture force

The average forces required for rupturing walnuts and kernels in three loading orientations as a function of moisture content are given in Figure 4A and 4B. During

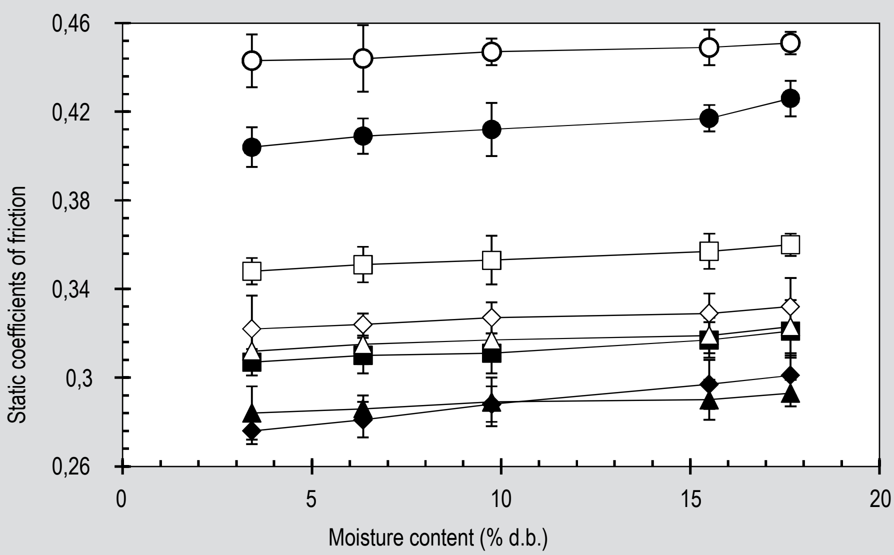

Figure 3. Effect of moisture content on static coefficient of friction of nut (black circle = plywood; black square = galvanized iron sheet; black triangle = glass; black diamond = steel) and kernel (white circle = plywood; white square = galvanized iron sheet; white triangle = glass; white diamond = steel) of Persian walnut.

Table 3. The relationships between static coefficient of friction (μ) of Persian walnut and kernel and moisture content (Mc).

Parameter	Nut		Kernel	
	Equation	R^2	Equation	R^2
Galvanized iron sheet	μ = 0.303 + 0.001 Mc	0.962	μ = 0.345 + 0.0001 Mc	0.987
Glass	μ = 0.283 + 0.0006 Mc	0.942	μ = 0.310 + 0.0001 Mc	0.941
Plywood	μ = 0.399 + 0.001 Mc	0.928	μ = 0.441 + 0.001 Mc	0.977
Steel	μ = 0.270 + 0.001 Mc	0.998	μ = 0.320 + 0.0001 Mc	0.969

the drying or rewetting processes of whole nuts, to a desired moisture content, it is not possible to control the moistures of shell and kernel. The force required to initiate nut rupture decreased significantly ($P<0.01$) in the x-axis, y-axis and z-axis orientations as the moisture content increased from 3.41 to 17.65% d.b. (Figure 4A). Similar trends were also observed by Aydin (2003) for almond nut, Pliestic *et al.* (2006) for filbert nut and Aydin (2002) for hazelnut. This decrease might have resulted from the fact that when the nut absorbed water, the shell became soft and weak. This weakness was responsible for the initial reduction in rupture force. The nut loaded in the x-, y- and z-axis orientation, respectively, required 534.2, 69.6 and 195.2 N at 3.41% d.b. and 406.7, 26.92 and 133.3 N at 17.65% d.b. to initiate shell rupture. Therefore, the force decrease in the x-, y- and z-axis for nut orientation was 23.86, 61.32 and 31.71 N as the moisture content increased from 3.41 to 17.65% d.b., respectively. These results indicated that walnut required less compressive force to rupture when loaded under the y-axis as compared to the x- and z-axis orientation. Thus, the cracking operation of the walnut with a maximum of kernel quality should be designed by forming the nuts in the y-axis orientation of loading at a moisture content of 17.65% d.b.

Pliestic *et al.* (2006) obtained a similar result working with filbert nut. They proved that the maximum force for filbert nut rupture occurred in the x-axis orientation and the minimum force transversely in y-axis direction, in the moisture range from 6.19 to 28.71% d.b. This fact could be due to the similar range for moisture content, nut size and dimensions, and the loading rate applied for mechanical damage.

However, for hazelnut (Aydin, 2002), almond nut (Aydin, 2003), shea nut (Olaniyan and Oje, 2002), apricot pit (Vursavus and Ozguven, 2004) and macadamia nut (Braga *et al.*, 1999), the highest force was obtained from nuts loaded along the width position, while those loaded along the length position required the least force to crack. This discrepancy can be attributed to variations in the shape and moisture content of the used nuts.

Variation in kernel rupture force by an increase in moisture content is somewhat more different than the variation of the nut rupture force. The effect of moisture content and orientation of loading on the kernel rupture force is presented in Figure 4B. It can be seen that, rupture force decreases as moisture content increases for all three axes from 3.41 to 17.65% d.b ($P<0.05$). The linear relationship of the kernel rupture force with moisture content was also observed by Arslan and Vursavus (2008) and Gupta and Das (2000) for almond kernel and sunflower kernel, respectively. The low rupture forces at higher moisture contents might have resulted from the fact that the kernel tended to be very soft at high moisture content. The kernel loaded in the x-, y- and z-axis orientation required 15.77, 9.31 and 22.54 N at 3.41% d.b. and 14.50, 8.23 and 20.38 N at 17.65% d.b, respectively, to initiate kernel rupture. Therefore, the kernel loaded in a y-axis orientation ruptured at a lower force than the kernel loaded in the x-axis orientation. Thus, the force required for initiating kernel rupture in the y-axis orientation was 59% lower than the x-axis orientation at 3.41% d.b. Furthermore, this value was 56.75%, at a moisture level of 17.65% d.b. These results indicate that walnut kernels required less compressive force to extract the kernel when loaded along the y-axis as compared to the other two compression axes. Similar trends were also observed by Vursavus and Ozguven (2004) for apricot pit and by Pliestic *et al.* (2006) for filbert nut. Cold-press technique is a commercially available method to oil extraction from walnut kernels (Gharibzahedi *et al.*, 2011b). In the cold-pressed products minor components are affected, thus colour, flavour and other quality players of the oil are preserved (Parry and Yu, 2004). Martinez *et al.* (2008) found that the highest recovery (89.3%) and quality of oil during screw-pressing of walnut kernels was obtained at 7.5% d.b. From a technological point of view, it might be concluded that the optimum kernel rupture force is obtained in along the y-axis and at a moisture content of 6.35% d.b. Table 4 gives the parameters of the equations and their R^2 values for the relationship between the rupture force and the moisture content of walnut and its kernel under different orientations of loading.

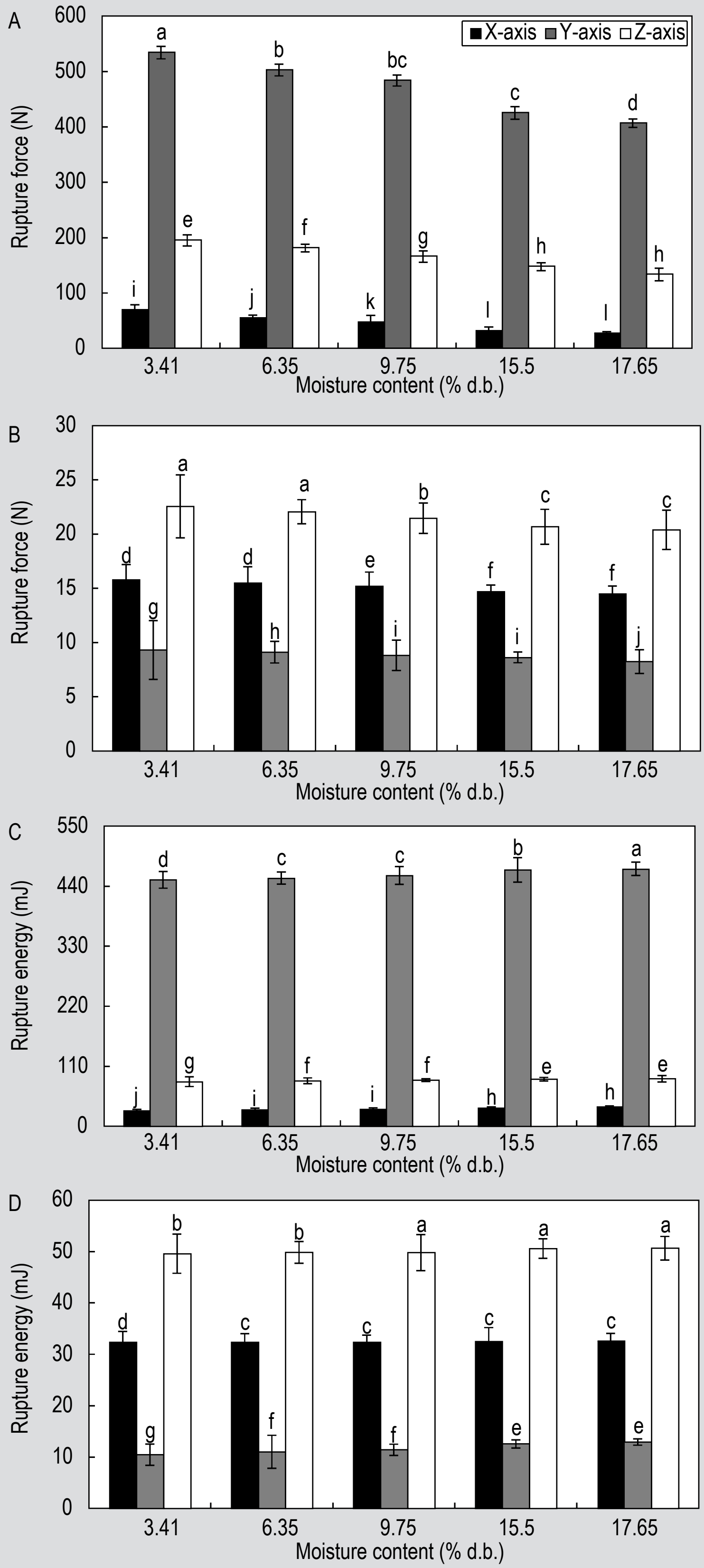

Figure 4. Effect of (A) nut shell and (B) kernel moisture content on rupture force and (C and D) on rupture energy for a loading rate of 10 and 50 mm/min, respectively (black bars = x-axis; grey bars = y-axis; white bars = z-axis). Bars with different letters differ significantly from each other (Duncan's test, *P*<0.05).

Table 4. Equations representing the relationship between the rupture force (F) and rupture energy (E) and moisture content (Mc) for Persian walnut and its kernel under different orientations of loading.

Orientation loading	Rupture force (F)		Rupture energy (E)	
	Equation	R^2	Equation	R^2
Nut				
x-axis	F = 76.17 - 2.866 Mc	0.980	E = 27.35 - 0.436 Mc	0.956
y-axis	F = 208.2 - 4.13 Mc	0.994	E = 445.9 - 1.480 Mc	0.993
z-axis	F = 76.17 - 2.866 Mc	0.991	E = 80.86 - 0.365 Mc	0.986
Kernel				
x-axis	F = 16.06 - 0.088 Mc	0.999	$E = 0.001\ Mc^2 + 0.018\ Mc + 32.39$	0.985
y-axis	F = 9.541 - 0.068 Mc	0.952	E = 9.875 - 0.171 Mc	0.995
z-axis	F = 23.0 - 0.150 Mc	0.997	$E = 0.003\ Mc^2 + 0.001\ Mc + 49.58$	0.952

Rupture energy

The mean energy for initial rupture of the nut as a function of nut shell moisture content and compression axis are depicted in Figure 4C. Significant differences among the three axes and the effect of shell moisture content on the absorbed energy was observed ($P<0.05$). It can be observed in Figure 4C that energy increased by an increase in moisture content from 3.41 to 17.65% d.b. for walnut compressed along all orientations. Walnuts loaded in the x-, y-, and z-axis orientation requires 451.66, 28.67 and 81.78 mJ at 3.41% d.b. and 471.77, 35.66 and 87.31 mJ at 17.65% d.b., respectively, to initiate nut rupture. Therefore, the highest rupture energy (471.77 mJ) was obtained at a moisture content of 17.65% d.b. for loading along the x-axis, while the lowest (28.67 mJ) was at a moisture content of 3.41% d.b. for loading along the y-axis. Generally, compression along the x-axis required more energy for initial rupturing than the two other axes. This is in agreement with the research of Oloso and Clarke (1993) on cashew nut and that of Güner *et al.* (2003) on hazelnut. It can be seen that there is a dependence between the nut size and rupture energy. As the nut size increased by increasing the moisture content for all three axes, the area of contact increased between the nut and compression plates and thus increased the rupture energy. Kılıçkan and Güner (2008) by evaluating mechanical behaviour of olive fruits also found that rupture energy increased as olive fruit and fruit pit sizes increased for all axes. Koyuncu *et al.* (2004) also observed that the geometric mean diameter and thickness of the nut shell affected the energy required to rupture the shell to the break and kernel extraction quality for cracking of walnuts. According to equation 7, energy absorbed at nut rupture was a function of both force and deformation up to rupture point. It was obvious that the lower the moisture content, the higher the rupture force and the less deformation in all axis. In other words, at higher moisture content, the shell of the walnuts became soft and tends to flatten easily under compression. Thus, deformation increased with an increase in the applied load and greater amount of energy per unit volume would be taken up by the nut before cracking (Gharibzahedi *et al.*, 2012b). Other researchers have reported that absorbed energy decreases when moisture content increases for almond nut (Aktas *et al.*, 2007; Arslan and Vursavus, 2008).

Figure 4D shows the energy required for kernel rupture for different moisture content values and load positions. The energy absorbed to rupture the shell, generally increased as the moisture content increased in all directions. As can be seen in figure 4, at all directions and at all moisture contents, the kernel ruptured at much lower energy comparing to the nut. In the y- and z-axis orientation, the values of the energy absorbed for kernels were not significantly different as moisture content increased. However, the relationship between energy absorbed by the kernels and the moisture content was statistically significant ($P<0.05$) in the x-axis orientation. Therefore, kernels loaded in the x-, y- and z-axis orientation, requires 32.34, 10.47 and 49.58 mJ at 3.41% d.b. and 32.56, 12.92 and 50.65 mJ at 17.65% d.b., respectively, to initiate nut rupture. For the kernel, the highest rupture energy (50.65 mJ) was obtained at a moisture content of 17.65% d.b. for loading along the z-axis, while the lowest (10.47 mJ) was at a moisture content of 3.41% d.b. for loading along the y-axis. A machine based on the findings of the present work can be seen as a means of mechanizing the existing manual method where cracking is by impact or instantaneous compression. Gupta and Das (2000) also reported that energy absorbed by sunflower kernels increased as the moisture content increased from 4 to 20% d.b. Arslan and Vursavus (2008) noted an increase in absorbed energy for almond kernels in the moisture range of 6.16-26.79% d.b. Furthermore, Table 4 gives the parameters of the equations and their R^2 values relating rupture energy to the moisture content of walnut and its kernel under different orientations of loading.

4. Conclusions

The results obtained through the study of engineering properties of walnut and its kernel can be summarized as follows:

- The length, width, thickness and geometric mean diameter, unit mass, volume, surface area and sphericity of shelled and kernel walnuts increased by increasing the moisture content from 3.41 to 17.65% d.b.
- The bulk density of walnut and kernel at different moisture levels decreased from 315.51 to 300.12 kg/m^3 and from 377 to 364 kg/m^3, respectively, while the true density of walnut and kernel at different moisture levels increased from 688.05 to 664.83 kg/m^3 and from 1,043.6 to 1,028.7 kg/m^3, respectively. Also, the porosity of walnut and kernel increased from 54.11 to 54.85% and from 63.87 to 64.61%, respectively.
- As the moisture content increased from 3.41 to 17.65% d.b., the angle of repose for walnut and kernel increased linearly from 38.05 to 39.1° and from 40.6 to 41.5°, respectively. The static coefficient of friction of walnut and kernel increased with moisture content. For walnut, the plywood surface offered the maximum friction followed by galvanized iron sheet, steel and glass. For kernel, the static coefficient of friction was the greatest against plywood, followed by galvanized iron sheet, glass and the least for steel.
- The nut shell required the lowest rupture force and energy for cracking the nut and kernel at moisture content from 3.41 to 17.65% d.b. in the y-axis orientation of loading. Therefore, since the rupturing operation is expected to be done with a minimum of energy and resulting in a maximum of kernel quality, the y-axis direction was more suitable than the x- and z-axis.

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