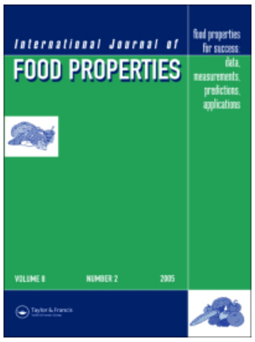

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GEOMETRIC AND MECHANICAL PROPERTIES OF MUNG BEAN (*VIGNA RADIATA* L.) GRAIN: EFFECT OF MOISTURE

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In this research, selected geometric and mechanical properties of mung bean grain were evaluated as a function of moisture content. Five levels of moisture content ranging from 7.28 to 17.77% d.b. (dry basis) were used. The average length, width, thickness, arithmetic and geometric mean diameters, sphericity, thousand grain mass and angle of repose ranged from 5.145 to 6.199 mm, 3.760 to 4.474 mm, 3.537 to 4.223 mm, 4.147 to 4.965 mm, 4.090 to 4.893 mm, 0.795 to 0.789, 52.3 to 64.6 g, and 25.87 to 29.38° as the moisture content increased from 7.28 to 17.77% d.b., respectively. The bulk density was found to be decreased from 821.3 to 745.2 kg/m^3, whereas the grain volume, true density, porosity, terminal velocity, and projected area were found to be increased from 27.88 to 47.33 mm^3, 1230.0 to 1456.7 kg/m^3, 30.43 to 46.57%, 4.86 to 5.29 m/s, and 17.48 to 19.26 mm^2, respectively. There is a 43% increase in surface area from grain moisture content of 7.28 to 17.77% d.b. The static coefficient of friction on various surfaces increased linearly with the increase in moisture content. The rubber as a surface for sliding offered the maximum friction followed by galvanised iron, medium density fibreboard, stainless steel, aluminium and glass sheet. As moisture content increased from 7.28 to 17.77%, the rupture forces values ranged from 67.39 to 39.44 N; 63.86 to 42.18 N, and 53.96 to 41.79 N for thickness (Z axis), length (Y-axis) and width (X-axis), respectively.

Keywords: ***Mung bean grain,*** **Vigna radiata L.,** ***Geometric and mechanical properties.***

INTRODUCTION

Mung bean, *Vigna radiata* (L.) Wilczek has been grown in India since ancient times. It is still widely grown in Southeast Asia, Africa, South and North America, and Australia, principally for its protein rich edible grains. The mung bean is commonly known in Asia as the green gram. Other common names include moong, mungo, golden gram, and chop-suey bean.[1] Its Turkish name is known as "maş." Mung beans are grown widely for use as a human food (as dry beans or fresh sprouts), but they can be used as a green manure crop and as forage for livestock.

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World's mung bean cultivation area is nearly 4 million ha, and 2 million tonnes of yield is obtained from this area.[2] About 70% of the world production of mung bean is in India.[3] Mung bean is grown in South East Anatolia and southern coastal provinces of Turkey, however, there are no statistical data related to the cropping area, production and yield of this crop.[4,5] The yields of mung beans depend largely on weather conditions, soil, cultural practices, and variety. Yields can range from 350 to 2,250 kg/ha. Mung bean grains might be between 13 – 15% moisture at harvest time. In developing countries, the mung beans are hand picked as the pods mature. Because the major use of mung bean is for sprouts; excellent germination must be maintained by careful harvesting and storage systems. Furthermore, because the grain is small, careful handling and attention to planting machinery adjustments is necessary to ensure planting with little damage to the grain. Prior to storing, remove all leaf material, stems, immature pods, dirt, insect parts and other debris. Mung beans at about 12% moisture can then be stored in regular grain bins previously fumigated to control bean weevils.[1] Mung bean contains 26.4 g protein, 0.72 g non-protein nitrogen, 4.5 g ash, 1.75 g fat, 6.15 g crude fiber, and 61.2 g carbohydrates in 100 g on dry weight basis.[6]

The geometric and mechanical properties of mung bean are important to design the equipment for processing, transportation, sorting, separation and storing. Designing such equipment without taking these into consideration may yield poor results. Therefore the determination and consideration of these properties has an important role.

The major moisture-dependent physical properties of biological materials are shape, size, mass, bulk density, true density, porosity and static friction coefficient against various surfaces.[7] Other researchers have studied these properties for various grains and seeds such as black-eyed pea,[8] Turkish Göynük Bombay bean,[9] caper seed,[10] chick pea seed,[11] chilli,[12] cotton seed,[13] cumin,[14] fenugreek,[15] gram,[16,17] green gram,[18] guna,[19] hemp,[20] karingda,[21] linseed,[22] millet,[23] moth gram,[24] okra,[25,26] pigeon pea,[27] pulse grain,[28] pumpkin,[29,30] quinoa,[31] safflower,[32] soybean,[33] sunflower,[34] vetch,[35] and white lupin.[36] Size, shape, and physical dimensions of mung bean are important in sizing, sorting, sieving, and other separation processes. For instance, sphericity is one of the most important properties because it affects how easily mung bean can be processed by the food industry. The volume and density of the grain play an important role in numerous technological processes and in the evaluation of product quality. In determining the true density of seeds and grains, researchers have used either gas displacement[21,37,38] or liquid displacement[7,8,16–18,33] methods. The liquid displacement method is simpler and involves the immersion of a quantity of grain or seed fully in liquid (water or toluene) and noting the amount of liquid displaced. When toluene is used, a thin toluene-resistant coating is applied over the grain to prevent the absorption of moisture during the experiment. The porosity affects the resistance to airflow through bulk bean. Terminal velocity is very critical in the design of pneumatic conveyor, transporting mung bean using air and separation grain from undesirable materials such as shells, hulls, leaves and small branches. The terminal velocity is affected by the density, shape, size, and moisture content of samples. The coefficient of static friction plays also an important role in transports (load and unload) of goods and storage facilities. The static coefficient of friction of grains and seeds has been determined by various investigators[16–18,21,28,33] using the inclined plane method. These investigations have shown that coefficient of friction increases with moisture content and varies with the surface on which the grain slides. Various investigations[8,17,20,21,25,34] on different grains show that the angle of repose increases with moisture content. To determine this angle, a specially constructed box with a removable front panel has been used. Therefore, the aim of this study was to investigate the moisture-dependent geometric and mechanical properties of mung bean such as dimensions, sphericity, volume, surface and projected areas, thousand grains mass, bulk density, true density, porosity, angle of repose, static friction coefficient on various surfaces, rupture strength, and terminal velocity.

MATERIALS AND METHODS

Sample Preparation

The mung bean grains used in this study were obtained from a local market. 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 was determined by oven drying at 105 ± 1°C for 24 h.[8,21] The initial moisture content of the grains was 7.28 % d.b. The desired moisture contents were obtained by adding calculated amounts of distilled water on the grains. The samples were then poured into separate polyethylene bags and the bags sealed tightly. The samples were kept at 5°C in a refrigerator for a week to enable the moisture to distribute uniformly throughout the sample. Before starting a test, the required quantity of the grain was taken out of the refrigerator and allowed to warm up to the room temperature for about 2 h.[14] All the geometric and mechanical properties of the grains were determined at moisture levels of 7.28, 10.41, 12.60, 14.71, and 17.77% d.b. with ten replications at each level.

Determination of Spatial Dimensions, Size, and Sphericity for Geometric Properties

To determine the average size of the grain, 100 grains were randomly picked and their three axial dimensions namely, major L, medium W and minor T were measured using a calliper with a sensitivity of 0.01 mm. The average diameter of 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.[7,8]

$$D_a = (L + W + T)/3; \quad \text{and} \tag{1}$$

$$D_g = (LWT)^{1/3}. \tag{2}$$

According to Mohsenin,[7] the degree of sphericity, Φ can be expressed as follows:

$$\phi = D_g/L. \tag{3}$$

Baryeh and Mangope[27] have also stated that the seed volume, V and grain surface area, S may be given by:

$$V = \frac{\pi B^2 L^2}{6(2L - B)}, \quad \text{and} \tag{4}$$

$$A_s = \frac{\pi B L^2}{2L - B}, \tag{5}$$

where $B = (WT)^{1/2}$. The surface area A_s in mm^2 of mung bean grains was also found by analogy with a sphere of same geometric mean diameter, using the following relationship.[8,23]

$$A_s = \pi D_g^2. \tag{6}$$

The projected area A_p was determined from the pictures of mung beans which were taken by a digital camera (Nikon Coolpix 4100), in comparison with the reference area to the sample area by using the Global Lab Image 2-Streamline (trial version) program.[9]

Determination of Gravimetric Properties

The thousand grain mass was determined by means of a digital electronic balance having an accuracy of 0.001 g. The methods described by Mohsenin[7] and Singh and Goswami[14] were used to determine the bulk and true (kernel) densities of mung bean grain at different moisture levels. The bulk density was determined by filling a circular container of 500 ml in volume with the grain from a height of 150 mm at a constant rate and then weighing the contents. No separate manual compaction of grains was done. The bulk density was calculated from the mass of the grains and the volume of the container. The true density defined as the ratio between the mass of mung bean and true volume of grain was determined using the toluene (C_7H_8) displacement method. Toluene was used in place of water because it is absorbed by seeds to a lesser extent. The volume of toluene displaced was found by immersing a weighed quantity of grain in the toluene. The porosity of mung bean at various moisture contents was calculated from bulk and true densities using the relationship given by Mohsenin[7] as follows:

$$\varepsilon = 100\left[1 - \left(\rho_b / \rho_t\right)\right]. \tag{7}$$

Determination of Frictional Properties

The angle of repose was determined by using a topless and bottomless cylinder of 10 cm diameter and 15 cm height. The cylinder was placed on a table and filled it with grams and raised slowly until it form a cone. The diameter and height of cone was recorded. The angle of repose, θ was calculated by using the formula as:[12,17]

$$\theta = \tan^{-1}\left(2H/D\right). \tag{8}$$

The static coefficient of friction of mung bean against six different structural materials, namely rubber, galvanised iron, aluminium, stainless steel, glass and medium density fibreboard (mdf) was determined. A polyvinylchloride 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.[14,18,34] The coefficient of friction was calculated from the following relationship:

$$\mu = \tan\alpha. \tag{9}$$

Determination of Aerodynamic Properties

The terminal velocity, V_t of the grains was determined using an air column similar to the one used by Unal et al.,[8] Singh and Goswami,[14] and Suthar and Das.[21] 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 was gradually increased till the grain mass gets suspended in the air stream. The air velocity which kept the grain suspension was recorded by a digital anemometer (Thies clima, Germany) having a least count of 0.1 m/s.[8] Ten replications were taken for each sample.

Determination of Rupture Strength Properties

Rupture strength P_r was determined by forces applied to three axial dimensions (length, width, and thickness). The shelling resistance of grain was determined under the point load by using a penetrometer (Bosch BS45 tester).[8]

Statistical Analysis

The results were processed by the SPSS software (V.14.0 for Windows). One way analysis of variance and a Duncan's test were used to analyze the results. Differences were considered significant at $p < 0.05$, unless otherwise specified.

RESULTS AND DISCUSSION

Spatial Dimensions, Size, Diameters, Areas, Volume, and Sphericity of Mung Bean

The length, width, thickness, arithmetic diameter, and geometric diameter of mung beans at moisture contents of 7.28, 10.41, 12.60, 14.71, and 17.77% (dry basis) are presented in Table 1. It is observed from the Table 1 that all dimensions of gram increased with the increase of moisture content. For the increase of moisture contents from 7.28 to 17.77% (dry basis), the increase of length, width, thickness, arithmetic diameter and geometric diameter were 20.49, 18.99, 19.39, 19.73, and 19.63%, respectively. The arithmetic and geometric diameters were lower than the length and higher than the width and thickness. Unal et al.,[8] Chowdhury et al.,[17] Nimkar and Chattopadhyay,[18] Baümler et al.,[32] and Gupta and Das[34] found similar results for black-eyed pea, gram, green gram,

Table 1 Means and standard errors of the grain dimensions at different moisture content.

	Linear dimensions, mm			Average diameters, mm	
Moisture content, % d.b.	Length (L)	Width (W)	Thickness (T)	Arithmetic mean (D_a)	Geometric mean (D_g)
7.28	5.145 ± 0.021^a	3.760 ± 0.014^a	3.537 ± 0.015^a	4.147^a	4.090^a
10.41	5.499 ± 0.006^b	3.988 ± 0.004^b	3.771 ± 0.004^b	4.419^b	4.357^b
12.60	5.704 ± 0.005^c	4.120 ± 0.004^c	3.903 ± 0.004^c	4.576^c	4.510^c
14.71	5.896 ± 0.005^d	4.268 ± 0.004^d	4.033 ± 0.004^d	4.732^d	4.665^d
17.77	6.199 ± 0.017^e	4.474 ± 0.012^e	4.223 ± 0.009^e	4.965^e	4.893^e

$^{a\text{–}e}$Means superscript with different alphabets in the same column differ significantly ($p < 0.05$).

safflower, and sunflower seeds, respectively. The following regression equations were developed for length, width, thickness, arithmetic diameter and geometric diameter with moisture content (M_c, % dry basis).

$$Length\ (mm),\quad L = 4.4413 + 0.0994M_c. \quad (\mathrm{R}^2 = 0.998) \tag{10}$$

$$Width\ (mm),\quad W = 3.2723 + 0.0677M_c. \quad (\mathrm{R}^2 = 0.994) \tag{11}$$

$$Thickness\ (mm),\quad T = 3.0802 + 0.0648M_c. \quad (\mathrm{R}^2 = 0.998) \tag{12}$$

$$Arithmetic\ Diameter\ (mm),\quad D_a = 3.5979 + 0.0773M_c. \quad (\mathrm{R}^2 = 0.999) \tag{13}$$

$$Geometric\ Diameter\ (mm),\quad D_g = 3.5508 + 0.0758M_c. \quad (\mathrm{R}^2 = 0.999) \tag{14}$$

The values of sphericity were calculated individually with Eq. (3) by using the data on geometric mean diameter and the major axis (L) of the grain and the results obtained are presented in Fig. 1A. The results indicated that the sphericity of the grain was found decreased from 0.795 to 0.789 in the specified moisture levels. The relationship between sphericity and moisture content M_c in % d.b. can be represented by the following equation:

$$\phi = 0.798 - 0.0005M_c, \tag{15}$$

with a value for R^2 of 0.892. The sphericity of mung bean was compared with those of other grains and it was observed that sphericity of grain at a given moisture level was lower than those of black-eyed pea,[8] Türkish Göynük bombay bean,[9] green gram,[18] moth gram,[24] okra seed,[26] and pigeon pea.[27]

The grain surface area increases with increasing grain moisture content. Eq. (6) gives higher surface areas than Eq. (5). This is due to the different grain shapes assumed for the equations. There is a 43% increase in surface area from grain moisture

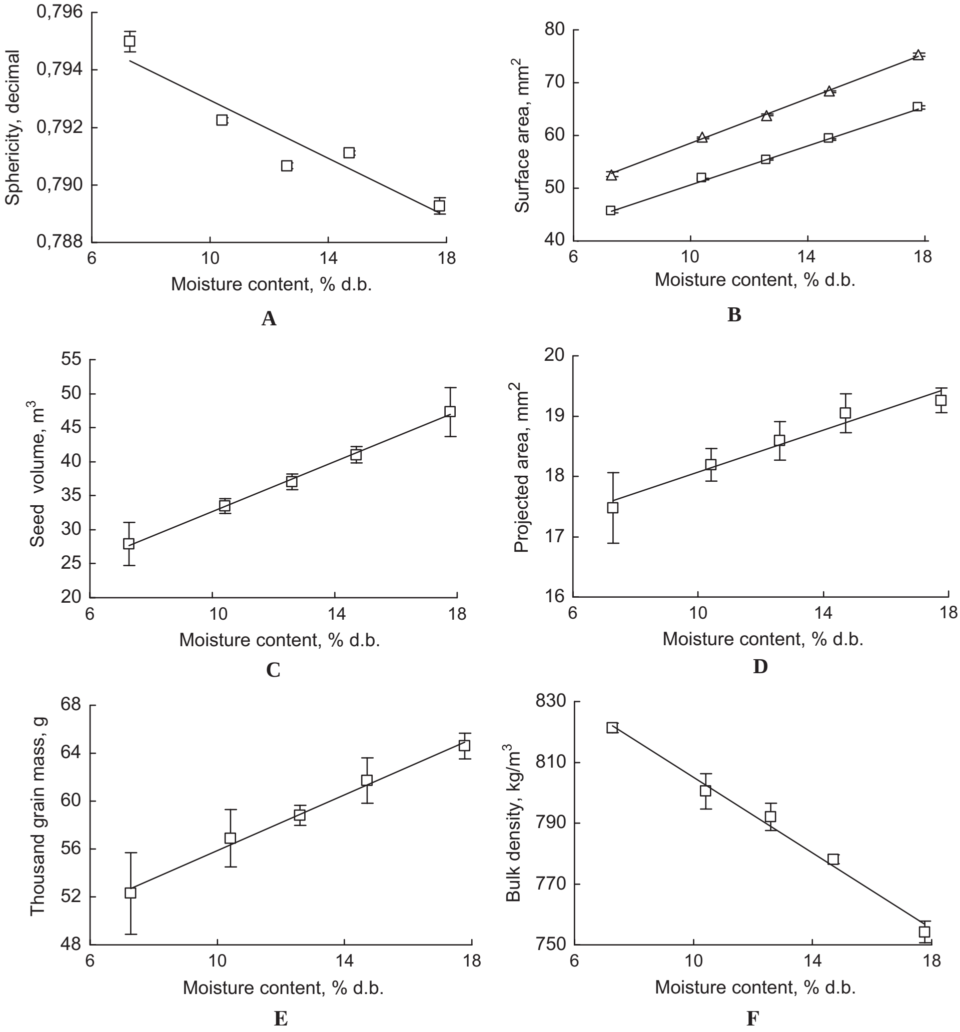

Figure 1 (A.) Effect of moisture content on sphericity of mung bean; (B.) effect of moisture content on surface area of mung bean; (C.) effect of moisture content on volume of mung bean; (D.) effect of moisture content on projected area of mung bean; (E.) effect of moisture content on thousand grains mass; and (F.) effect of moisture content on bulk density of mung bean.

content of 7.28–17.77% d.b. in both cases (Fig. 1B). The relationship can be expressed as follows:

$$A_s = 37.121 + 2.1377 M_c \qquad \mathrm{R}^2 = 0.999, \tag{16}$$

and

$$A_s = 32.333 + 1.8435 M_c \qquad \mathrm{R}^2 = 0.999, \tag{17}$$

for Eqs. (6) and (5), respectively. Unal et al.,[8] Altuntaş et al.,[15] Sacilik et al.,[20] Baryeh,[23] and Deshpande et al.[33] obtained similar results working with black-eyed pea, fenugreek, hemp seed, millet, and soybean. Baryeh and Mangope,[27] however, found the surface area of pigeon pea to decrease with increasing grain moisture content.

The values obtained for grain volume of mung bean are graphically shown in Fig. 1C. The grain volume increases from 27.87 mm^3 at 7.28% grain moisture content to 47.30 mm^3 at 17.77% grain moisture content. This is explained by the increase in the grain dimensions as the grain moisture content increase. The change was significant at 5% level of significance. Linear increases in volume with increase in grain moisture content have been observed by Unal et al.[8] for black-eyed pea, Dutta et al.[16] for gram, Aviara et al.[19] for guna seed, Nimkar et al.[24] for moth gram, Deshpande et al.[33] and for soybean and Öğüt[36] for white lupin. Otherwise, Baryeh and Mangope[27] found the volume of pigeon pea to decrease nonlinearly with increase in seed moisture content. These differences could be due to the shape and dimensional change characteristics of the different grains. The variation of moisture content and grain volume can be expressed mathematically as follows:

$$V = 14.261 + 1.8379M_c, \tag{18}$$

with values for the coefficient of determination R^2 of 0.998. The projected area of mung bean increased from 17.48–19.26 mm^2, while the moisture content of grain increased from 7.28 to 17.77% d.b. (Fig. 1D). The variation in projected area A_p in mm^2 with moisture content of grain can be represented by the following equation:

$$A_p = 16.328 + 0.1742M_c, \tag{19}$$

with a value for the coefficient of determination R^2 of 0.964. Linear increases in projected area with increase in grain moisture content have been observed by Unal et al.[8] for black-eyed pea, Tekin et al.[9] for Türkish Göynük bombay bean, Dursun and Dursun[10] for caper seed, and Deshpande et al.[33] for soybean.

Gravimetric Properties of Mung Bean

Experimental values obtained for thousand grain mass of mung bean are graphically shown in Fig. 1E. It can be seen from Fig. 1E that thousand grain mass M_{1000} increased linearly from 52.3–64.6 g ($p < 0.05$) when the moisture content was increased from 7.28 to 17.77% d.b. The relationship between thousand grain mass and moisture content can be represented as:

$$M_{1000} = 44.237 + 1.1648M_c, \tag{20}$$

with a value of R^2 of 0.992. Mung bean has a relatively small grain size, compared with other commonly grown pulse crops; for example at moisture content of 10.41% d.b., the thousand grain mass for mung bean is 56.9 g, while it is 245 g for black-eyed pea,[8] 139 g for gram,[17] 111 g for pigeon pea,[27] and 111 g for soybean.[33] Nimkar and Chattopadhyay[18] found the one thousand grain mass of green gram variety to be 31.4 g at 17.88% grain moisture content, which is half the value for the 17.77% moisture content for the variety used in this study.

The grain bulk density at different moisture levels varied from 821.3 to 754.2 kg/m^3 (Fig.1F) and indicated a decrease in bulk density with an increase in moisture content with significant ($p < 0.05$) variation. This was due to the fact that an increase in mass owing to moisture gain in the grain sample was lower than accompanying volumetric expansion of the bulk. The percent decrease in bulk density for mung bean was 7.9% corresponding to the increase in moisture content from 7.28 to 17.77% d.b. The negative linear relationship of bulk density with moisture content was also observed by various other research workers.[10,17–19,24–26,31–33,35,36] Bulk density mung bean (778.1 kg/m^3), at moisture content of 14.71% d.b. was found to be greater than caper seed (403.5 kg/m^3),[10] gram (769 kg/m^3),[17] guna seed (502.6 kg/m^3),[19] okra seed (580.7 kg/m^3),[25,26] quinoa seed (713.5 kg/m^3),[31] safflower (450.4 kg/m^3),[32] and soybean (724.4 kg/m^3),[33] whereas it was smaller than green gram (782.4 kg/m^3),[18] moth gram (814.3 kg/m^3),[24] vetch seed (845.8 kg/m^3),[35] and white lupin (802 kg/m^3).[36] The bulk density of grain was found to bear the following relationship with moisture content:

$$\rho_b = 867.31 - 6.2192 M_c, \tag{21}$$

with a value for the coefficient of determination R^2 of 0.99. The true density of the grain was measured at different moisture levels and it was found linearly increased and varied from 1230.0 to 1456.7 kg/m^3 (Fig. 2A). The variation in true density with moisture content was significant ($p < 0.05$). This increase indicates that there is a higher grain mass increase in comparison to its volume increase as its moisture content increases. This agrees with finding of Tekin et al. [9] for Turkish Göynük bombay bean, Aviara et al.[19] for guna seeds, Selvi et al.[22] for linseed, Baryeh[23] for millet, Gupta and Das[34] for sunflower seeds, and Yalçin and Özarslan[35] for vetch seed. It is, however, contrary to results of Konak et al., [11] Altuntaş et al.,[15] Chowdhury et al.,[17] Suthar and Das,[21] and Nimkar et al.,[24] who found the true density to decrease with moisture content for chickpea, fenugreek, gram, karingda, and moth gram seeds, respectively. These seeds therefore, have lower weight increase in comparison to volume increase as their moisture content increases. The true density and the moisture content of grain can be correlated as follows:

$$\rho_t = 1067.3 + 22.043 M_c, \tag{22}$$

with a value for R^2 of 0.997. The correlation between the bulk density and true density is shown in Fig. 2B. The figure reveals that the bulk density decreases linearly on the contrary the true density increases. The relation may be represented mathematically as:

$$\rho_b = 1166.5 - 0.2807 \rho_t \quad (\mathrm{R}^2 = 0.983). \tag{23}$$

Bulk porosity was evaluated using mean values of bulk density and true density in Eq. (7). As shown in Fig. 2C, the bulk porosity was found to increase linearly from 30.43 to 46.57% in the specified moisture levels and this change was significant at a 5% level of significance. The results indicate that the increase in bulk porosity value of mung bean is

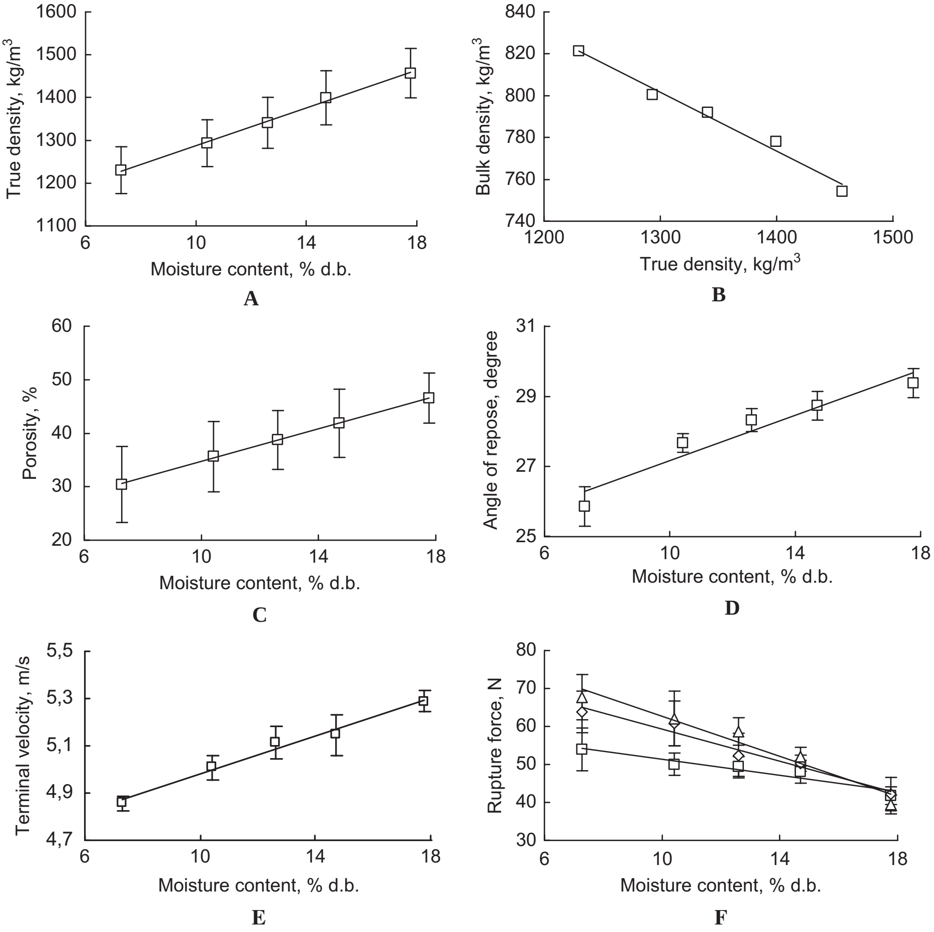

Figure 2 (A.) Effect of moisture content on true density; (B.) bulk density variation with true density; (C.) effect of moisture content on porosity of mung bean; (D.) effect of moisture content on angle of repose of mung bean; (E.) effect of moisture content on terminal velocity; (F.) effect of seed moisture content on rupture force: (Δ) thickness; (◇) length; (□) width.

53% with the corresponding increase in moisture contents from 7.28 to 17.77% d.b. Similar observations of increase in bulk porosity with increase in grain moisture content have been reported.[11,17,18,27,33,36] Bulk porosity of mung bean (38.7%), at moisture content of 12.6% d.b., was found to be smaller than chickpea (43.6%),[11] green gram (41.6%),[18] pigeon pea (41.7%),[27] and soybean (38.8%),[33] while it was greater than gram (33.4%)[17] and white lupin (21.5%).[36] The relationship between porosity and moisture content of the grain can be represented by the following equation:

$$\varepsilon = 19.493 + 1.5257 M_c, \tag{24}$$

with a value for R^2 of 0.999.

Frictional Properties of Mung Bean

The results obtained for angle of repose with increase in grain moisture content are shown in Fig. 2D. It was observed that angle of repose increases linearly from 25.87 to 29.38° with increase in moisture content for mung bean and this change was significant at a 5% level of significance. The results indicated that the increase in angle of repose for mung bean was 13.57% for the corresponding increase in moisture contents of 7.28 to 17.77% d.b. Similar results on effect of grain moisture on angle of repose have been reported for black-eyed pea,[8] chickpea,[11] fenugreek,[15] green gram,[18] karingda,[21] millet,[23] moth gram,[24] okra,[25] and pigeon pea.[27] At a moisture content of 12.6% d.b. the angle of repose of mung bean (28.3°) was found to be smaller than fenugreek (29.2°),[15] karingda seed (35.2°),[21] millet (39.9°),[23] okra seed (29.9°),[25] and sunflower seed (37.0°),[34] whereas it was greater than black-eyed pea (21.8°),[8] chickpea (26.8°),[11] green gram (27.4°),[18] moth gram (27.6°),[24] and pigeon pea (22.4°).[27] The variation in angle of repose with the moisture content can be correlated as follows:

$$\theta = 23.942 + 0.3231 M_c, \tag{25}$$

with a value for R^2 of 0.929. The static coefficient of friction obtained experimentally on six structural surfaces against moisture content in the range of 7.28 to 17.77% d.b., are presented in Table 2. It is observed that the static coefficient of friction for mung bean increased with increase in moisture content on all surfaces. At all moisture contents, the static coefficient of friction was greatest against rubber (0.386 – 0.433) followed by galvanised iron (0.374 – 0.417), medium density fibreboard (0.360 – 0.392), stainless-steel (0.348 – 0.382), aluminium (0.344 – 0.362), and the least for glass (0.327 – 0.350). It was observed that moisture had more effect than the material surface on the static coefficient of friction. This is owing to the increased adhesion between the grain and the material surface at higher moisture values. At all moisture contents, the least static coefficient of friction were on glass material. This may be owing to smoother and more polished surface of the glass material than the other materials used. Similar results were reported by Unal et al.,[8] Chowdhury et al.,[17] Nimkar and Chattopadhyay,[18] Baryeh,[23] Amin et al.,[28] and Gupta and Das.[34] When compared with other seeds, the static coefficient of friction for mung bean on the galvanised iron sheet was lower than for green gram[17] and gram,[18] but higher than black-eyed pea[8] and millet,[23] whereas it was more or less similar to

Table 2 Static coefficient of friction for mung bean.

Moisture content, % d.b.	Coefficient of friction, μ					
	Rubber	Galvanised iron	Medium density fibreboard	Stainless steel	Aluminium	Glass
7.28	0.386 (0.029)^{a}	0.374 (0.010)^{a}	0.360 (0.022)^{a}	0.348 (0.018)^{a}	0.344 (0.023)^{ns}	0.327 (0.017)^{a}
10.41	0.402 (0.034)^{ab}	0.384 (0.028)^{ab}	0.368 (0.023)^{ab}	0.358 (0.025)^{ab}	0.350 (0.016)^{ns}	0.337 (0.014)^{ab}
12.60	0.406 (0.037)^{ab}	0.392 (0.030)^{ab}	0.372 (0.036)^{ab}	0.364 (0.032)^{ab}	0.352 (0.017)^{ns}	0.337 (0.019)^{ab}
14.71	0.410 (0.024)^{ab}	0.404 (0.033)^{ab}	0.380 (0.038)^{ab}	0.372 (0.038)^{ab}	0.356 (0.025)^{ns}	0.346 (0.015)^{b}
17.77	0.433 (0.034)^{b}	0.417 (0.034)^{b}	0.392 (0.020)^{b}	0.382 (0.041)^{b}	0.362 (0.024)^{ns}	0.350 (0.023)^{b}

Note: Values in the parentheses are standard deviation. $^{a\text{–}b}$Means superscript with different alphabets in the same column differ significantly ($p < 0.05$).

those of pulse grains[28] and sunflower seed.[34] The regression equations for static coefficient of friction on different surfaces can be expressed as:

$$\mu = C_1 + C_2 M_c. \tag{26}$$

The regression coefficients and coefficients of determination for static coefficient of friction on various surfaces are given in Table 3.

Aerodynamic Properties of Mung Bean

The variation in terminal velocity values of mung bean with the increase in moisture content is shown in Fig. 2E. It was observed that terminal velocity increases linearly from 4.86 to 5.29 m/s with the increase in moisture content and this change was significant at a 5% level of significance. The results indicated the per cent increase in terminal velocity of mung bean was 8.85% for the corresponding increase in moisture content of 7.28 to 17.77% d.b. The result obtained was in conformity with the reported studies for black-eyed pea,[8] green gram,[18] karingda seed,[21] millet,[23] okra,[26] and pigeon pea.[27] At moisture content of 12.6% d.b. the terminal velocity of mung bean (5.11 m/s) was found to be smaller than chickpea (9.3 m/s),[11] green gram (10.4 m/s),[18] moth gram (11.3 m/s),[24] and pigeon pea (8.5 m/s),[27] while it was greater than linseed (2.9 m/s)[22] and millet (3.5 m/s).[23] Unal et al.[8] for black-eyed pea, Suthar and Das[21] for karingda and Çalişir et al.[26] for okra have found similar results. The relationship between terminal velocity V_t in m/s and moisture content can be represented by the following equation:

$$V_t = 4.5802 + 0.04 M_c, \tag{27}$$

with a value for R^2 of 0.983.

Rupture Strength Properties of Mung Bean

The results of the rupture strength tests are presented in Fig. 2F. The results show that the rupture strength along any of the three major axes is highly dependent on the moisture content for the range of moisture content investigated (7.28–17.77% d.b.). It indicates that greater forces were necessary to rupture the grains with lower moisture. The

Table 3 Regression coefficients and coefficients determination for static coefficients of friction on different surfaces.

Surface	Regression coefficients C_1	Regression coefficients C_2	Coefficient of determination (R^2)
Rubber	0.3562	0.0041	0.94
Galvanised iron	0.3420	0.0042	0.99
Medium density fibreboard	0.3368	0.0030	0.98
Stainless steel	0.3243	0.0032	1.00
Aluminium	0.3324	0.0016	0.99
Glass	0.3113	0.0022	0.95

Table 4 Relationships between rupture force P_r> in N and moisture content of mung beans M_c> in % d.b. along the three major axes.

Axes	Equation	Coefficient of determination (R^2)
Z (thickness)	$P_r(T) = 89.09 - 2.6361M_c$	0.95
Y (length)	$P_r(L) = 80.536 - 2.1204M_c$	0.97
X (width)	$P_r(W) = 61.928 - 1.057M_c$	0.92

highest forces were obtained while loading along the thickness (Z-axis), whereas loading along the width (X-axis) required the least force to rupture. The small rupturing forces at higher moisture content might have resulted from the fact that the grain became more sensitive to cracking at high moisture. The relationship between the rupture strengths and moisture content of the grain along the three major axes is presented in Table 4. Unal et al.,[8] Konak et al.,[11] Özarslan,[13] and Yalçin and Özarslan[35] reported as similar decrease in rupture strength when the moisture content was increased for black-eyed pea, chick pea, cotton, and vetch seeds, respectively.

CONCLUSIONS

The following conclusions are drawn from the investigation on geometric and mechanical properties of mung bean grain for five moisture content range’s from 7.28–17.77% d.b. Physical properties of mung bean grains studied in this work linearly with an increase in grain moisture content with high correlation. The dimensions of the mung bean grain increased: the length by 20.49%, the width by 18.99%, the thickness by 19.39%. The sphericity, volume, projected area, and thousand grain mass of grains varied from 0.795 to 0.789, 27.88 to 47.33 mm^3, 17.48 to 19.26 mm^2, and 52.3 to 64.6 g, respectively. There is a 43% increase in surface area from grain moisture content of 7.28 to 17.77% d.b. in both equations. The bulk density decreased from 821.3 to 745.2 kg/m^3, whereas true density increased from 1230.0 to 1456.7 kg/m^3 in the specified moisture levels. The porosity, terminal velocity and angle of repose increased linearly from 30.43 to 46.57%, 4.86 to 5.29 m/s, and 25.87 to 29.38°, respectively. The static coefficient of friction on various surfaces increased linearly with increase in moisture content. The rubber as a surface for sliding offered the maximum friction followed by galvanised iron, medium density fibreboard, stainless steel, aluminium, and glass sheet. The parameters used to indicate mung bean grain mechanical behaviour were dependent on the shell moisture content for along the axes. As moisture content increased from 7.28 to 17.77%, the rupture forces values ranged from 67.39 to 39.44 N; 63.86 to 42.18 N, and 53.96 to 41.79 N for thickness (Z axis), length (Y-axis), and width (X-axis), respectively.

NOMENCLATURE

A_p	Projected area, mm^2
A_s	Surface area, mm^2
C_1,C_2	Regression coefficients
D	Diameter of the cone, mm
D_a	Arithmetic mean diameter of grain, mm
D_g	Geometric mean diameter of grain, mm

H	Height of the cone, mm
L	Length of grain, mm
M_c	Moisture content, % d.b.
M_{1000}	Thousand grain mass, g
P_r	Rupture force, N
R^2	Coefficient of determination
T	Thickness of grain, mm
V	Grain volume, mm^3
V_t	Terminal velocity, m/s
W	Width of grain, mm
ρ_b	Bulk density, kg/m^3
ρ_t	True density, kg/m^3
$\in$	Porosity, %
μ	Coefficient of friction, decimal
α	Angle of tilt, deg
θ	Angle of repose, deg
Φ	Sphericity of grain, decimal

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