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Science and Technology
Meri-Rastilantie 3 B, FI-00980
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Journal of Food, Agriculture & Environment Vol.11 (1): 215-220. 2013

www.world-food.net

Moisture dependent physical and mechanical properties of organic beans (*Phaseolus vulgaris* L.)

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Received 10 September 2012, accepted 18 January 2013.

Abstract

The physical and mechanical properties of organic bean grains (*Phaseolus vulgaris* L.) were determined as a function of moisture content in the range of 16.14-29.03% dry basis (d.b.). The average length, width and thickness were 17.55, 9.75 and 5.83 mm, at a moisture content of 16.14% d.b., respectively. Nonetheless, the thousand grain mass increased from 643 to 730 g, the projected area from 148.81 to 184.71 mm^2, the true density from 1110 to 1285 kg m^{-3}, the porosity from 36.89% to 48.79% and the terminal velocity from 6.25 to 7.45 m s^{-1} in the moisture range from 16.14% to 29.03% d.b. The static coefficient of friction of organic bean grains increased the linearly against surfaces of six structural materials, namely, rubber (0.43-0.49), stainless steel (0.30-0.34), aluminium (0.42-0.45), galvanized iron (0.32-0.35), MDF (medium density fibreboard) (0.29-0.33) and glass (0.29-0.32) as the moisture content increased from 16.14% to 29.03% d.b. The shelling resistance of organic bean grains decreased from 180 to 145 N as the moisture content increased.

Key words: Physical and mechanical properties, engineering properties, organic beans.

Introduction

Organic beans (*Phaseolus vulgaris* L.) are cultivated for fresh and dry consumption and common raw material in the canned food industry. On average, the bean contains 22.3 g protein, 1.6 g oil, 61.3 g total carbohydrates, 340 kcal energy per 100 g (dry). Turkey had about 1,033,811 da of dry bean harvesting area, 212,758 tons of dry bean annual production with a yield of 206 kg/da of bean [1].

The knowledge of physical properties constitutes important and essential engineering data in the design of machines, storage structures, and processes. The value of this basic information is not only important to engineers but also to food scientists, processors, and other scientists who may exploit these properties and find new uses. The size and shape are, for instance, important in their electrostatic separation from undesirable materials and in the development of sizing and grading machinery [2]. The shape of the material is important for an analytical prediction of its drying behaviour. Bulk density and porosity are major considerations in designing near-ambient drying and aeration systems, as these properties affect the resistance to airflow of the stored mass. The theories used to predict the structural loads for storage structures have bulk density as a basic parameter. The angle of repose is important in designing the equipment for mass flow and structures for storage. The frictional characteristics are important for the proper design of agricultural product handling equipment [3].

The major moisture-dependent physical properties of biological materials are shape and size, densities, porosity, mass of grains and friction against various surfaces. These properties have been studied for various crops such as soybean [4], pumpkin grains [5], lentil [6], cumin grain [7], sunflower grain [8], white lupine [9], coffee [10], green gram [11], Turkish mahaleb [12], pigeon pea [13], chick pea grain[14], cotton [15], okra grain [16], hemp [17], quinoa seeds [18], vetch [19], *Balanites aegyptiaca* nuts [20], caper seed [21], sweet corn seed [22], potato [23], black-eyed pea [24], Turkish Göynük Bombay beans [25], white speckled red kidney beans [26], organic chickpea [27] and white kidney bean [28].

Despite an extensive search, no published literature was available on the detailed physical properties of organic beans and their dependency on operation parameters that would be useful for the design of processing machineries. In order to design equipment and facilities for the handling, conveying, separation, drying, aeration, storing and processing of organic beans, it is necessary to their physical properties as a function of moisture content. Therefore, an investigation was carried out to determine moisture-dependent physical properties of organic beans in the different moisture contents. The purpose of this study was to investigate some moisture-dependent physical properties, namely, axial dimensions, arithmetic and geometric mean diameters, sphericity, thousand grain mass, surface and projected areas, bulk and true densities, porosity, terminal velocity, static coefficient of friction and shelling resistance of organic beans.

Materials and Methods

The organic bean grains used in the study were obtained from a local market (Marmara Region, Bursa, Turkey). The grains were cleaned manually to remove all foreign matter such as dust, dirt, stones and chaff as well as immature, broken grains. The initial moisture content of the grains in dry basis was determined using a digital moisture meter (Pfeuffer HE 50, Germany).

The samples of each one 1500 grains of the 16.14%, 17.86%, 21.95%, 25.16% and 29.03% moisture contents were prepared by adding the amount of distilled water calculated from [17-22]:

$$Q = \frac{W_i(M_f - M_i)}{(100 - M_f)} \quad (1)$$

The samples were then placed inside polyethylene bags and sealed tightly. The samples were kept at 5°C in a common refrigerator for a week to enable the moisture to distribute uniformly throughout the sample. Before starting a test, 1000 grains from each one polyethylene bag was taken out of the refrigerator and allowed to equilibrate to the room temperature for about 2 h [7].

All the physical properties of the grains were determined at five moisture content levels ranging from 16.14% to 29.03% d.b. with 10 replications at each moisture content level.

To determine the average size of the grain, 100 grains were randomly chosen from the polyethylene bags and their three axial dimensions, namely, length (L), width (W) and thickness (T), were measured using a digital compass (Tronic, CHINA) with an accuracy of 0.01 mm [2].

The average diameter of the grain was calculated by using the arithmetic mean and geometric mean of the three axial dimensions. The arithmetic mean diameter D_a and geometric mean diameter D_g of the grain were calculated by using the following relationships [2]:

$$D_a = (L + W + T)/3 \quad (2)$$

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

The sphericity of grains f was calculated by using the following relationship [2]:

$$\phi = \frac{(LWT)^{1/3}}{L} \quad (4)$$

The one thousand grain mass was determined by means of an electronic balance (Baster, Germany) reading to 0.001 g [24].

The surface area A_s in mm^2 of the grains was found by analogy with a sphere of same geometric mean diameter, using the following relationship [29].

$$A_s = \pi D_g^2 \quad (5)$$

The projected area A_p was determined from the pictures of the grains taken by a digital camera (Sony; 10.1 Mpixels, China), in comparison with the reference area to the sample area by using the Global Lab Image 2-Streamline (trial version) program [30].

The average bulk density of the grain was determined using the standard test weight procedure [8] by filling a container of 500 ml with the grain from a height of 150 mm at a constant rate and then weighing the content.

The average true density was determined using the toluene displacement method. The volume of toluene (C_7H_8) displaced was found by immersing 50 g of organic bean grains in toluene [22]. The porosity was calculated from the following relationship [2]:

$$P_f = (1 - \frac{\rho_b}{\rho_t})100 \quad (6)$$

The terminal velocities of the grains at different moisture contents were measured using a cylindrical air column in which the material was suspended in the air stream [11]. The air column was 28 mm in diameter. Relative opening of a regulating valve provided at blower output end was used to control the airflow rate. In the beginning, the blower output was set at minimum. For each experiment, a sample was dropped into the air stream from the top of the air column. Then airflow rate (range from 0 to 17 ms^{-1}) was gradually increased till the grain mass was suspended in the air stream. The air velocity which kept the grain in suspension was recorded by a digital anemometer (Thies clima, Germany) having a least count of 0.1 m/s [31].

The static coefficient of friction of organic bean grains against six different structural materials, namely rubber, galvanized iron, aluminium, stainless steel, glass and MDF (medium density fibreboard) was determined. A polyvinylchloride (PVC) cylindrical pipe of 50 mm diameter and 100 mm height was placed on an adjustable tilting plate, faced with the test surface and filled with the grain sample. The cylinder was raised slightly so as not to touch the surface. The structural surface with the cylinder resting on it was raised gradually with a screw device until the cylinder just started to slide down and the angle of tilt was read from a graduated scale [7]. The coefficient of friction was calculated as:

$$\mu = \tan\alpha \quad (7)$$

Shelling resistance R_s was determined by forces applied to one axial dimension (thickness). The shelling resistance of grain was determined under the point load by using a penetrometer (Bosch BS45 tester, Germany) [24].

Results and Discussion

Grain dimensions: The mean values of the axial dimensions of the organic bean grains at different moisture contents are presented in Fig. 1. All three axial dimensions increased with an increase in moisture content. The mean dimensions of 100 grains measured at a moisture content of 16.14% d.b. are: length 17.55 ± 1.42 mm, width 9.75 ± 0.30 mm, and thickness 5.83 ± 0.24 mm. The average diameter also increased with increasing moisture content as axial dimensions. The arithmetic and geometric mean diameter ranged from 11.041 to 13.33 mm and from 9.98 to 12.36 mm as the moisture content increased from 16.14% to 29.03% d.b.,

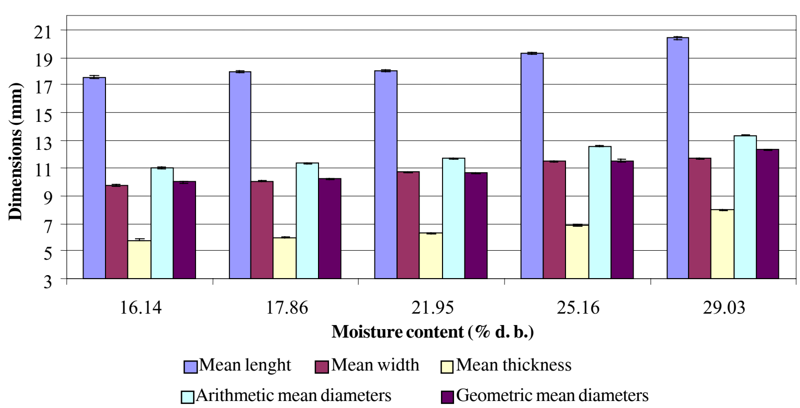

Figure 1. Effect of moisture content on the dimensions of organic beans.

respectively. The values of dimensions of a single organic bean were higher than those of lentils, cotton seeds, sweet corn and pea [5,15, 22, 32].

One thousand grain mass: It can be seen from Fig. 2 that thousand grain mass M_{1000} increased linearly from 643 to 730 g when the moisture content was increased from 16.14 to 29.03% d.b. Increase of 11.91% in the one thousand grain mass was recorded within the above moisture range. The relationship between the thousand grain mass and moisture content can be represented as:

$$M_{1000} = 615 + 21.6M_c \qquad (R^2 = 0.9528) \qquad (8)$$

Organic bean has a relatively big grain size, compared with other commonly grown legume crops; for example at moisture content of 16.14% d.b., the thousand grain mass for green gram is 643 g while it is 245.4 g for black-eyed pea [24], 111.0 g for soybean[4], 173 g for gram [33] and 28.2 g for green gram [11]. On the other hand, it has small grain size, compared with Turkish Göynük Bombay beans, about 1700 g [25].

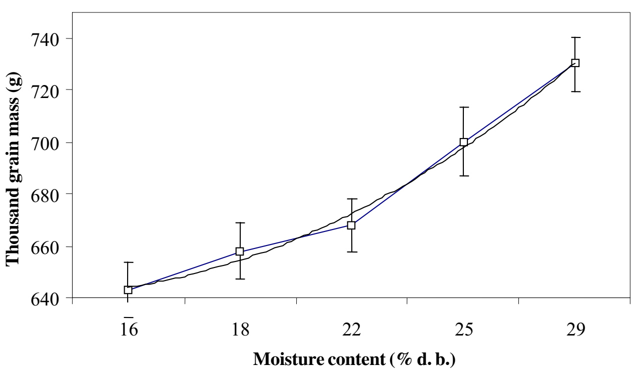

Figure 2. Effect of moisture content on the one thousand grains mass of organic beans.

Surface area of grain: The variation of the surface area with the organic bean grain moisture content is shown in Fig. 3. The surface area of organic bean grains increased linearly from 314.170 to 480.358 mm² when the moisture content increased from 16.14% to 29.03% d.b.

The variation of moisture content and surface area can be expressed mathematically as follows:

$$A_s = 253.66 + 42.135M_c \qquad (9)$$

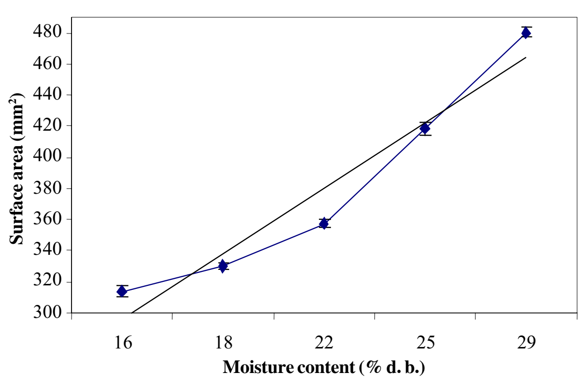

Figure 3. Effect of moisture content on surface area of organic beans.

with a value for the coefficient of determination $R^2 = 0.9373$.

Linear increase in surface area with increase in grain moisture content have been observed by Dursun and Dursun [21] for caper seed, Deshpande *et al.* [4] for soybean and Saçılık *et al.* [17] for hemp seed.

Projected area of grain: The projected area of organic bean grains increased from 148.81 to 184.71 mm² with increasing moisture content (Fig. 4). The variation in projected area with moisture content of organic bean grains can be represented by:

$$A_p = 94.379 + 3.1723M_c \qquad (R^2 = 0.8963) \qquad (10)$$

Linear increase in projected area with increase in grain moisture content was observed by Unal *et al.* [24] for black-eyed pea, Tekin *et al.* [25] for Turkish Göynük Bombay bean, Dursun and Dursun [21] for caper seed, Deshpande *et al.* [4] for soybean and Saçılık *et al.* [17] for hemp seed.

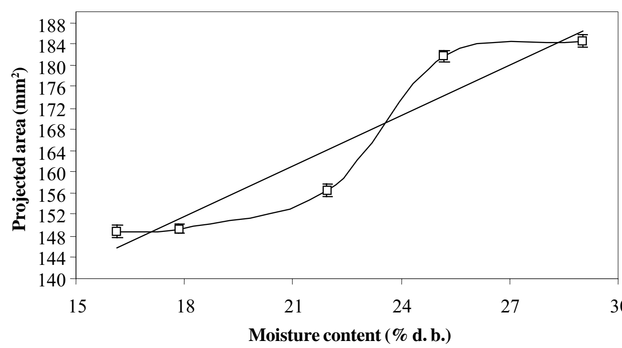

Figure 4. Effect of moisture content on projected area of organic beans.

Sphericity: The values of sphericity were calculated individually with Equation (4) by using the data on geometric mean diameter and the major axis of the grain and the results obtained are presented in Fig. 5. The results indicated that the sphericity of the grain increased from 0.569 to 0.608 in the specified moisture levels. This relationship can be represented by:

$$\phi = 0.5561 + 0.0103M_c \qquad (R^2 = 0.9352) \qquad (11)$$

The sphericity of organic bean was compared with those of other grains and the sphericity of grain at a given moisture level was lower than those of black-eyed pea [24], Türkish Göynük Bombay bean [25] and green gram [11].

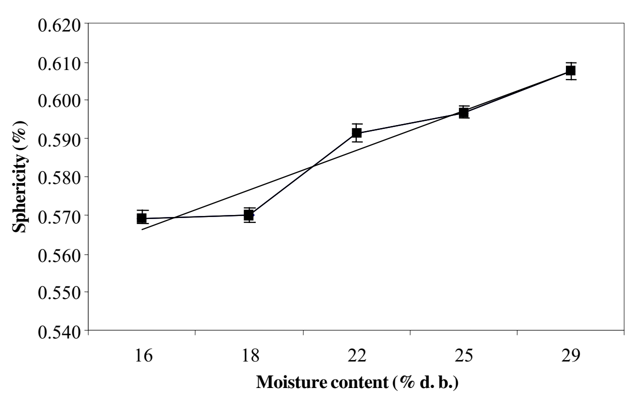

Figure 5. Effect of moisture content on sphericity of organic beans.

Bulk density: The bulk density decreased from 793 to 658 kg/m³ when the moisture content decreased from 16.14% to 29.03% d.b., respectively (Fig. 6). The decrease in bulk densities with increase in moisture contents indicates that the decrease in weight owing to moisture gain in the sample is greater than the accompanying volumetric contraction of the bulk. Similar trends have been reported for black-eyed pea [24], Turkish Göynük Bombay beans [25] and green gram [11]. The variation in bulk density (r_b) was linear with the moisture content (M_c) and can be represented by the following regression equation:

$$\rho_b = 937.39 - 9.7324 M_c \quad (12)$$

with a R^2 value of 0.9641.

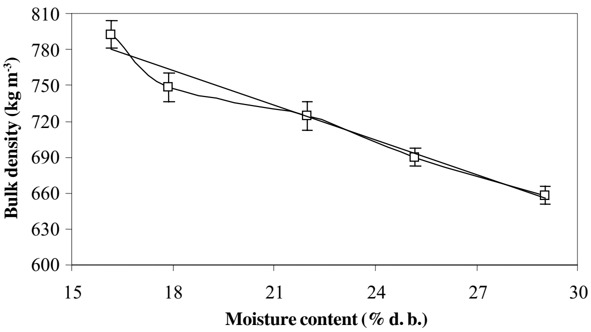

Figure 6. Effect of moisture content on bulk density of organic beans.

True density: The true density varied from 1110 to 1285 kg/m³ when the moisture level increased from 16.14% to 29.03% d.b. (Fig.7). True density and the moisture content of grain can be correlated as follows:

$$\rho_t = 956.63 + 11.82 M_c \quad (13)$$

with a value for R^2 of 0.8429.

A similar increasing trend in true densities have been observed by Baryeh [34] for millet, Unal *et al.* [24] for black-eyed pea and Tekin *et al.* [25] for Turkish Göynük bombay bean.

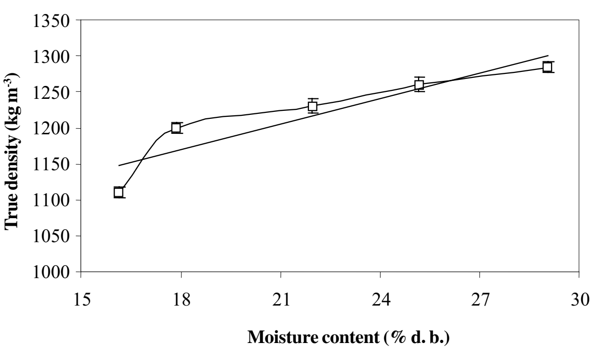

Figure 7. Effect of moisture content on true density of organic beans.

Porosity: Porosity was evaluated using mean values of bulk density and true density in Equation (6). As shown in Fig. 8, the porosity increased linearly from 36.84 to 48.79% in the specified moisture levels. A comparison of porosity of organic bean with that of other grains [8, 9, 11, 14, 20, 24, 35] revealed that it increased with moisture content in the same way as in other grains. The organic bean had close porosity values with sunflower seed, white lupine, green gram, chick pea, black-eyed pea, *Balanites aegyptiaca* nuts, okra seed and sweet corn seed, respectively. The relationship between bulk porosity and the moisture content of the grain was obtained as:

$$P_f = 20.801 + 0.9584 M_c \quad (14)$$

with a value for R^2 of 0.9879.

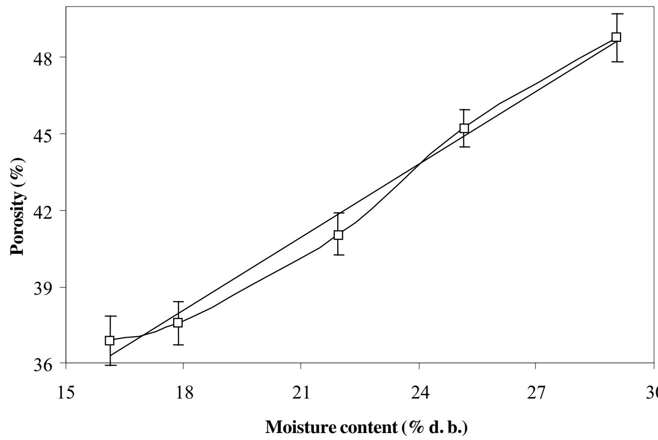

Figure 8. Effect of moisture content on porosity of organic beans.

Terminal velocity: Experimental results for the terminal velocity of organic bean grains at various moisture levels are plotted in Fig. 9. As moisture content increased, the terminal velocity V_t increased linearly from 6.25 to 7.45 ms^{-1} in the specified moisture range. The relationship between terminal velocity and moisture content can be represented with the following relationship:

$$V_t = 4.8964 + 0.09 M_c \qquad (R^2 = 0.9288) \quad (15)$$

The results were similar to those reported by Çarman [35], Nimkar and Chattopadhyay [11], Suthar and Das [36], Unal *et al.* [24] and Singh and Goswami [7] but the values were lower than those for lentil and green gram, and higher than those for karingda seed, black-eyed pea and cumin seed, respectively. The increase in terminal velocity with increase in moisture content within the study range can be attributed to the increase in mass of an individual grain per unit frontal area presented to the air stream.

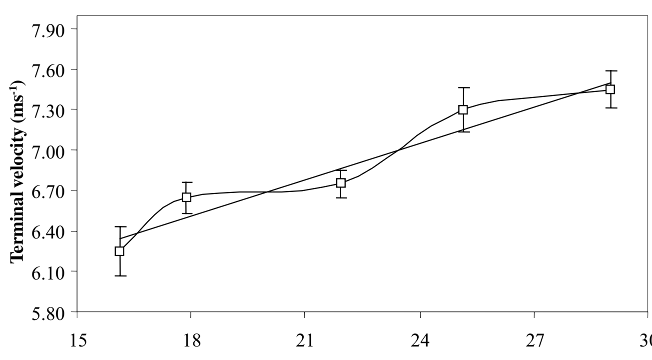

Figure 9. Effect of moisture content on terminal velocity of organic beans.

Static coefficient of friction: The effects of moisture content and surface nature of materials on the static and kinetic coefficients of friction of organic bean grains are shown in Fig. 10. The static coefficient of friction on the rubber surface varied from 0.43 to 0.49, on the stainless steel from 0.30 to 0.34, on the aluminium from 0.42 to 0.45, on the galvanised iron from 0.32 to 0.35, on the MDF (medium density fibreboard) sheet from 0.29 to 0.33 and on the glass from 0.29 to 0.32 for moisture contents between 16.14 and 29.03% d.b., respectively. The maximum static coefficients of friction were noticed on rubber surface, followed by aluminium, galvanised iron, stainless steel, MDF and glass surfaces.

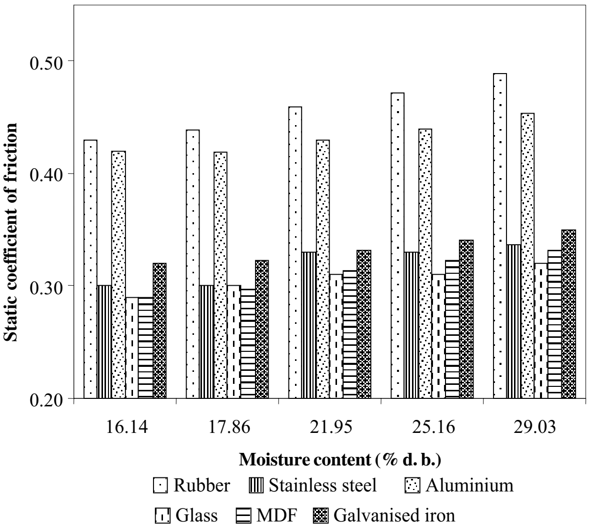

Figure 10. Effect of moisture content on static coefficient of friction of organic beans against various surface.

All the static coefficients of friction increased linearly in the moisture range of 16.14-29.03% d.b. Similar trends have been reported for soybeans, red kidney beans, unshelled peanuts [37], black-eyed pea [24], Turkish Göynük Bombay beans [25], cumin seed[7] and lentil seeds [35].

Shelling resistance: The shelling resistance of organic beans decreased with the increase in moisture content (Fig.11). The smaller shelling resistance at higher moisture content might have resulted from the fact that the grains became more sensitive to cracking at high moisture [24]. The variation in shelling resistance of white kidney beans R_s in N with moisture content can be represented by:

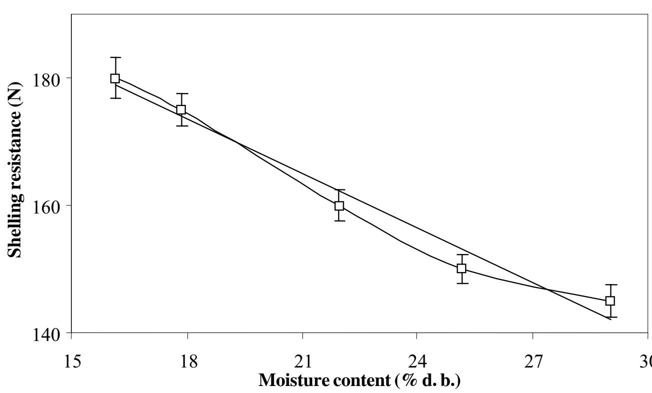

Figure 11. Effect of moisture content on shelling resistance of organic beans.

$$R_s = 224.9 - 2855 M_c \quad (16)$$

with value for R^2 of 0.9722.

A similar trend in shelling resistance had been observed by Baryeh [13] for millet, Unal *et al.* [24] for black-eyed pea, Özarslan [15] for cotton, Tekin *et al.* [25] for Turkish Göynük Bombay bean and Konak *et al.* [14] for chick pea grains.

Conclusions

The mean dimensions of 100 grains measured at a moisture content of 16.14% d.b. were: length 17.55 ± 1.42 mm, width 9.75 ± 0.30 mm, and thickness 5.83 ± 0.24 mm. The average diameter also increased with increasing moisture content as axial dimensions. The arithmetic and geometric mean diameter ranged from 11.041 to 13.33 mm and from 9.98 to 12.36 mm as the moisture content increased from 16.14% to 29.03% d.b., respectively.

Thousand grain mass M_{1000} increased linearly from 643 to 730 g when the moisture content was increased from 16.14 to 29.03% d.b. Increase of 11.91% in the one thousand grain mass was recorded within the above moisture range.

The surface area of organic bean grains increased linearly from 314.170 to 480.358 mm² when the moisture content increased from 16.14% to 29.03% d.b.

The projected area of organic bean grains increased from 148.81 to 184.71 mm² with increasing moisture content.

The bulk density decreased from 793 to 658 kg/m³ when the moisture content decreased from 16.14% to 29.03% d.b., respectively

The true density varied from 1110 to 1285 kg/m³ when the moisture level increased from 16.14% to 29.03% d.b.

The porosity was found to increase linearly from 36.84 to 48.79% in the specified moisture levels.

As moisture content increased, the terminal velocity V_t was found to increase linearly from 6.25 to 7.45 ms^{-1} in the specified moisture range.

The static coefficient of friction on the rubber surface varied from 0.43 to 0.49, on the stainless steel from 0.30 to 0.34, on the aluminium from 0.42 to 0.45, on the galvanised iron from 0.32 to 0.35, on the MDF(medium density fibreboard) sheet from 0.29 to 0.33 and on the glass from 0.29 to 0.32 for moisture contents between 16.14 and 29.03% d.b., respectively. The maximum static coefficients of friction were noticed on rubber surface, followed by aluminium, galvanised iron, stainless steel, MDF and glass surfaces.

The shelling resistance of organic beans decreased with the increase in moisture content.

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Nomenclature

A_p	projected area	mm²
A_s	surface area	mm²
C_1, C_2	Regression coefficients	
D_a	arithmetic mean diameter of grain	mm
D_g	geometric mean diameter of grain	mm
L	length of grain	mm
M_c	moisture content	% d.b.
M_{1000}	thousand grain mass	g
M_f	final moisture content of sample	% d.b.
M_i	initial moisture content of sample	% d.b.
P_f	porosity	%
Q	mass of water to added	g
R_s	shelling resistance	N
R^2	coefficient of determination	dimensionless
T	thickness of grain	mm
V_t	terminal velocity	m/s
W	width of grain	mm
W_i	initial mass of sample	g
ρ_b	bulk density	kg/m³
ρ_t	true density	kg/m³
ϕ	sphericity of grain	dimensionless
μ	coefficient of friction	dimensionless