Determination of some engineering properties of morama bean (*Tylosema esculentum*)

Pius Emesu, Phumuza Mabuza

(*Department of Agricultural Engineering and Land Planning, Botswana College of Agriculture, Botswana*)

Abstract: The morama bean (Tylosema esculentum) is an underutilised legume native to the Kalahari region of Southern Africa. Some engineering properties relevant to the mechanisation of its processing have been characterised, namely; size, shape, surface area, projected area, volume, density, porosity, 1000-grain mass, static angle of repose, static coefficient of friction and texture. At moisture content of 7.4% (w.b.), the average length, width and thickness of the beans were 19.25, 17.21 and 13.39 mm, respectively. Geometric mean, equivalent diameter and arithmetic mean diameters were 16.4, 16.51 and 16.61 mm, respectively. Morama beans are spherical in shape, having average sphericity of 85.45%, aspect ratio of 0.90 and flakiness ratio of 0.78. Surface area, projected area and volume of the beans were 850.43 mm^2, 261.95 mm^2 and 2,352.82 mm^3, respectively. Mean true and bulk densities were, respectively, 1,075.13 and 795.31 kg/m^3 with bulk porosity derived as 25.76%. Mean 1000-grain mass was 2.21 kg. Static angle of repose was 12.98°, while static coefficient of friction of morama against plywood, galvanized iron, stainless steel, plastic, and itself, were 0.2, 0.26, 0.2, 0.18, and 0.24, respectively. Texture analysis by flat-plate compression testing showed that the beans required an average of 546.78 N to break and absorbed up to 470.03 mJ of energy before breaking, with hardness computed as 120.52 N/mm.

Keywords: morama, dimensional properties, gravimetric properties, flow properties, texture

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1 Introduction

Morama (*Tylosema esculentum*), also known as gemsbok bean, is an under-utilised wild legume native to the Kalahari region of Southern Africa (Van der Maesen, 2006; Powell, 1987). The bean has attracted attention as a plant resource with economic potential for exploitation, with successful experimental cultivation being reported in Kenya, Israel, Australia and United States of America. It contains approximately 30% protein and 40% oil (Mosele et al., 2011; Jideani et al., 2009) being similar in composition to groundnuts and soybeans (Ntare, 2007; Giller and Dashiell, 2007).

The bean grows inside an ovoid to oblong pod containing one to six seeds, which have a hard inedible brownish-black outer cortex (Van der Maesen, 2006). The seeds are roasted or boiled before consumption, developing a pleasant, sweet flavour comparable to that of roasted almonds. Maruatona et al. (2010) reported that heating the bean improves its *in vitro* protein digestibility; while Chingwaru et al. (2011) reported that extracts of the bean and its tuber have high antibacterial and anticandidal properties in concentrations comparable to conventional drugs.

One challenge to the utilisation of the bean is the tough cortex that encases the cotyledon, which is traditionally cracked manually. This is an arduous task, hampering larger-scale processing and exploitation of the bean. In order to design an appropriate device for the decortication of the morama bean, its engineering properties need to be determined.

To successfully design the equipment for agricultural

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Corresponding author: Pius Emesu, Department of Agricultural Engineering and Land Planning, Botswana College of Agriculture, Botswana. Email: pemesu@bca.bw, pemesu@yahoo.com

processing, knowledge of the physical and mechanical or engineering properties of the agricultural produce is essential (Tabatabaeefer et al., 2003; Irtwange, 2009). Also during the processing and handling of the agricultural materials, these properties are needed for setting the operational parameters of the equipment for efficient operations. Different researchers report the use of characteristic dimensions to determine the size of seeds (Sirisomboon et al., 2007; Irtwange and Igbeka, 2002; Gürsoy and Güzel, 2010; Mirzabe et al., 2013). Size and shape are important for separation, sorting, grading and quality evaluation of agricultural produce (Sahin and Sumnu, 2006). Furthermore, the characteristic dimensions allow calculation of the surface area and volume of grains, important technological considerations. For instance, surface area of crops and fruits is useful in respiration measurements, determination of quality and quantity, colour, and in aerodynamic computations (Sitkei, 1986; Singh and Heldman, 2009). Porosity affects the bulk density of materials, which determines produce storage requirement and conveyor capacity. It is also a critical factor in drying and ventilation processes, while the true density is useful in materials separation processes. Coefficient of friction influences the lateral pressure that grains experience in silo/bin storage (Bucklin et al., 1993). The angle of repose and coefficient of friction are important grain flow parameters which influence the design of seed containers and other storage structures and accessories. Also, angle of repose is a useful parameter for calculation of grain discharge rates from storage vessels. Furthermore, the static coefficient of friction limits the maximum angle of inclination of conveyors and hoppers of storage bins and the power requirement for conveyors depends on the magnitude of frictional force. Moisture content, a compositional property of agricultural materials, is important in that it influences most of the other engineering properties (Degirmenciouglu and Srivastava, 1996; Henderson et al., 1997; Sahin and Sumnu, 2006; Singh and Heldman, 2009).

For the design of a nut-cracker for argan, a tough native Moroccan nut, Kisaalita et al. (2010) employed the mechanical properties determined using a material testing machine. Ercisli et al. (2011) have studied the mechanical strength of walnuts while Ledbetter (2008) reported on the shell cracking strength in almonds. Furthermore, physical and mechanical properties of jatropha fruits and nuts have been studied and their applications reported by Sirisomboon et al. (2007). Currently, studies on the morama bean has been mostly on the chemical, compositional and nutritional properties, with limited investigation of the engineering properties from an engineering standpoint (Jideani et al., 2009; Maruatona et al., 2010; Mosele et al., 2011; Chingwaru et al., 2011). To close the knowledge gap with respect to the engineering properties of the morama bean, the current study sought to determine some physical and mechanical properties which are relevant to the mechanisation of its processing in order to increase its utilisation as a food resource. These include size, shape, surface area, volume, density, porosity, angle of repose, coefficient of friction and mechanical strength.

2 Materials and methods

Morama beans were obtained from three districts in Southern Botswana, namely; Southern, Kgatleng and Kweneng. As Jideani et al. (2009) have reported that no significant differences exist in functional and compositional properties of different bean varieties from Botswana, the samples from the three areas were taken as replications for the different tests carried out. The beans were stored in sealed plastic bags at room temperature. Samples for analysis from each of the three areas were drawn by hand in a random manner from the bags containing them. Moisture content was determined according to the AOAC method 925.10 by oven drying at 130°C for 1 hour (AOAC, 2005).

2.1 Dimensional properties

2.1.1 Determination of morama bean size

Bean size was described using the axial dimensions and descriptors computed from them. Bean length, width and thickness, representing the major, intermediate and minor diameters, were measured using a digital vernier calliper (TA, M5 0-300 mm model, China) of 0.01 mm precision (Sahin and Sumnu, 2006). Geometric mean diameter (D_g), equivalent diameter (D_e) and arithmetic mean diameter (D_a) were computed from the axial dimensions using Equations (1)-(3), respectively (Heidarbeigi et al., 2009):

$$D_g = \sqrt[3]{LWT} \tag{1}$$

$$D_e = \left[L \frac{(W+T)^2}{4} \right]^{\frac{1}{3}} \tag{2}$$

$$D_a = \left(\frac{L+W+T}{3} \right) \tag{3}$$

where, L is length, mm; W is width, mm; and T is thickness, mm.

2.1.2 Determination of bean shape

From the axial dimensions, bean shape was described numerically by calculating sphericity index (φ) as percentage and aspect ratio (R_a) using Equations (4) and (5), respectively (Gürsoy and Güzel, 2010):

$$\varphi = \left(\frac{\sqrt[3]{LWT}}{L} \right) \times 100 = \left(\frac{D_g}{L} \right) \times 100 \tag{4}$$

$$R_a = \frac{W}{L} \tag{5}$$

Flakiness ratio (R_f) was also computed (Equation (6)) to further categorise bean shape (Ebrahimzadeh et al., 2013; Encyclopaedia Britannica, 1978):

$$R_f = \frac{T}{W} \tag{6}$$

2.1.3 Determination of bean surface area, projected area and volume

The surface area (S) and projected area (A_p) of the beans in mm^2, and volume (V) in mm^3 were calculated using Equations (7)-(9) (Mirzabe et al., 2013):

$$S = \pi D_g^2 \tag{7}$$

$$A_p = \left(\frac{\pi WL}{4} \right) \tag{8}$$

$$V = \left(\frac{\pi D_g^3}{6} \right) \tag{9}$$

2.2 Gravimetric properties

2.2.1 Density and porosity determination

True density (ρ_t) was obtained by dividing the mass of sample by its volume determined by solvent (toluene) displacement as described by Irtwange and Igbeka (2002). Equation (10) was used to calculate the true density, expressed in kg/m^3:

$$\rho_t = \frac{\text{weight of sample}}{\text{volume of toluene displaced}} \tag{10}$$

Bulk density (ρ_b) of the beans was determined by weighing the beans packed in a container having a predetermined volume of 710 cm^3 (Heidarbeigi et al., 2009). The beans were packed by gently tapping the container to allow them to settle in the container. The volume of the container was determined by filling it with water and the water was then poured out into a calibrated measuring cylinder and the volume recorded. The following expression (Equation (11)) was used to determine the bulk density of the beans in kg/m^3:

$$\rho_b = \frac{\text{weight of material packed}}{\text{bulk volume}} \tag{11}$$

Porosity (ε) was computed as a percentage from the true and bulk densities using Equation (12) (Varnamkhasti et al., 2007):

$$\varepsilon = \left(1 - \frac{\rho_b}{\rho_t} \right) \times 100 \tag{12}$$

2.2.2 Thousand grain mass

One hundred beans were counted and weighed on an electronic balance. Mass of 100 beans was then multiplied by 10 to express the 1000-grain mass in kg (Sirisomboon et al., 2007).

2.3 Flow properties of morama beans

2.3.1 Static angle of repose

Static angle of repose was determined by filling an open sided cylindrical plastic vessel of 156 mm height and 105 mm internal diameter, placed on a flat wooden surface. The vessel was carefully and slowly raised and the beans flowed out to form a circular pile, whose height (H) and diameter (D) in mm were measured using a ruler (Irtwange and Igbeka, 2002; Mirzabe et al., 2013). The angle of repose (θ_r) in degrees was then computed using Equation (13):

$$\theta_r = \tan^{-1} \left(\frac{2H}{D} \right) \tag{13}$$

2.3.2 Static coefficient of friction

The static coefficient of friction (μ) of morama beans against plywood, galvanized iron, stainless steel and plastic surfaces was determined after the method of Mirzabe et al. (2013). An open-ended plastic cylinder of 156 mm height and 105 mm diameter was placed onto the test surface and filled with morama beans. The cylinder was raised slightly so as not to make contact with the test surface. Then the test surface was gradually raised using a screw until the cylinder started to slide over the surface. Trigonometric rules were employed to calculate the angle of inclination (α) of the surface to the base by measuring the vertical height and length of the tilted surface. The static coefficient of friction was obtained from α using Equation (14):

$$\mu = \tan\alpha \qquad (14)$$

Tangent of the angle of repose (θ_r) of morama was also computed as the coefficient of friction of morama on itself (Henderson et al., 1997).

2.4 Texture determination

Compression tests using a 75 mm flat plate were conducted using a texture analyser (Multitest 5-i, Food Technology Corporation, Virginia, USA). A sample of the beans was loaded onto the test table; the machine was then operated to determine the peak force, displacement at cracking, hardness and energy absorbed by the beans on compression (Ercisli et al., 2011; Ledbetter, 2008). The crosshead, bearing a 5,000 N load cell, was set to run at a speed of 30 mm/min and to stop compressing at 20% breakage.

2.5 Data analysis

Raw data was captured and processed using Microsoft Office Excel (2010 version) spreadsheet and R Statistical Software version 3.0.2 (R Core Team, 2013), with descriptive statistics being computed to analyse and present the results. Tukey's Honestly Significant Difference test was used for multiple comparison of means to determine whether statistically significant differences existed among the data on coefficient of static friction against different surfaces at $p<0.05$ level of significance (Faraway, 2002).

3 Results and discussion

3.1 Dimensional properties

Morama bean size and shape descriptors are presented in Table 1. Average bean length, width and thickness were, respectively, 19.25, 17.21 and 13.39 mm. These findings corroborate those of Jideani et al. (2009) and Mosele et al. (2011), suggesting uniformity in size of morama bean species growing in Southern Botswana. The radar plot in Figure 1 is useful to visualise the overlap between the length and width of beans of different sizes as would happen, for instance, when the width of a larger sized bean would be greater or the same as the length of a smaller sized bean. This is a useful consideration on the gap to allow for in the design of morama decortication or separation machines (Irtwange, 2009).

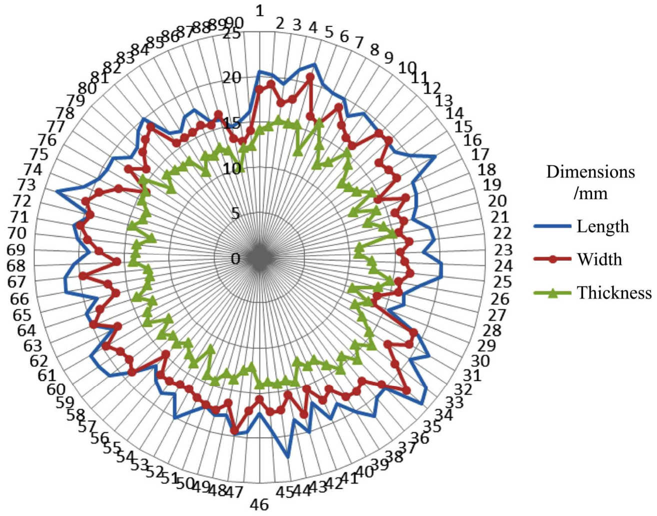


Figure 1 Radar chart depicting morama bean axial dimensions

Surface area, projected area and volume of morama beans are also presented in Table 1.

Table 1 Dimensional properties of morama beans

Parameters	N	Mean	S.D	Minimum value	Maximum value
Length (L), mm	90	19.25	1.86	14.8	24.21
Width (W), mm	90	17.21	1.72	12.92	21.97
Thickness (T), mm	90	13.39	1.22	10.13	16.25
Geometric mean diameter (D_g), mm	90	16.40	1.29	12.63	19.67
Equivalent Diameter (D_e), mm	90	16.51	1.31	12.71	19.97
Arithmetic mean diameter (D_a), mm	90	16.61	1.33	12.79	20.16
Sphericity (φ), %	90	85.45	3.93	76.24	93.64
Aspect Ratio (R_a)	90	0.9	0.06	0.74	1.04
Flakiness ratio (R_f)	90	0.78	0.09	0.6	1.01
Surface area (S), mm^2	90	850.43	131.56	500.93	1215.61
Projected area (A_p), mm^2	90	261.95	47.78	154.65	417.75
Volume (V), mm^3	90	2352.82	540.75	1054.26	3985.32

Note: N is number of observations and SD is standard deviation.

Gürsoy and Güzel (2010) have employed dimensional properties of grains to compute aerodynamic properties like terminal velocity and drag coefficients, important for pneumatic conveyance and separation. Jideani et al.

(2009) reported much higher values than those from the current study with respect to morama surface area and much lower volumes, probably arising from differences in methodology.

As the density plots in Figure 2 reveal, bean size distribution per dimension was normal. Bean thickness showed the least degree of variance, with a range of 6.12 mm, while length varied the most with a range of 9.41 mm. Further testing for normality using Q-Q plots (Figure 3) confirmed the distribution to be normal as deduced from the approximately straight-line relationship evident between the sample and theoretical quantiles (Sitkei, 1986; Maindonald, 2008; Faraway, 2002). Irtwange (2009) has indicated that information on the frequency distribution of grain size can be used to predict threshing efficiency of a cowpea thresher.

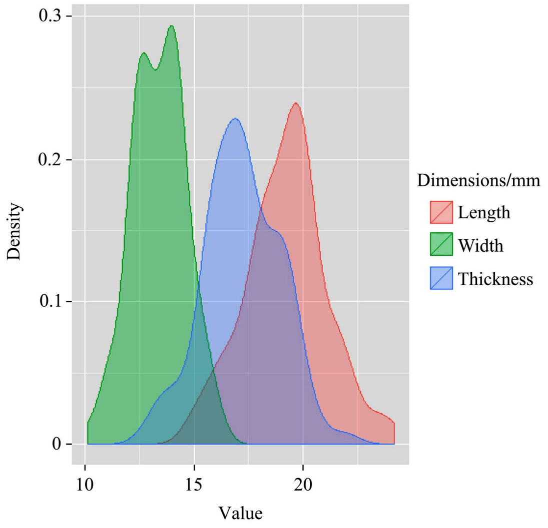
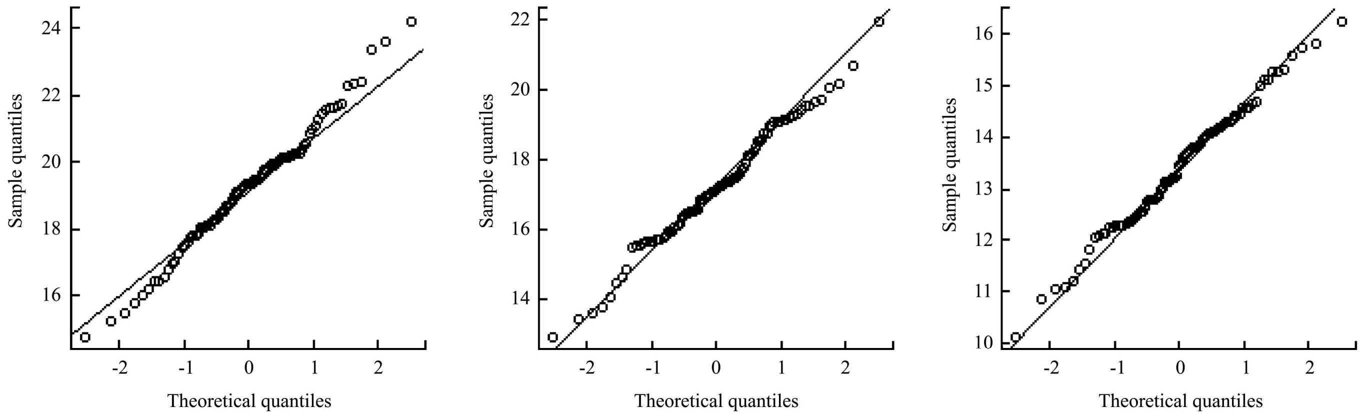


Figure 2 Probability density plot of morama bean dimensions

Bean geometric mean diameter ranged between 12.63 and 19.67 mm, being 16.41 mm on average. Geometric mean diameter (D_g) of a material is an expression of its size as a one-dimensional quantity measured in three dimensions (Takayama et al., 1991). D_g has been used to calculate the projected area, shape factor and terminal velocities of agricultural materials in studies on their aerodynamic behaviour during processing and conveyance (Gürsoy and Güzel, 2010). As it is a measure of size from three dimensions, it would be useful in determining aperture or size of openings in morama processing and handling equipment (Irtwange, 2009; Sitkei, 1986).

Equivalent diameter of a sample material represents the equivalent diameter of a sphere having a volume equal to that of the sample (Gürsoy and Güzel, 2010). From the definition of D_g previously stated, it follows that for a spherical object D_g would be the same as D_e. Mean equivalent diameter was 16.51, ranging between 12.71 and 19.97 mm. Closeness of D_e to D_g and D_a suggests a high degree of sphericity, which was 85.45% for morama beans. Sphericity is a measure of how close the shape of a material approaches that of a sphere (Encyclopaedia Britannica, 1978). It has been found to significantly affect fluidisation stability during drying of some cereal grains and soybeans; particles with higher sphericity developed more stable fluidised beds (Khoshtaghaza and Chayjan, 2007). The correlation coefficient between D_g and D_e for morama is 0.998, which further confirms the conclusion that the bean is highly spherical in shape.



a. Normal Q-Q plot for length b. Normal Q-Q plot for width c. Normal Q-Q plot for thickness

Figure 3 Normal probability plots for morama bean dimensions

Arithmetic mean diameter lay between width and thickness in magnitude, being, on average 16.61 mm. This shows that a notable difference exists between the major and minor diameters of the bean. However, as the bean has a high aspect ratio (0.9) and its average flakiness ratio is greater than 0.67, it qualifies to be described as spherical according to a classification presented in the Encyclopaedia Britannica Micropaedia (1978). Sphericity, aspect and flakiness ratios are some indices used to measure and characterise shape of agricultural materials (Ebrahimzadeh et al., 2013; Sitkei, 1986).

3.2 Flow properties

Granular flow parameters of morama beans are presented in Table 2. Morama beans have a low angle of repose, showing that little cohesion exists among the seeds. The smooth nature of the bean cortex, coupled with the high sphericity of the bean are deemed to contribute to this observation. This result is in agreement with the finding by Jideani et al. (2009). This would suggest that morama beans would be best conveyed by rolling, rather than sliding. The low coefficient of friction of the beans makes it amenable to mixing during its processing as, for instance when it is roasted. Moreover the coefficient of friction of the bean on itself is low; being highest when tested against galvanized iron. Coefficient of friction against galvanized iron was significantly different when compared to all the other surfaces tested. This implies that galvanized iron would produce significantly higher frictional resistance to the motion of the beans as compared to all the other surfaces tested. Degirmencioglu and Srivastava (1996) have developed models for screw conveyor performance using dimensional analysis and report that coefficient of friction values for material against metal in the range 0.414-0.374 affect the volumetric efficiency and power requirements, while coefficient of friction of material against material in the range 0.554-0.466 affected volumetric efficiency and power requirements. This may then suggest that conveyance of morama using screw conveyors during its processing would not significantly reduce the performance of the conveyor. Sirisomboon et al. (2007) reported μ of 0.64 for jatropha nuts against steel and 0.46 against stainless steel. While Khodabakhshian et al. (2010) reported values ranging from 0.35 to 0.52 for a range of moisture contents among three varieties of sunflower, tested on galvanized iron sheet. Furthermore, Irtwange (2009) has stated that for ease of flow of threshed cowpea grains through the discharge chute of a cowpea thresher, the slope of the chute should be equal to the angle of friction of the grains in degrees.

Table 2 Granular flow properties of morama beans

Parameter	N	Mean	SD
Static angle of repose (θ_r), (°)	3	12.98	0.93
Static coefficient of friction (μ) on:			
Plywood	3	0.2^{bcd}	0.01
Galvanized iron	3	0.26^{e}	0.01
Stainless steel	3	0.2^{ad}	0.00
Plastic	3	0.18^{ab}	0.01
Self (morama on morama)	3	0.24^{c}	0.02

Note: N is number of observations and SD is standard deviation; for μ, values sharing a common superscript bear NO statistically significant difference at $p<0.05$ level of significance.

3.3 Gravimetric properties

Gravimetric properties of morama are presented in Table 3. Average bean moisture content was 7.39% (w.b.). The low moisture content arising from natural sun drying and the tough cortex encasing its nutritious cotyledons would confer a long shelf life to the bean; an important food security factor. True density of 1,075 kg/m^3 and 1000-grain mass of 2.2 kg both indicate that morama is a compact and heavy bean. 1000-grain mass is also indicative of maturity and growing conditions that crops have been subjected to (Sablami and Ramaswamy, 2003). It may also be inferred that morama beans would pack quite well due to the low bulk porosity of 25.76%. Morama bulk density (795 kg/m^3) is higher than bulk densities of legume seeds such as kidney bean (*Phaseolus vulgaris*), pea (*Pisum sativum*) and black-eyed pea (*Vigna sinensis*), reported to be 467 (8.2% m.c.), 504 (8.2% m.c.), and 432 kg/m^3 (5.66% m.c.), respectively (Altunas and Demirtola, 2007). Bulk density and porosity are useful parameters in determining the packaging and storage requirements for agricultural materials, separation of materials, and in mass transfer calculations for processes such as heating and cooling (Sahin and Sumnu, 2006; Singh and Heldman, 2009). Ghorbani et al. (2013) reported that bulk density is a key factor in estimating energy requirements for hammer milling of chopped alfalfa.

Table 3 Gravimetric properties of morama beans

Parameter	N	Mean	SD
True density, kg/m^3	9	1075.13	59.06
Bulk density, kg/m^3	9	795.31	18.41
Porosity, %	9	25.76	5.56
1000-grain mass, kg	9	2.21	0.32
Moisture content (w.b.), %	6	7.39	0.38

Note: N is number of observations and SD is standard deviation

The current findings on density and porosity bear some difference with those reported by Jideani et al. (2009), most probably arising from their use of water as displacement fluid to determine bean volume, in contrast to our use of toluene. Toluene has been recommended as it is absorbed less by seeds, and has the ability to fill even shallow dips in seeds owing to its low surface tension (Sitkei, 1986).

3.4 Texture analysis

Compression of the beans using a texture analyser has enabled the numerical quantification of the deformation properties of the bean (Table 4), paving the way for design of a decorticator that would crack the bean most efficiently. Average peak force to crack the bean samples was 546.78 N, with no sample exceeding 1 kN. On average, the beans absorbed 470 mJ of energy before cracking and deformed to 4.88 mm before cracking. Hardness, computed by dividing the peak force by the displacement at cracking, was 120.52 N/mm on average. Argan – a native Moroccan nut – is purported to be the toughest nut in the world; reportedly needing an average of 1,575.55 N to crack and absorbed 10,129 mJ (10.13 J) of energy before cracking (Kisaalita et al., 2010). Almond nuts have been reported to need around 490 N to crack (Ledbetter, 2008), while walnuts compressed widthwise needed 185-227 N to rupture (Ercisli et al., 2011). Morama mechanical strength is about one third that of Argan, but it is stronger in comparison to almonds and walnuts. This comparison would guide the design considerations for proposed morama processing equipment. Sirisomboon et al. (2007) have suggested that the clearance between the compression surfaces for dehulling or shelling jatropha should be equal to the size of the fruit or nut, less the deformation at cracking/rupture point.

Table 4 Textural properties of morama beans

Parameter	N	Mean	SD	Minimum value	Maximum value
Peak force, N	40	546.78	128.35	231.4	878.5
Energy absorbed, mJ	40	470.03	193.94	94.39	1 101.9
Hardness, N/mm	40	120.52	49.67	46.37	280.45
Deformation at cracking, mm	40	4.88	1.16	2.43	8.4

Note: N is number of observations and SD is standard deviation.

4 Conclusions

Dimensional, gravimetric and mechanical properties of morama beans found in Southern Botswana have been characterised. The beans have the average geometric mean diameter of 16.4 mm, and are spherical in shape, having average sphericity index of 85.45%. The beans have true and bulk densities of, respectively, 1,075 and 795 kg/m^3, with a low bulk porosity of 25%. Mechanical compression testing revealed that indeed it is a tough bean, needing, on average, a force of 546.78 N to crack it. In magnitude, this is about 1/3 of the force needed to crack argan, reportedly the toughest nut in the world (Kisaalita et al., 2010). The beans absorbed 470.03 mJ of energy before cracking; breakage occurring on deformation by 4.88 mm on average, which is an important design consideration for its decortication.

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