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The physical properties of pistachio nut and its kernel as a function of moisture content and variety. Part III: Frictional properties

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Abstract

In this study, the frictional properties (emptying and filling angles of repose and static coefficient of friction on five structural surfaces) of five Iranian commercial varieties of pistachio nut and its kernel (namely; Akbari, Badami, Kalle-Ghuchi, Momtaz and O'hadi) were evaluated as a function of moisture content (at five levels ranged from fresh pistachio nut at harvesting to commercially dried conditions). The results showed that the emptying angle of repose of nuts was the greatest for Kalle-Ghuchi (27.36 ± 0.59) and the least for Badami (25.09 ± 1.74) at all moisture contents studied. However, in kernels, the greatest value was offered by O'hadi (28.48 ± 1.61) and the lowest by Akbari (26.924 ± 0.97). The filling angle of repose of pistachio nuts and kernels was the highest for Badami and the lowest for O'hadi at different moisture levels. Both angles of repose of pistachio nuts and kernels decreased linearly as the moisture content decreased. The static coefficient of friction value for Badami nut variety on all five structural surfaces (fiberglass, glass, galvanized iron sheet, plywood, and rubber) was the greatest, but in case of kernel, the greatest value was observed for Kalle-Ghuchi (0.503–0.615) on rubber surface and the lowest for O'hadi (0.333–0.512) on fiberglass surface. The highest friction coefficient for all pistachio varieties (both nut and kernel) obtained on rubber surface and the lowest on fiberglass surface at all moisture content levels. The static coefficient of friction of both nuts and kernels on all five test surfaces decreased linearly with decreasing the moisture content.

Keywords: Emptying angle of repose; Filling angle of repose; Static coefficient of friction; Frictional surfaces

1. Introduction

Pistachio is cultivated in Middle East, United states and Mediterranean countries. Pistachio nut is one of the major agricultural products produced in Iran, mainly in Rafsanjan, Kerman and south Khorasan provinces. It has been reported that Iran has produced about 275,000 Mt of pistachio nut in 2003, which is approximately 54.7% of the world's pistachio production, and exported approximately 184,946 tones of nut to different countries, a value about 679.94 million US$ profit (Food & Agriculture Organization, 2003). Thus, one of the most non-petroleum valuable products of Iran exports is annually the pistachio nut that has great impact on its economic.

The frictional properties (angles of repose and coefficients of friction) are important in designing equipments and machines for harvesting, conveying, dehulling, separating, sorting, handling, processing, storage etc. The static coefficient of friction is used to determining the angle at which chutes must be positioned in order to achieve consistent flow of material through the chute. In addition, it is important to designing the conveyors because friction is necessary to hold the nuts and kernels to the conveying surface without slipping or sliding backward. If the handling of the crop is needed, the rougher surface like rubber must be used, and on the other hand, if it is necessary to discharge the product, the smoother surface like fiberglass might be so useful. The frictional properties data will be useful in hopper design, since the hopper walls' inclination angle should be greater than the angle of repose to ensure the continuous flow of the crops (gravity

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Nomenclature

D	diameter of heap at its base (mm)	θ_f	filling angle of repose (°)
H	height of heap above the floor (mm)	θ_{en}	emptying angle of repose of nuts (°)
h_1	height of a point on the surface of slipping pile of nuts (mm)	θ_{ek}	emptying angle of repose of kernels (°)
h_2	height of a point above h_1 on the surface of sloping pile of nuts (mm)	θ_{fn}	filling angle of repose of nuts (°)
M_c	moisture content (db%)	θ_{fk}	filling angle of repose of kernels (°)
x_1	horizontal distance (mm)	μ	static coefficient of friction
x_2	horizontal distance (mm)	μ_{fg}	static coefficient of friction on fiberglass
α	angle of tilt (°)	μ_{gl}	static coefficient of friction on glass
θ_e	emptying angle of repose (°)	μ_{gi}	static coefficient of friction on galvanized iron
		μ_{pl}	static coefficient of friction on plywood
		μ_{ru}	static coefficient of friction on rubber

flow). Therefore, it can be concluded that the data on frictional properties of pistachio as a function of different factors such as moisture content and variety are very important.

Many researchers have been studied the frictional properties of food and agricultural products such as Fraser, Verma, and Muir (1978) for faba beans, Dutta, Nema, and Bhardwaj (1988) for gram, Oje and Ugbor (1991) for oilbean seed, Joshi, Das, and Mukherjee (1993) for pumpkin seed, Carman (1996) for lentil seed, Singh and Goswami (1996) for Cumin seed, Suthar and Das (1996) for karingda, Visvanathan, Palanisamy, Gothandapani, and Sreenarayanan (1996) for Neem Nut, Gupta and Das (1997) for sunflower seed, Jain and Bal (1997) for Pearl millet, Ogut (1998) for white Lupin, Aviaral, Gwandzag, and Haque (1999) for Guna seed, Chandrasekar and Viswanathan (1999) for coffee, Olajide and Ade-Omowaye (1999) for Locust bean, Nimkar and Chattopadhyay (2001) for green gram, Aydin (2002) for Hazelnut, Aydin (2002) for Turkish Mahaleb, Baryeh (2002) for millet, Baryeh and Mangope (2002) for QP-38 variety pigeon pea, Demir, Dogan, Ozcan, and Haciseferogullari (2002) for hackberry, Gezer, Haciseferogullari, and Demir (2002) for apricot pit, Kalimullah and Gunasekar (2002) for Arecanut, Konak, Carman & Aydin (2002) for Chick pea, Ogunjimi, Aviara, and Aregbesola (2002) for Locust bean, Ozarslan (2002) for Cotton, Aydin (2003) for Almond, Bart-Plange and Baryeh (2003) for Category B cocoa bean, Olajide and Igbeka (2003) for Groundnut kernels, Sacilik, Ozturk, and Keskin (2003) for Hemp seed, Abalone (2004) for Amaranth seed, Amin, Hossain, and Roy (2004) for lentil seed, Calisir and Aydin (2004) for cherry laurel, Calisir, Haciseferogullari, Ozcan, and Arslan (2004) for wild plum, Ozcan, Haciseferogullari, and Demir (2004) for capers flower buds, Ozdemir and Akinci (2004) for hazelnut, Ozguven and Kubilay (2004) for pine, Paksoy and Aydin (2004) for edible squash seeds, Tunde-Akintunde and Akintunde (2004) for sesame seed, Altuntas and Yildiz (2007) for faba bean grain, Dursun and Durson (2005) for Caper seed, Kashaninejad, Mortazavi, Safekordi, and Tabil (2005) for pistachio, Oyelade, Odugbenro, Abioye, and Raji (2005) for African star apple seeds.

As it can be found from literature review, there was no published paper about the frictional properties of pistachio, except for Kashaninejad et al. (2005) work, who studied only the static coefficient of friction of pistachio nut and its kernel for O'hadi cultivar. Because of the lack of the data on frictional properties of pistachio nuts and kernels, the aim of this research was to investigate the frictional properties (repose angles and friction coefficient) of pistachio nut and its kernel as a function of moisture content and variety. The emptying and filling angle of repose and static coefficient of friction on five structural surfaces has been evaluated for five major commercial Iranian pistachio varieties (Akbari, Badami, Kalle-Ghuchi, Momtaz & O'hadi) at five moisture content levels.

2. Materials and methods

2.1. Sample preparation and moisture content determination

More than 60 pistachio varieties cultivate in different regions of Iran, but the O'hadi (or Fandoghi), Momtaz, Badami (or Sefid), Akbari and Kalle-Ghuchi are the major commercial varieties, which was selected for this research work. These cultivars were obtained from Feizabad city, Khorasan province in Iran during summer season in 2005 year. The samples were manually peeled and cleaned to remove all foreign matters as well as immature and broken nuts. The nuts were cracked and the kernels separated from the shells by hand. The initial moisture content of each pistachio variety was determined using oven method at 103 ± 2 °C until a constant weight was reached (Kashaninejad et al., 2005). To vary the moisture content of pistachio nut or kernel, the predetermined quality of samples was dried down to the desired moisture content. All the physical properties of the pistachio nut and its kernel were determined at five moisture levels with at least three replications at each level of moisture content.

2.2. Frictional characteristics

The static coefficient of friction of pistachio nut and its kernel at five moisture content levels was measured for five frictional surfaces, namely glass, fiberglass, rubber, plywood, and galvanized iron sheets. A fiberglass topless and bottomless box of 0.15 m length, 0.10 m width, and 0.04 m height was placed on an adjustable inclined plane, faced with the test surface and filled with the sample. The box was raised slightly (5–10 mm), so as not to touch the surface. The structural surface with the box resting on it was inclined gradually with a screw device until the box just started to slide down over the surface and the angle of tilt (α) was read from a graduated scale. The static coefficient of friction (μ_s) was then calculated from the following equation (Mohsenin, 1978):

$$\mu_s = \tan \alpha \quad (1)$$

The filling or static angle of repose is the angle with the horizontal at which the pistachio will stand when piled. This was determined using a topless and bottomless cylinder of 0.15 m diameter and 0.25 m height. The cylinder was placed at the centre of a raised circular plate having a diameter of 0.35 m and was filled with pistachio nut or its kernel. The cylinder was raised slowly until it formed a cone on a circular plane. The height of the cone was measured and the filling angle of repose (θ_f) was calculated by the following relationship (Ozguven & Kubilay, 2004):

$$\theta_f = \tan^{-1}\left(\frac{2H}{D}\right) \quad (2)$$

where H and D are the height and diameter of the cone, respectively.

In order to determine the emptying or dynamic angle of repose, a fiberglass box of $0.2 \times 0.2 \times 0.2$ m, having a removable front panel was used. The box was filled with the pistachio nut or kernel samples at the moisture content being investigated, and then the front panel quickly slid upwards allowing the samples to flow out and assume a natural heap. The emptying angle of repose (θ_e) was obtained from measurements of height of samples at two points (h_1 and h_2) in the sloping pistachio heap and the horizontal distance between two points (x_1 and x_2) using the following equation (Bart-Plange & Baryeh, 2003; Jain & Bal, 1997; Paksoy & Aydin, 2004):

$$\theta_e = \tan^{-1}\left[\frac{h_2 - h_1}{x_2 - x_1}\right] \quad (3)$$

2.3. Data analysis

All experiments were performed for each treatment at least in three replications. Minimum, maximum, mean and standard deviations were determined by a spread sheet software program namely Microsoft Excel 2003 and the regression equations and coefficient of determination were obtained by statistical curve fitting software program namely Curve Expert version 1.34.

3. Results and discussion

3.1. Emptying angle of repose

3.1.1. Nuts

The results of the emptying angle of repose of pistachio nuts (θ_{en}) for five varieties at different moisture levels are shown in Fig. 1. As it can be seen, the emptying angle of repose with pistachio nut varieties was the greatest for Kalle-Ghuchi (26.52–28.07°) then Akbari (24.10–27.99°), Momtaz (23.38–28.07°), O'hadi (21.54–28.32°) and the lowest obtained for the Badami (22.55–27.30°), as moisture contents increased from 5.11% to 46.00% (w.b.), 5.56% to 35.67% (w.b.), 3.89% to 36.89% (w.b.), 5.44% to 34.78% (w.b.) and 3.11% to 32.22% (w.b.), respectively. It is also observed that the emptying angle of repose, for all five pistachio nut varieties increased with increase in moisture content (M_c, %w.b.). It seems that it is due to the higher moisture contents and therefore higher stickiness of the surface of the nuts that confines the easiness of sliding nuts on each other. The greater value for Kalle-Ghuchi variety is also due to the higher moisture content and higher sphericity of it in comparison with other varieties (refer to the paper with the same title, Part I). The equations representing relationship between emptying angle of repose of pistachio nuts and moisture content for each pistachio variety and their coefficient of determination (R^2) is presented in Table 1. As it can be found, there was linear relationships with very high correlation between emptying angle of repose and moisture content for all pistachio nut varieties.

The emptying angle of repose for pistachio nuts were greater than reported values for Locust bean seeds (Olajide & Ade-Omowaye, 1999 Ogunjimi et al., 2002), Hemp seeds (Sacilik et al., 2003), Quinoa seeds (Vilche, Gely, & Santalla, 2003), Edible squash seeds (Paksoy & Aydin, 2004), Hazel nut (Ozdemir & Akinci, 2004), African star apple seeds (Oyelade et al., 2005) and lower than reported values for Pumpkin seeds (Joshi et al., 1993), Guna seeds (Aviaral et al. (1999)), Green gram (Nimkar & Chattopadhyay, 2001), Chick pea seeds (Konak, Carman, & Aydin, 2002), QP-38 variety Pigeon pea (Baryeh & Mangope, 2002),

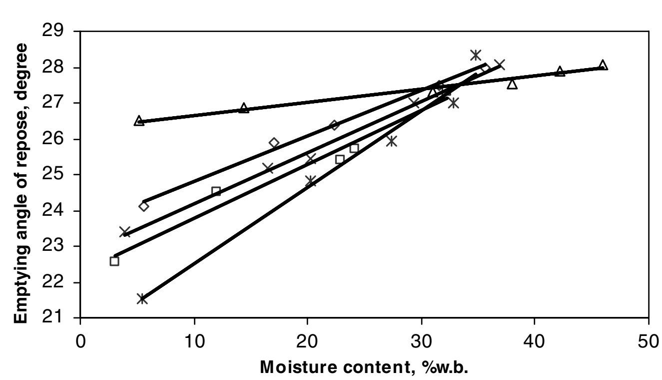

Fig. 1. Emptying angle of repose for pistachio nuts as a function of variety and moisture content ((◇) Akbari; (□) Badami; (△) Kalle-Ghuchi; (×) Momtaz and (✳) O'hadi).

Table 1
Equation representing relationship between angles of repose and moisture content for pistachio varieties (nuts and kernels)

Variety	Angle of repose	M_C (w.b.%)	Nut	R^2	M_C (w.b.%)	Kernel	R^2
Akbari	Filling	5.56–35.67	$\theta_{fn} = 0.1591M_C + 14.774$	0.9957	5.78–35.67	$\theta_{fk} = 0.0814M_C + 24.491$	0.9881
	Emptying		$\theta_{en} = 0.1268M_C + 23.531$	0.9925		$\theta_{ek} = 0.0779M_C + 25.192$	0.9804
Badami	Filling	3.11–32.22	$\theta_{fn} = 0.1988M_C + 14.837$	0.9865	6.33–32.22	$\theta_{fk} = 0.0560M_C + 25.737$	0.9834
	Emptying		$\theta_{en} = 0.1511M_C + 22.245$	0.9693		$\theta_{ek} = 0.2231M_C + 23.204$	0.9901
Kalle-Ghuchi	Filling	5.11–46.00	$\theta_{fn} = 0.0498M_C + 16.347$	0.9758	5.11–46.00	$\theta_{fk} = 0.0447M_C + 25.249$	0.9911
	Emptying		$\theta_{en} = 0.0359M_C + 26.303$	0.9674		$\theta_{ek} = 0.0852M_C + 25.643$	0.9783
Momtaz	Filling	3.89–36.89	$\theta_{fn} = 0.1173M_C + 15.606$	0.9981	4.11–36.89	$\theta_{fk} = 0.0262M_C + 25.674$	0.9813
	Emptying		$\theta_{en} = 0.1424M_C + 22.779$	0.9961		$\theta_{ek} = 0.0743M_C + 25.777$	0.9879
O'hadi	Filling	5.44–34.78	$\theta_{fn} = 0.0896M_C + 15.155$	0.9803	5.33–34.78	$\theta_{fk} = 0.0855M_C + 24.030$	0.9920
	Emptying		$\theta_{en} = 0.2148M_C + 20.345$	0.9805		$\theta_{ek} = 0.1367M_C + 25.330$	0.9834

Turkish Mahaleb (Aydin, Ogut, & Konak, 2002), Category B Cocoa beans (Bart-Plange & Baryeh, 2003), Sesame seeds (Tunde-Akintunde & Akintunde, 2004) and Caper seed (Dursun & Durson (2005)). The smoother surface of the pistachio nuts is probably responsible for the lower values of emptying angle of repose in comparison with products mentioned above.

3.1.2. Kernels

The emptying angle of repose of the pistachio kernels (θ_{ek}), as presented in Fig. 2, showed that the O'hadi (26.17–30.39°) had the greatest value then Badami (24.39–30.39°), Kalle-Ghuchi (25.99–30.21°), Momtaz (26.00–29.86°), and the lowest was for the Akbari (25.73–27.9°), as moisture contents increased from 5.33% to 34.78% (w.b.), 6.33% to 32.22% (w.b.), 5.11% to 46.00% (w.b.), 4.11% to 36.89% (w.b.) and 5.78% to 35.67% (w.b.), respectively. It can be found that the emptying angle of repose with all pistachio kernels varieties increased as the moisture content increased. Fig. 2 also indicated that there was the linear relationship between emptying angle of repose of pistachio kernels and moisture content. The regression equations obtained and their high R^2 values confirmed these linear behaviors (Table 1). These high correlations may be due to the smooth surface of nuts and their high sphericity.

The emptying angle of repose values obtained for pistachio kernels were greater than the values reported for Groundnut kernels (Olajide & Igbeka, 2003), Hazel kernels (Ozdemir & Akinci, 2004) and lower than Pumpkin seed kernels (Joshi et al., 1993). It seems that the higher sphericity and smoother surface of the kernels facilitated rolling over and sliding on each other.

3.2. Filling angle of repose

3.2.1. Nuts

The variation of the filling angle of repose (θ_{fn}) for the pistachio nuts with moisture content is shown in Fig. 3. As it can be seen, the filling angle of repose for Akbari, Badami, Kalle-Ghuchi, Momtaz and O'hadi varieties ranged from 15.66° to 20.60°, 15.20° to 21.12°, 16.60° to 18.84°, 16.00° to 19.86° and 15.72° to 18.47° at moisture contents ranged from 5.56% to 35.67%, 3.11% to 32.22%, 5.11% to 46.00%, 3.89% to 36.89%, and 5.44% to 34.78% (w.b.), respectively. The greatest value of filling angle of repose was for Badami, and then Akbari, Momtaz, Kalle-Ghuchi and the lowest obtained for O'hadi. The lowest values for the O'hadi and Kalle-Ghuchi could be attributed to the higher sphericity (refer to the paper with the same title, Part I) allowing them to slide and roll over on

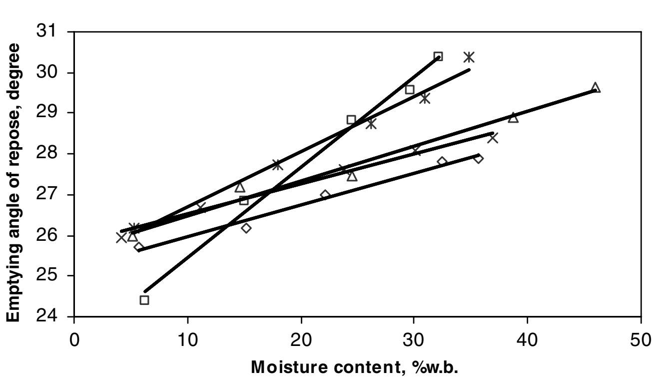

Fig. 2. Emptying angle of repose for pistachio kernels as a function of variety and moisture content ((◇) Akbari; (□) Badami; (△) Kalle-Ghuchi; (×) Momtaz and (✻) O'hadi).

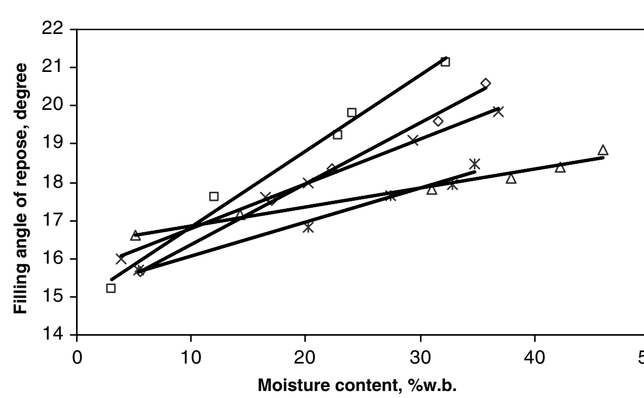

Fig. 3. Filling angle of repose for pistachio nuts as a function of variety and moisture content ((◇) Akbari; (□) Badami; (△) Kalle-Ghuchi; (×) Momtaz and (✻) O'hadi).

each other easily. The effect of moisture content on the emptying angle of repose showed that the θ_{fn} increased with increase in moisture content of pistachio nuts (Fig. 3). It can also be found that there was linear relationship between filling angle of repose and moisture content for all five pistachio varieties. The equations governing the filling angle of repose and moisture content for pistachio nuts and their very high correlation are presented in Table 1.

The reported values for filling angle of repose for other products such as Category B cocoa beans (Bart-Plange & Baryeh, 2003) and Caper seed (Dursun & Durson, 2005) were greater than values for pistachio nuts.

3.2.2. Kernels

The effect of moisture content and pistachio variety on the filling angle of repose of kernels (θ_{fk}) are shown in Fig. 4. As It can be found, the filling angle of repose with Akbari, Badami, Kalle-Ghuchi, Momtaz and O'hadi kernels varied between 25.03° and 27.54°, 26.04° and 27.60°, 25.49° and 27.24°, 25.73° and 26.59° and 24.50° and 27.02° at moisture contents ranged from 5.78% to 35.67%, 6.33% to 32.22%, 5.11% to 46.00%, 4.11% to 36.89%, and 5.33% to 34.78% (w.b.%), respectively. It can be seen that the greatest filling angle of repose value was for the Badami and then Kalle-Ghuchi, Akbari, Momtaz and the lowest for O'hadi.

The reported value for Arecanut kernel filling angle of repose (Kalimullah & Gunasekar, 2002) is considerably lower than the value for pistachio kernels that it is due to the higher sphericity of Arecanut in comparison with pistachio.

The results of this research indicated that the filling angle of repose of kernels with each pistachio variety increased as the moisture content increased in the range studied (Fig. 4). The regression equation obtained for predicting the filling angle of repose with pistachio kernels varieties as a function of moisture content are given in Table 1. It can be found that there were positive linear relationships of filling angle of repose with moisture content.

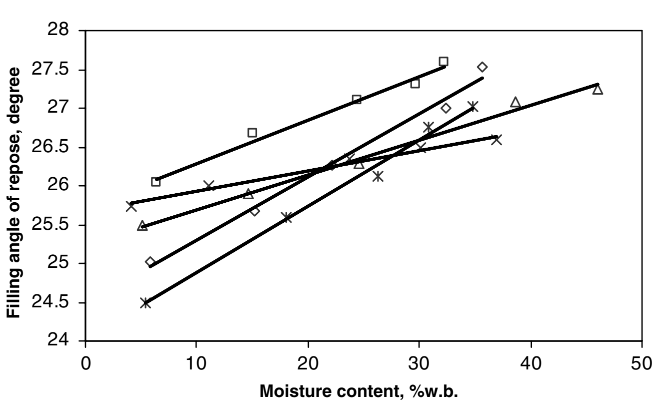

Fig. 4. Filling angle of repose for pistachio kernels as a function of variety and moisture content ((◇) Akbari; (□) Badami; (△) Kalle-Ghuchi; (×) Momtaz and (✱) O'hadi).

3.3. Static coefficient of friction

3.3.1. Nut

Experimental data of static coefficient of friction for pistachio nuts on frictional surfaces of fiberglass (μ_{fg}), glass (μ_{gl}), galvanized iron sheet (μ_{ga}), plywood (μ_{pl}), and rubber (μ_{ru}) at various moisture levels are plotted against moisture content as shown in Figs. 5–8 and 9, respectively. As presented in Fig. 5, the static coefficient of friction on fiber-

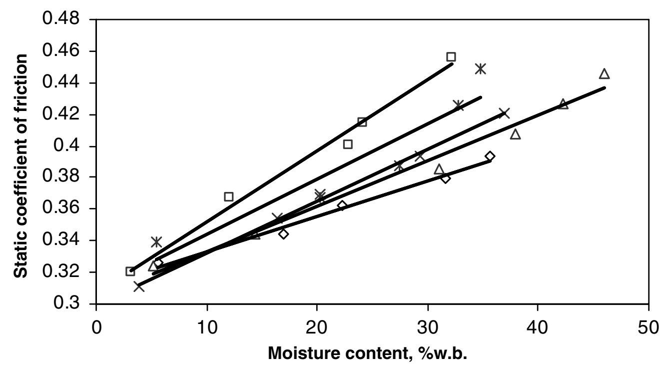

Fig. 5. The static coefficient of friction of pistachio nut on fiberglass surface as a function of moisture content and variety ((◇) Akbari; (□) Badami; (△) Kalle-Ghuchi; (×) Momtaz and (✱) O'hadi).

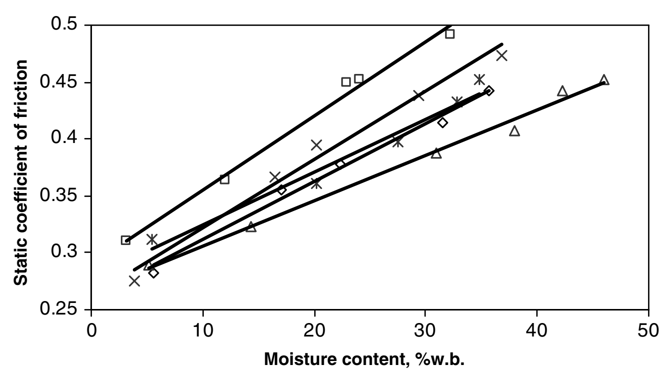

Fig. 6. The static coefficient of friction of pistachio nut on glass surface as a function of moisture content and variety ((◇) Akbari; (□) Badami; (△) Kalle-Ghuchi; (×) Momtaz and (✱) O'hadi).

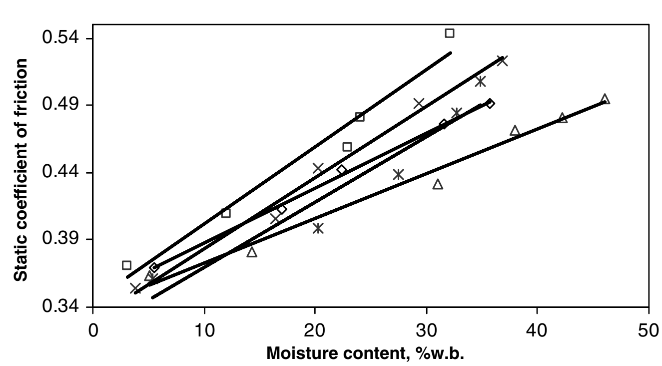

Fig. 7. The static coefficient of friction of pistachio nut on galvanized iron sheet surface as a function of moisture content and variety ((◇) Akbari; (□) Badami; (△) Kalle-Ghuchi; (×) Momtaz and (✱) O'hadi).

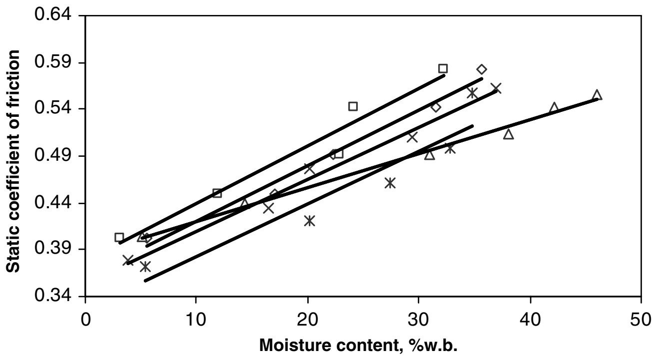

Fig. 8. The static coefficient of friction of pistachio nut on plywood surface as a function of moisture content and variety ((◇) Akbari; (□) Badami; (△) Kalle-Ghuchi; (×) Momtaz and (✱) O'hadi).

glass surface for Badami (0.320–0.456) was the greatest and then, O'hadi (0.339–0.437), Kalle-Ghuchi (0.324–0.446), Momtaz (0.311–0.421) and the lowest value obtained for Akbari (0.326–0.394). The static coefficient of friction with respect to fiberglass surface for pistachio nuts were greater than reported value for Pine nuts (Ozguven & Kubilay, 2004).

As shown in Fig. 6, on glass surface at all moisture contents, the highest friction was obtained for Badami (0.310–0.492), followed by O'hadi (0.312–0.452), Momtaz (0.275–0.474), Kalle-Ghuchi (0.290–0.452) and the lowest for Akbari (0.283–0.442). Based on reported values of static coefficient of friction on glass surface it was concluded that this values for pistachio nuts were greater than oil bean seed (Oje & Ugbor, 1991), Locust bean seed (Olajide & Ade-Omowaye, 1999), lentil (Amin et al., 2004) and less than O'hadi variety of pistachio (Kashaninejad et al., 2005).

As seen in Fig. 7, the static coefficient of friction on galvanized iron sheet surface was the greatest for Badami (0.371–0.543), then followed by Momtaz (0.354–0.523), Akbari (0.369–0.491), O'hadi (0.360–0.508) and finally the lowest for Kalle-Ghuchi (0.364–0.495). The static coefficient of friction on galvanized iron sheet surface for pistachio nuts were greater than the reported values for Faba beans (Fraser et al., 1978), Pearl millet (Jain & Bal, 1997), Locust bean seed (Olajide & Ade-Omowaye, 1999), capers buds (Ozcan et al., 2004), pine nuts (Ozguven & Kubilay, 2004), lentil (Amin et al., 2004), gumbo fruit (Akar & Aydin, 2005), O'hadi variety of pistachio (Kashaninejad et al., 2005), caper seed (Dutta et al., 1988), Faba beans (Altuntas & Yildiz, 2007) and less than cumin seed (Singh & Goswami, 1996), karingda (Suthar & Das, 1996), category B cocoa (Bart-Plange & Baryeh, 2003), wild plum (Calisir et al., 2004) and African star apple seed (Oyelade et al., 2005).

However, the results obtained for friction coefficient for pistachio nuts on plywood surface as shown in Fig. 8 indicated that the highest value was for Kalle-Ghuchi (0.492–0.782), then followed by Badami (0.521–0.768), Akbari (0.478–0.763), Momtaz (0.491–0.741) and the lowest for O'hadi (0.497–0.633). In comparison with reported values of static coefficient of friction on plywood surface, the obtained values for pistachio nuts were greater than Turkish hazelnut (Ozdemir & Akinci, 2004), lentil (Amin et al., 2004), Faba bean (Altuntas & Yildiz, 2007; Fraser et al., 1978), Sultani and Amarya varieties of gumbo fruit (Akar & Aydin, 2005), African star apple seed (Oyelade et al., 2005) and less than Karingda (Suthar & Das, 1996), Locust bean seed (Olajide & Ade-Omowaye, 1999), category B cocoa (Bart-Plange & Baryeh, 2003), capers buds (Ozcan et al., 2004), Pine (Ozguven & Kubilay, 2004), wild plum (Calisir et al., 2004), caper seed (Dursun & Durson (2005)), and O'hadi variety of pistachio (Kashaninejad et al., 2005).

As it can be seen in Fig. 9, the greatest coefficient of friction on rubber surface was for Badami (0.521–0.768), and the least was for O'hadi (0.497–0.633) and Kalle-Ghuchi (0.492–0.782), Akbari (0.478–0.763) and Momtaz (0.491–0.741) in the between, respectively. The static coefficient of friction with respect to rubber surface for pistachio nuts were greater than reported value for category B cocoa (Bart-Plange & Baryeh, 2003), Sultani and Amarya varieties of gumbo fruit (Akar & Aydin, 2005) and less than capers buds (Ozcan et al., 2004), wild plum (Calisir et al., 2004), caper seed (Dursun & Durson, 2005) and Faba bean (Altuntas & Yildiz, 2007).

It was also observed that the static coefficient of friction for each pistachio variety on all five structural surfaces increased as the moisture content increased (Figs. 5–9). The highest static coefficient of friction was obtained on the rubber surface followed by plywood, galvanized iron, glass, and finally fiberglass surfaces. This trend is due to the roughness of the surfaces, which in case of the fiberglass, the smoothness and polished surface of it, has revealed the minimum friction value.

As can be seen from Figs. 5–9 the highest friction on all frictional surfaces at all moisture levels were offered by Badami variety. It might be due to the higher moisture content of this variety. It means that at higher moisture contents, the nut became rougher and sliding characteristics

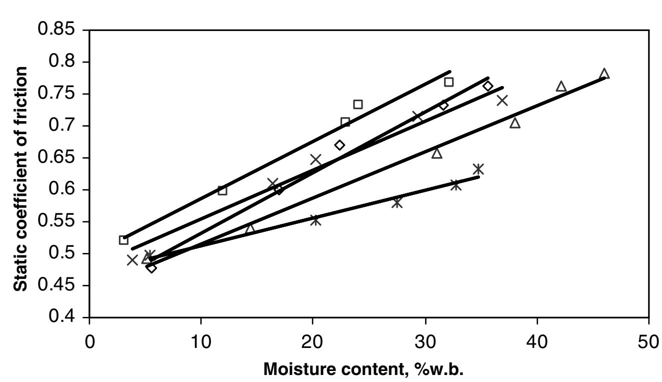

Fig. 9. The static coefficient of friction of pistachio nut on rubber surface as a function of moisture content and variety ((◇) Akbari; (□) Badami; (△) Kalle-Ghuchi; (×) Momtaz and (✱) O'hadi).

are diminished, so that the static coefficient of friction increased. Also due to increasing the stickiness and adhesion between nuts and material surfaces at higher moisture contents, resulting adhesive force plays an important role in increasing the value for the static coefficient of friction. It was observed that the material surface had greater impact on static coefficient of friction than the moisture content.

The regression equations and their R^2 values obtained by fitting the experimental data of static coefficient of friction as a function of moisture content are listed in Table 2. It can be found that the relationship of static coefficient of friction of pistachio nut with moisture content was linear for all friction surfaces and varieties.

These linear behaviors are in accordance with similar reported papers for cumin seed (Singh & Goswami, 1996), sunflower seed (Gupta & Das, 1997), white lupin (Ogut, 1998), coffee bean (Chandrasekar & Viswanathan, 1999), cotton seed (Ozarslan, 2002), Hacihaliloglu variety of apricot pit (Gezer et al., 2002), millet (Baryeh, 2002), almond (Aydin, 2003), cherry laurel (Calisir & Aydin, 2004), edible squash (Paksoy & Aydin, 2004), Sultani and Amarya varieties of Gumbo fruit (Akar & Aydin, 2005), O'hadi variety of pistachio nut (Kashaninejad et al. (2005)). In contrast the non-linear relationship are reported for the chick pea (Konak et al., 2002), Arecanut (Kalimullah & Gunasekar (2002)), hazelnut (Aydin, 2002) and QP-38 pigeon pea (Baryeh & Mangope, 2002) too.

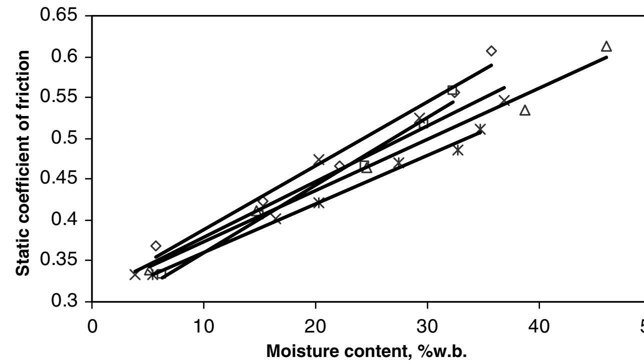

Fig. 10. The static coefficient of friction of pistachio kernel on fiberglass surface as a function of moisture content and variety ((◇) Akbari; (□) Badami; (△) Kalle-Ghuchi; (×) Momtaz and (✱) O'hadi).

3.3.2. Kernel

The variation of the static coefficient of friction for pistachio kernels on five frictional surfaces are displayed in Figs. 10–14 as a function of moisture content and variety. As shown in Fig. 10, the friction on fiberglass surface, Akbari had the highest value (0.368–0.607), followed by Kalle-Ghuchi (0.340–0.613), Badami (0.333–0.559), Momtaz (0.333–0.546) and the lowest was for O'hadi (0.333–0.512). As seen in Fig. 11, on the glass surface, the friction coefficient for kernels varied from 0.346 to 0.621, 0.342 to 0.598, 0.330 to 0.594, 0.342 to 0.548, and 0.326 to 0.542, for Akbari, Momtaz, Kalle-Ghuchi, O'hadi and Badami,

Table 2
Equations representing relationship between the static coefficient of friction and moisture content for pistachio nuts and kernels

Varieties	Surfaces	Nuts			Kernels		
		M_C (%w.b.)	Equation	R^2	M_C (%w.b.)	Equation	R^2
Akbari	Fiberglass	5.556–35.667	$\mu_{fg} = 0.0022M_C + 0.3107$	0.983	5.778–35.667	$\mu_{fg} = 0.0078M_C + 0.3106$	0.977
	Glass		$\mu_{gl} = 0.0051M_C + 0.2600$	0.990		$\mu_{gl} = 0.0088M_C + 0.2913$	0.988
	Galvanized iron sheet		$\mu_{ga} = 0.0041M_C + 0.3463$	0.997		$\mu_{ga} = 0.0084M_C + 0.2981$	0.991
	Plywood		$\mu_{pl} = 0.0060M_C + 0.3601$	0.983		$\mu_{pl} = 0.0080M_C + 0.339$	0.982
	Rubber		$\mu_{ru} = 0.0094M_C + 0.4372$	0.984		$\mu_{ru} = 0.0103M_C + 0.3394$	0.996
Badami	Fiberglass	3.111–32.222	$\mu_{fg} = 0.0045M_C + 0.3073$	0.987	6.333–32.222	$\mu_{fg} = 0.0083M_C + 0.2776$	0.986
	Glass		$\mu_{gl} = 0.0065M_C + 0.2913$	0.991		$\mu_{gl} = 0.0084M_C + 0.2721$	1.00
	Galvanized iron sheet		$\mu_{ga} = 0.0057M_C + 0.3444$	0.968		$\mu_{ga} = 0.0082M_C + 0.3260$	0.988
	Plywood		$\mu_{pl} = 0.0062M_C + 0.3776$	0.949		$\mu_{pl} = 0.0092M_C + 0.3100$	0.994
	Rubber		$\mu_{ru} = 0.0089M_C + 0.4961$	0.982		$\mu_{ru} = 0.0135M_C + 0.3085$	0.989
Kalle-Ghuchi	Fiberglass	5.111–46.000	$\mu_{fg} = 0.0029M_C + 0.3040$	0.981	5.111–46.000	$\mu_{fg} = 0.0063M_C + 0.3111$	0.985
	Glass		$\mu_{gl} = 0.0040M_C + 0.2669$	0.992		$\mu_{gl} = 0.0064M_C + 0.3060$	0.994
	Galvanized iron sheet		$\mu_{ga} = 0.0033M_C + 0.3394$	0.983		$\mu_{ga} = 0.0042M_C + 0.4295$	0.995
	Plywood		$\mu_{pl} = 0.0036M_C + 0.3846$	0.992		$\mu_{pl} = 0.0069M_C + 0.3403$	0.994
	Rubber		$\mu_{ru} = 0.0072M_C + 0.4438$	0.990		$\mu_{ru} = 0.0054M_C + 0.4734$	0.995
Momtaz	Fiberglass	3.889–36.889	$\mu_{fg} = 0.0033M_C + 0.2994$	0.998	4.111–36.889	$\mu_{fg} = 0.0068M_C + 0.3103$	0.948
	Glass		$\mu_{gl} = 0.0060M_C + 0.2617$	0.985		$\mu_{gl} = 0.0075M_C + 0.3130$	0.993
	Galvanized iron sheet		$\mu_{ga} = 0.0053M_C + 0.3304$	0.989		$\mu_{ga} = 0.0044M_C + 0.4401$	0.991
	Plywood		$\mu_{pl} = 0.0055M_C + 0.3546$	0.987		$\mu_{pl} = 0.0088M_C + 0.3322$	0.983
	Rubber		$\mu_{ru} = 0.0077M_C + 0.4764$	0.972		$\mu_{ru} = 0.0080M_C + 0.3752$	0.995
O'hadi	Fiberglass	5.444–20.222	$\mu_{fg} = 0.0035M_C + 0.3091$	0.879	5.333–34.778	$\mu_{fg} = 0.0059M_C + 0.3017$	0.991
	Glass		$\mu_{gl} = 0.0046M_C + 0.2787$	0.966		$\mu_{gl} = 0.0068M_C + 0.3070$	0.992
	Galvanized iron sheet		$\mu_{ga} = 0.0049M_C + 0.3209$	0.917		$\mu_{ga} = 0.0083M_C + 0.3104$	0.991
	Plywood		$\mu_{pl} = 0.0056M_C + 0.3262$	0.882		$\mu_{pl} = 0.0104M_C + 0.3019$	0.992
	Rubber		$\mu_{ru} = 0.0044M_C + 0.4687$	0.975		$\mu_{ru} = 0.0083M_C + 0.3505$	0.985

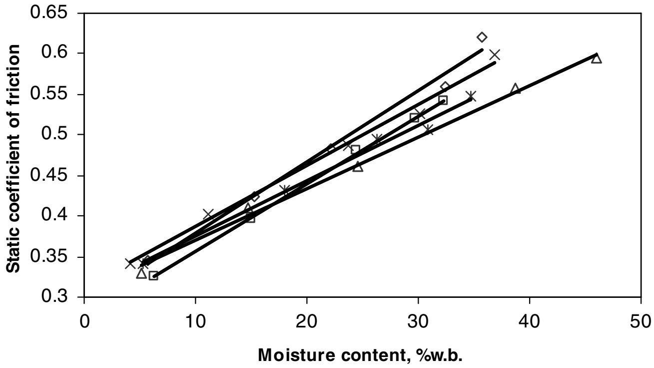

Fig. 11. The static coefficient of friction of pistachio kernel on glass surface as a function of moisture content and variety ((◇) Akbari; (□) Badami; (△) Kalle-Ghuchi; (×) Momtaz and (⁎) O’hadi).

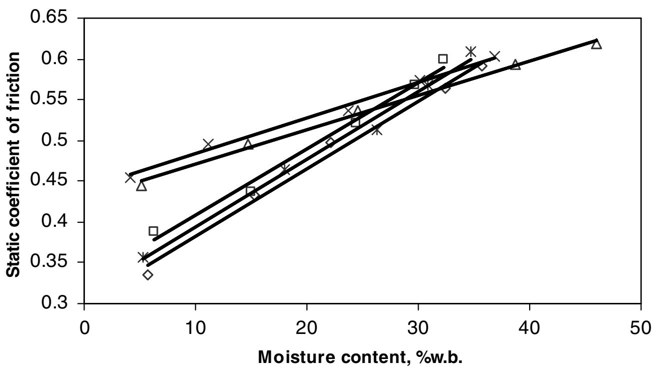

Fig. 12. The static coefficient of friction of pistachio kernel on galvanized iron sheet surface as a function of moisture content and variety ((◇) Akbari; (□) Badami; (△) Kalle-Ghuchi; (×) Momtaz and (⁎) O’hadi).

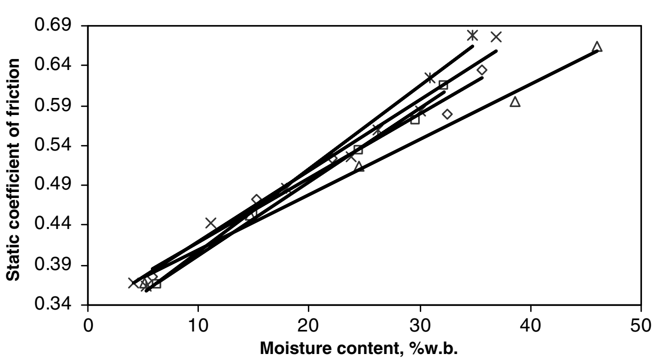

Fig. 13. The static coefficient of friction of pistachio kernel on plywood surface as a function of moisture content and variety ((◇) Akbari; (□) Badami; (△) Kalle-Ghuchi; (×) Momtaz and (⁎) O’hadi).

respectively. These values were less than reported values for O’hadi variety of Pistachio kernel (Kashaninejad et al., 2005).

As it can be found from Fig. 12, the friction coefficient on galvanized iron surface, Kalle-Ghuchi had the greatest friction value (0.445–0.618), and then Momtaz (0.445–0.603), Badami (0.388–0.599), O’hadi (0.357–0.609), and

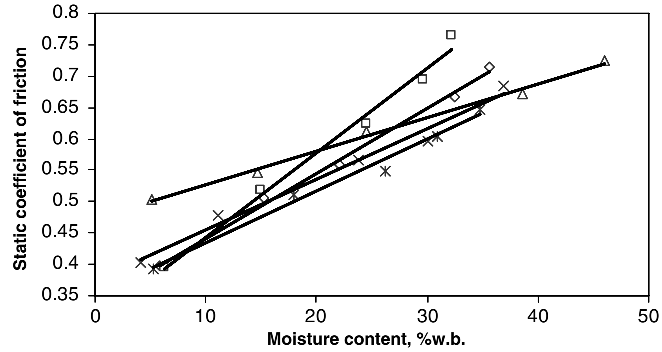

Fig. 14. The static coefficient of friction of pistachio kernel on rubber surface as a function of moisture content and variety ((◇) Akbari; (□) Badami; (△) Kalle-Ghuchi; (×) Momtaz and (⁎) O’hadi).

the lowest obtained for Akbari (0.336–0.591). The obtained values for O’hadi variety in this research was the same with reported values for this variety (Kashaninejad et al., 2005). Totally, the measured values for pistachio kernels were greater than karingda (Suthar & Das, 1996) and less than groundnut (Olajide & Igbeka, 2003).

The maximum coefficient of friction on plywood surface (Fig. 13) offered by O’hadi (0.364–0.678), followed by Momtaz (0.368–0.667), Kalle-Ghuchi (0.368–0.664), Akbari (0.376–0.634) and the minimum by Badami (0.366–0.615). The same values for O’hadi variety of pistachio kernel was presented (Kashaninejad et al., 2005). The values of coefficient of friction on plywood surface for all varieties of pistachio kernel were greater than karingda (Suthar & Das, 1996) and Turkish hazelnut (Ozdemir & Akinci, 2004) and less than groundnut (Olajide & Igbeka, 2003).

As presented in Fig. 14, the friction coefficient obtained for kernels on the rubber surface was 0.503–0.724 for Kalle-Ghuchi, 0.395–0.764 for Badami, 0.397–0.715 for Akbari, 0.402–0.685 for Momtaz and 0.393–0.647 for O’hadi.

Totally, in all varieties on test surfaces, as the moisture content of pistachio kernels increased, the static coefficient of friction increased. The greatest static coefficient of friction for kernels was observed on the rubber surface followed by plywood, galvanized iron sheet, glass, and finally fiberglass surfaces. This trend is also found in nuts, which is due to the roughness of the rubber surface that has revealed the maximum friction value in comparison to other surfaces.

As it can be seen in Figs. 10–14, the friction coefficient of kernels increased linearly as the moisture content increased for all varieties and frictional surfaces. Also due to increasing the stickiness and adhesion between kernels and material surfaces at higher moisture contents, the static coefficient of friction increased. Similar to the results obtained for pistachio nuts, it was observed that material surface had a more significant effect than the moisture content on the static coefficient of friction of kernels. The results of this research also showed that the static coefficient of friction for pistachio nuts was lower than their kernels against all five surfaces.

The relationships between moisture content and static coefficient of friction on all five test surfaces namely fiberglass, glass, galvanized iron sheet, plywood and rubber, can be represented by equations in Table 2. The linear relationship between static coefficient of friction and moisture content are reported for almond (Aydin, 2003) and O'hadi variety of pistachio kernel (Kashaninejad et al., 2005).

4. Conclusion

In this paper, the frictional properties of pistachio nut and its kernel including emptying and filling angle of repose, and static coefficient of friction investigated as a function of moisture content and variety. These characteristics are necessary in order to the designing of equipments and machines for the transporting, dehulling, sorting, handling, processing, drying, and storing pistachio nuts. The following are concluded from this investigation into the frictional properties of pistachio nuts and kernels:

1. The frictional properties of nuts and kernels for different varieties were dependent to their moisture content, significantly.
2. For all varieties, as the moisture content increased, the angle of reposes and static coefficient of friction increased linearly.
3. At all moisture contents, the emptying angle of repose of nuts was the greatest for Kalle-Ghuchi (27.36 ± 0.59) and the least for Badami (25.09 ± 1.74). However, in kernels, the greatest value was offered by O'hadi (28.48 ± 1.61) and the lowest by Akbari (26.924 ± 0.97).
4. The filling angle of repose of nuts at all moisture contents was the highest for Badami (18.59 ± 2.27) and the lowest for O'hadi (17.32 ± 1.07). In case of kernels, the same trend was observed.
5. The emptying angle of repose observed higher than filling angle of repose for all varieties at all moisture contents.
6. The angles of repose for kernels obtained higher than the nuts for all varieties at all moisture levels.
7. The static coefficient of friction of both nuts and kernels on all five test surfaces increased linearly with increasing the moisture content.
8. The highest friction for all pistachio varieties, at all moisture contents, for both nuts and kernels observed on rubber surface and the lowest for fiberglass surface.
9. The static coefficient of friction value for Badami nut variety on all five structural surfaces was the greatest.

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