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Measurement of Engineering Properties Necessary to the Design of Drumstick (*Moringa oleifera L.*) Pod Sheller

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Abstract

Purpose: Designing equipment for processing, sorting, and other post-harvest operations of agricultural products requires information about their physical properties. This study was conducted to investigate some of the mechanical and physical properties of *Moringa oleifera L.* pods and seeds. **Methods:** Properties such as the length, width, thickness, bulk density, porosity, mass, static coefficient of friction, and angle of repose were determined as a function of moisture content. Statistical data and force-deformation curves obtained at each loading orientation and moisture level were analyzed for bioyield point, bioyield strength, yield force, rupture point, and rupture strength using a testrometric machine. **Result:** The basic dimensions (length, width, and thickness) of moringa pods and seeds were found to increase linearly from 311.15 to 371.45 mm, 22.79 to 31.22 mm, and 22.24 to 29.88 mm, respectively, in the moisture range of 12 to 49.5% d.b. The coefficient of friction for both pods and seeds increased linearly with an increase in moisture content on all the surfaces used. The highest value was recorded on mild steel, with 0.581 for pods and 0.3533 for seeds, and the lowest on glass for pods, with a value of 0.501, and of 0.2933 for seeds on galvanized steel. The bioyield and rupture forces, bioyield and rupture energies, and deformation of the pods decreased with an increase in moisture content to a minimum value, then increased with further decrease within the moisture content range, while the yield force increased to a maximum value and then decreased as the moisture content increased. **Conclusion:** These results will help to determine the most suitable conditions for processing, transporting, and storing moringa pods, and to provide relevant data useful in designing handling and processing equipment for the crop.

Keywords: Angle of Repose, Deformation, Drumstick pod sheller, Moisture content, *Moringa oleifera*

Introduction

The drumstick tree (*Moringa Oleifera L.*) is a softwood perennial tree, distinguished by its long, drumstick-shaped pods that contain its seeds. It is a fast-growing drought-resistant tree, that is native to the southern foothills of the Himalayas of northwestern India, but which is broadly cultivated in tropical and subtropical areas (Ezejindu et al., 2014). Drumstick pods can reach over a foot in length, and each pod can provide a large number of seeds. This plant is believed to be a miracle tree possessing many valuable properties, which makes it of great scientific interest.

The pods and seeds of the drumstick (Figure 1) are generally used for agricultural, medicinal, and industrial purposes. These include the outstanding nutritional and medicinal qualities found in the leaves, pods, seeds, twigs, and stems, all of which are edible by man. The powdered seed is used as a supplement for animal feed, a fertilizer for crops, and a particularly effective water purifier. The water purification quality is important in many societies, where the only drinking water available may come from a dirty lake (Foidi and Paul, 2008). In addition to the above

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(a) Drumstick seeds

(b) Drumstick pods

Figure 1. Seeds (A) and pods (B) of *Moringa oleifera.*

uses, due to its high oil content, moringa can be processed into oil, flour and the cake remaining after oil extraction has been shown to retain the active ingredients for the coagulation of various undesirable moieties from a solution, making it a marketable commodity (Folkard and Sutherland, 1996). It has also been considered a potential source for biofuel material.

Despite the numerous economic benefits of moringa, processing operations are mostly manual. For such a crop, whose medicinal and industrial uses are growing rapidly, and whose manual harvesting is drudgery, there is a great need to develop appropriate machines and equipment for various processing operations. Although the mechanization of its processing has generated significant interest in recent times, little is yet known about the engineering properties of the pods and seeds. To make its mechanization a reality, it is therefore necessary to establish its prominent engineering properties.

Other researchers have determined the engineering properties of numerous grains, nuts, and seeds. Crops like locust bean pods and seeds (Oje, 1993), pumpkin seeds (Joshi et al., 1993), guna seeds (Aviara et al., 1999), okra seeds (Calisiret al., 2005), *Brachystegia eurycoma* seeds (Ndukwu, 2009), soya bean seeds (Tavakoli et al., 2009), roselle seeds (Bamgboye and Adejumo, 2009), and *Moringa oleifera* seeds (Aviara et al., 2013). Despite all of these research accounts, there is little or no information on the physical and mechanical properties of drumstick pods.

The aim of this work was to determine the engineering properties of *moringa* pods and seeds relevant to the design of a moringa sheller. These properties will provide relevant data useful in the design of handling and processing equipment for the crop.

Materials and methods

The drumstick pods and seeds used in this study were sourced from Ogbomosho in Oyo State, Nigeria on August 13, 2014. The samples were selected and cleaned manually. It was ensured that the seeds were free of dirt, broken seeds, and other foreign material.

Moisture content determination

The initial moisture content of the pods and seeds was determined by oven drying at 105°C for six hours, with weight loss monitored hourly to determine the time at which the weight became constant. The initial moisture content of the pods and seeds was 12.0% d.b. and 6.3% d.b., respectively. The samples were prepared by adding the amount of distilled water calculated using the expression in Equation (1). (Sacilik et al., 2003):

$$Q = \frac{W_1(M_f - M_1)}{(100 - M_f)} \quad (1)$$

Where Q is the quantity of water added (kg), W_1 is the initial mass of the sample (kg), M_f is the desired moisture content (% d.b.), M_1 and is the initial moisture content of the sample (% d.b.). The samples were then poured into separate polyethylene bags, and the bags were sealed tightly. These samples were kept at 5°C in a refrigerator for a week to enable the moisture to be uniformly distributed throughout the sample. Before starting the experiment, the required quantity of pods and seeds were removed from the refrigerator and allowed to equilibrate to room temperature for about 2 hours (Nimkar and Chattopadhyay, 2001). All of the physical and mechanical properties of the pods and seeds were determined at five different moisture contents in the range of 12-49.5% d.b. and 6.3-15% d.b. for both the pods and the seeds, respectively, with three replications at each moisture content.

Measurement of basic dimensions

Size and shape

To measure the dimensions, one hundred pods and

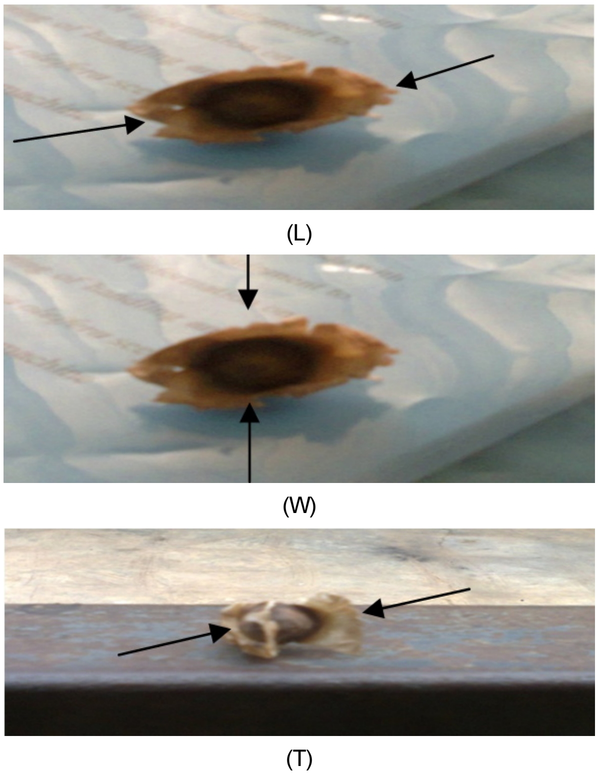

Figure 2. Principal axial dimensions (L, W, and T) of *Moringa oleifera* seed.

seeds were randomly selected. The basic dimensions (length, width, and thickness) (Figure 2) were determined using a measuring tape, and an electronic digital Vernier caliper (Model GMC- 20, (Taiwan) with an accuracy of 0.001 mm.

The geometric mean diameter D_g in mm, sphericity Ø, and surface area S were determined using the relationships in Equations (2) and (3), which was suggested by Ozguven and Vursavus (2005) and Mohsenin (1986).

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

$$\varnothing = \frac{LWT^{1/3}}{L} \tag{3}$$

Where L = length (mm), W = width (mm), and T = thickness (mm).

Thousand-pod and seed weight

The thousand pods weight (TPW) was measured by weighing 100 seeds in an electronic balance (Model MP1001, gallen kamp) to an accuracy of 0.01 g and multiplying by 10 to calculate the mass of 1000 pods.

True and bulk density

The true density was determined using the water displacement method. The volume of water displaced was found by immersing a weighted quantity of pods in a measured amount of water. A small metal bob was used as a sinker because the pods float in water (Joe, 1993). The volume of the pods was calculated by subtracting the volume of the bob from this difference.

The bulk density was determined by filling an empty 500 ml graduated cylinder with the seeds and weighed. The weight of the seeds was obtained by subtracting the weight of the cylinder from the weight of the cylinder and seeds. To achieve uniformity in bulk density, the graduated cylinder was tapped to cause the seeds to consolidate. The occupied volume was then noted. The process was replicated three times, and the bulk density for each replication was calculated from the following relation:

$$\rho_b = \frac{W_s}{V_s} \tag{4}$$

Where W is the weight of the seeds (kg) and v is the volume occupied by the sample (m^3).

Porosity

The porosity was calculated from the values of the bulk and true densities using the following relationship (Joshi et al., 1993):

$$P = 1 - \frac{\rho_b}{\rho_t} \times 100 \tag{5}$$

where ρ_t is the true density (kg/m^3) and ρ_b is the bulk density (kg/m^3).

Angle of repose

The angle of repose was determined by using a cylindrical container open at both ends. The cylinder was placed on a wooden table, filled with seeds, and raised slowly until the seeds formed a cone. The angle of repose was calculated using the equation below:

$$\propto_r = \tan^{-1}\left(\frac{2H}{D}\right) \tag{6}$$

Where H is the height of the cone (mm), $D$is the diameter of the cone (mm), andis the angle of repose (°). A similar method was reportedly used by Baryeh (2001) and Olaoye (2000).

Coefficient of friction

The static coefficient of friction of moringa pods on four surfaces, including wood, galvanized steel, aluminum, and glass, were determined. The coefficient of friction was calculated using the expression in Equation (7).

$$\mu = \tan\alpha \tag{7}$$

where α is the tilt angle of the adjustable plate and μ is the coefficient of friction.

Compression test

Compression tests were carried out at the Federal Institute of Industrial Research, Oshodi (FIIRO), Lagos, Nigeria, using a Testrometric AX type DBBMTCL machine. The results, statistical data and force-deformation curves, obtained at each loading orientation and moisture level were analyzed for bioyield point, bioyield strength, yield force, rupture point, and rupture strength.

Results and discussion

The physical and mechanical properties of the pods and seeds were measured at five different moisture contents: 12, 18.33, 28.5, 35, and 49.5% d.b., and 6.3, 7.77, 9.6, 12.8, and 15% d.b., respectively.

Physical and mechanical properties of *Moringa* pod and seed

The average values of the three principal dimensions of moringa pods and seeds, namely length, width, and thickness, determined at different moisture levels are presented in Tables 1 and 2. The average length, width, and thickness of the 100 pods increased linearly from 311.15 to 371.45mm, 22.79 to 31.22mm, and 22.24 to 29.88mm, respectively, in the moisture range of 12.0 to 49.5% d.b. (Figures 3 and 4). For the 100 seeds, the average length, width, and thickness increased linearly from 11.34 to 15.16 mm, 9.77 to 12.19 mm, and 10.53 to 13.24 mm, respectively, as the moisture content increased from 6.3 to 15% d.b. (Figure 5). Similar findings were reported by Aviara et al. (2000) for shea nuts and by Idowu et al. (2012) for sand box seeds.

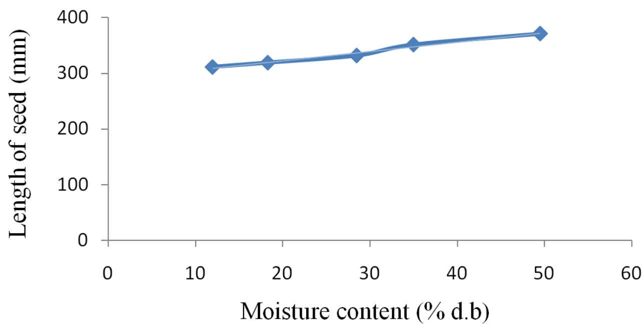

Figure 3. Effect of moisture content on length of *Moringa oleifera* pods.

Table 1. Physical properties of *Moringa oleifera* pods at different moisture levels

Moisture content (%)	Length (mm)	Width (mm)	Thickness	Geo. mean (mm)	Surface area (mm^2)	True density (kg/m^3)	Bulk density (kg/m^3)	Porosity (%)
12	311.15	22.79	22.24	53.87	9131.8	0.22	0.074	68.14
18.33	318.95	23.53	22.87	55.32	9637.5	0.27	0.072	69.87
28.5	331.9	25.04	26.07	59.95	11328.5	0.31	0.069	74.21
35	351.6	28.28	29.57	66.39	13945.7	0.43	0.065	84.43
49.5	371.45	29.88	31.22	70.86	15916.49	0.44	0.063	85.63

Table 2. Physical properties of *Moringa oleifera* seeds at different moisture levels

Moisture content (%)	Length (mm)	Width (mm)	Thickness (mm)	Geo. mean (mm)	Surface area (mm^2)	True density (kg/m^3)	Bulk density (kg/m^3)	Porosity (%)
6.3	11.34	10.53	9.77	10.51	350.22	0.653	0.35	67.31
7.77	12.78	10.76	10.17	11.17	394.68	0.80	0.3	72.2
9.6	13.02	11.13	10.46	11.46	414.73	0.84	0.27	79.00
12	15.05	12.01	11.19	12.58	503.02	0.90	0.25	81.28
15	15.16	13.24	12.19	13.39	545.75	0.94	0.22	78.32

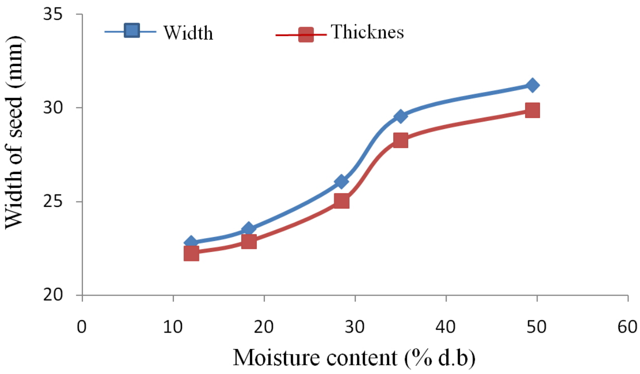

Figure 4. Effect of moisture content on dimension (mm) of *Moringa oleifera* pods.

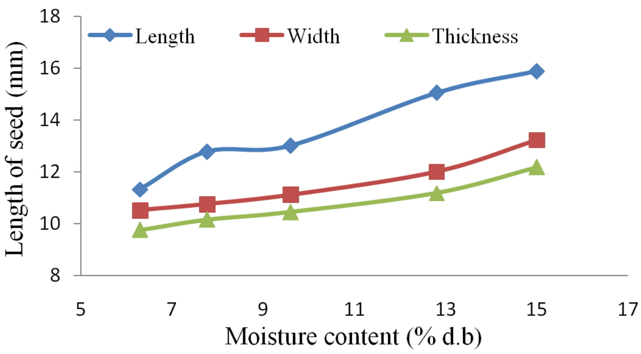

Figure 5. Effect of moisture content on dimension (mm) of *Moringa oleifera* seeds.

The following regression equations obtained for the linear dimensions of the pods are:

$$Lp = 1.663M+289.3\ (R^2 = 0.981) \tag{8}$$

$$Wp = 0.245M+19.60\ (R^2 = 0.947) \tag{9}$$

$$Tp = 0.2217M+19.304\ (R^2 = 0.948) \tag{10}$$

The following regression equations were developed for the linear dimensions of *Moringa oleifera* seeds with moisture content.

$$Ls = 0.4388M+8.9527\ (R^2 = 0.931) \tag{11}$$

$$Ws = 0.3016M+8.4279\ (R^2 = 0.951) \tag{12}$$

$$Ts = 0.2624M+8.0549\ (R^2 = 0.970) \tag{13}$$

The geometric diameter of the pods and seeds increased with moisture content as axial dimensions. The geometric

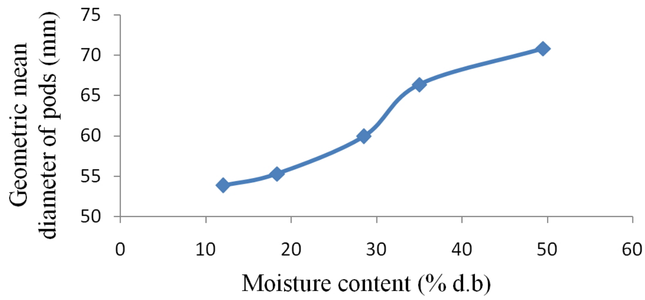

Figure 6. Effect of moisture content on geometric mean diameter of *Moringa oleifera* pods.

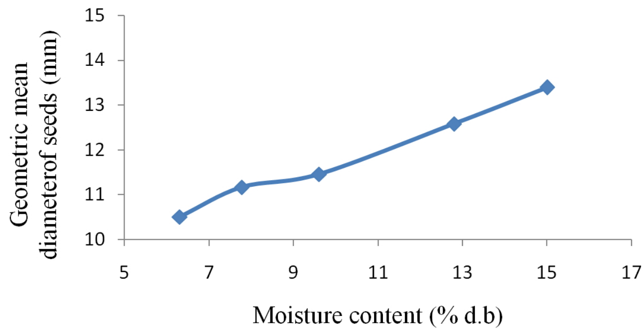

Figure 7. Effect of moisture content on geometric mean diameter of *Moringa oleifera* seeds.

mean diameter ranged from 55.32 to 70.86 mm, and from 10.51 to 13.31 mm for pods and seeds, respectively, as the moisture content increased from 12% to 49.5% d.b. (Figure 6) and 6.35 to 15% d.b. (Figure 7). The following regression equations were obtained for the preceding geometrical analysis:

$$D_{gp}=0.485M+47.35(R^2 =0.965) \tag{14}$$

$$D_{gs}=0.3216M+8.5143\ (R^2 = 0.991) \tag{15}$$

Surface area

The surface area increased non linearly with increasing moisture content for both pods and seeds. The surface area increased from 9131.825 to 15916.485 mm^2 for the pods (Figure 8) and 350.22 to 545.77 mm^2 for the seeds (Figure 9). The increase in surface area may be attributed to the increase in the three linear dimensions. Garnayak et al. (2008) reported a similar trend for Jatropha seed and Selvi et al. (2006) for linseed. The following regression equations were obtained for surface area:

$$S_p=0.394+169.3M+6746\ (R^2 = 0.964) \tag{16}$$

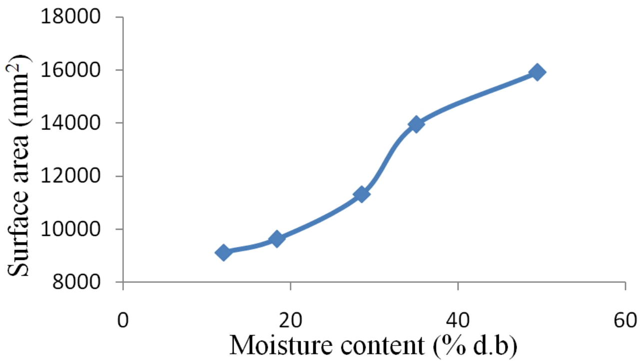

Figure 8. Effect of moisture content on surface area of *Moringa oleifera* pods.

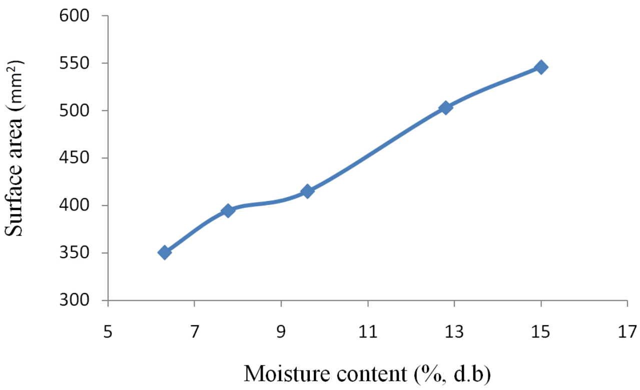

Figure 9. Effect of moisture content on surface area of *Moringa oleifera* seeds.

$$S_s = 22.372M + 211.39 \ (R^2 = 0.990) \tag{17}$$

Bulk density

The bulk density values for pods and seeds decreased with increasing moisture content (Figures 10 and 11). It decreased from 0.074kg/m^3 at 12% d.b. to 0.0633kg/m^3 at 49.5% d.b. for pods and from 0.35 to 0.22 kg/m^3 for seeds. The decreasing trend of bulk density was reported by Aviara et al. (2010) for *Mucuna flagellipes* nuts, Carman (1996) for lentil seeds, Visvanathan et al. (1996) for neem nuts, and Tunde-Akintunde and Akintunde (2007) for beniseed within the moisture range of 6.3 and 49.5% d.b..

Porosity

Figure 12 shows an increase in porosity with an increase in moisture content from 68.14 to 85.63% d.b. for pods and from 67.31 to 83.55% d.b. for seeds. The increase in porosity can be attributed to the expansion and swelling of seeds with an increase in moisture content. The increasing trend of porosity was reported by

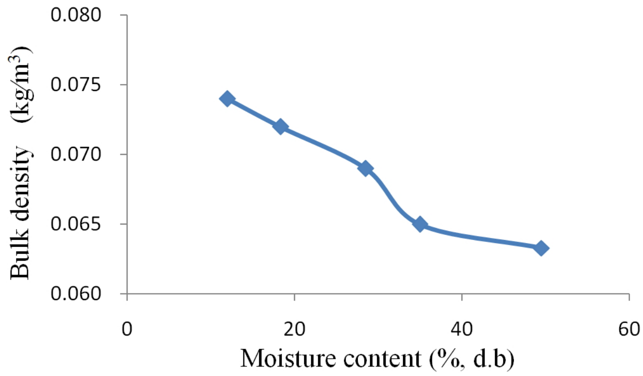

Figure 10. Effect of moisture content on bulk density of *Moringa oleifera* pods.

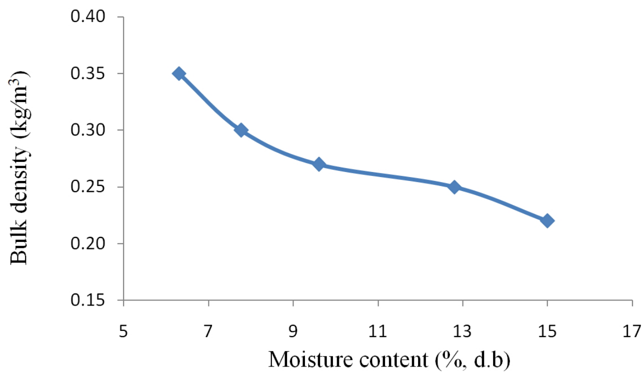

Figure 11. Effect of moisture content on bulk density of *Moringa oleifera* seeds.

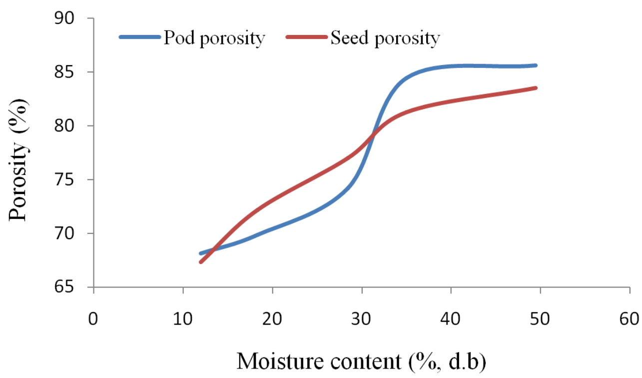

Figure 12. Effect of moisture content on porosity of *Moringa oleifera* pods and seeds.

Aviara et al. (2005) for *Balanites aegyptiaca* and by Konak et al. (2002) for chickpea seeds. The regression equations for pods and seeds are given as:

$$\delta_b = 0.5226M + 61.478 \ (R^2 = 0.884) \tag{18}$$

$$\delta_b = 0.4362M + 63.765 \ (R^2 = 0.932) \tag{19}$$

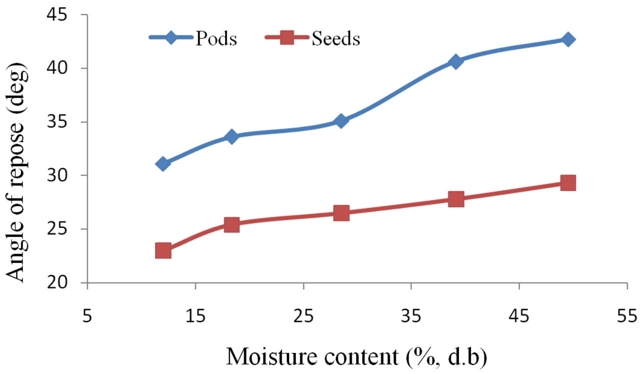

Figure 13. Effect of moisture content on angle of repose of *Moringa oleifera* pods and seeds.

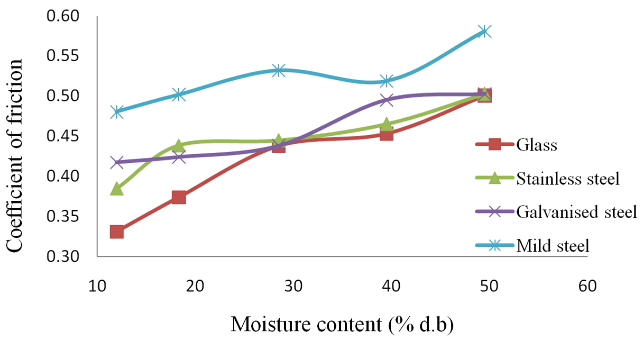

Figure 14. Effect of moisture content on coefficient of friction of *Moringa oleifera* pods.

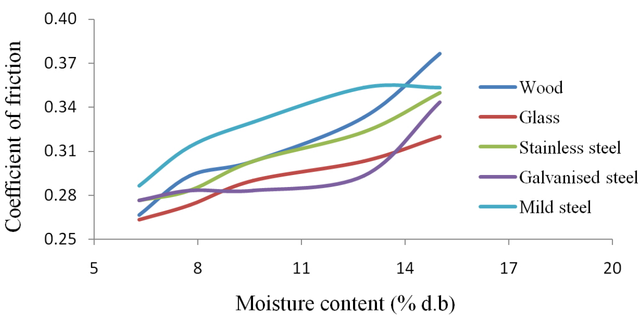

Figure 15. Effect of moisture content on coefficient of friction of *Moringa oleifera* seeds.

Mechanical properties

The results obtained for the angle of repose and the coefficient of friction of *Moringa oleifera* pods and seeds are presented in Figures 13, 14, and 15.

Angle of repose

The values of the angle of repose of moringa pods and seeds (Figure 13) were found to increase from 31.1° to 42.7° and from 23° to 29.3° in the moisture ranges of 12-49.5% d.b. and 6.3-15% d.b., respectively. The increase in filling angle may be due to an increase in surface roughness, as well as to the size of the individual pods, which affects their ability to form a heap. According to Tavakoli et al. (2009), values for the filling angle of repose increased from 31.16° to 36.90° with an increase in the moisture range of 7.34-21.58% d.b. for barley grains. Similar trends of an increase in the angle of repose with increasing moisture content were reported by Dursun and Dursun (2005) for caper seed, Aviara et al. (2013) for moringa seeds, Pradhan et al. (2008) for karanja kernels, and Yalcin and Ersan (2007) for coriander seeds. The following regression equations were obtained for the angle of repose:

$$\theta_p = 0.315M + 27.31 \; (R^2 = 0.971) \qquad (20)$$

$$\theta_s = 0.1537M + 21.869 \; (R^2 = 0.951) \qquad (21)$$

Coefficient of friction

Figure 14 presents the static friction coefficients of the pods on four surfaces, namely glass, stainless steel, galvanized steel, and mild steel, expressed as a function of moisture content in the moisture range of 12-49.5% d.b.

The coefficient of static friction for mild steel recorded the highest value (0.581), and the lowest value (0.501) was recorded on glass. The static coefficient of friction increased with an increase in moisture content on all surfaces.

The increase in the static coefficient of friction with increasing moisture content may be due to the increase in the weight of the pods from moisture absorption, which reduces its ability to slide. The higher the coefficient of friction is, the lower the mobility coefficient is, hence requiring a larger hopper opening, a larger hopper side wall slope, and a steeper angle of inclination in inclined grain transporting equipment such as chutes (Irtwange and Igbeka, 2002). As shown in Figure 15, a similar increasing trend with moisture content was observed on all surfaces for the static friction coefficient of the seeds.

Strength properties of moringa pods and seeds

The values of moringa pod and seed strength properties at moisture contents of 12 and 6.3% d.b., respectively, are presented in Tables 3 and 4. Figures 16 to 21 show the variation of bioyield force, bioyield deformation, yield force, bioyield energy, rupture force, and rupture energy with the moisture content of *Moringa oleifera* pods. It can

Table 3. Strength properties of *Moringa oleifera* pods at a moisture content of 12% d.b.

Measurement	Orientation	Mean value	Standard Dev.
Bioyield force (N)	Natural	102.589	46.6324
Deformation (mm)	Natural	5.01642	1.5564
Bioyield energy (J)	Natural	0.27072	0.17402
Yield force (N)	Natural	40.465	17.372
Rupture force (N)	Natural	91.594	47.3086
Rupture energy (J)	Natural	0.31766	0.17144

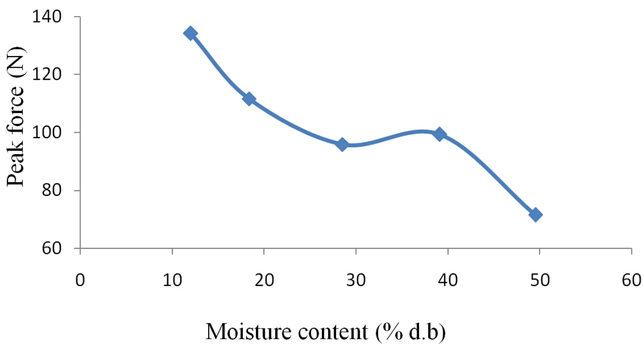

Figure 16. Effect of moisture content on bioyield force of *Moringa oleifera* pods under compression in natural loading.

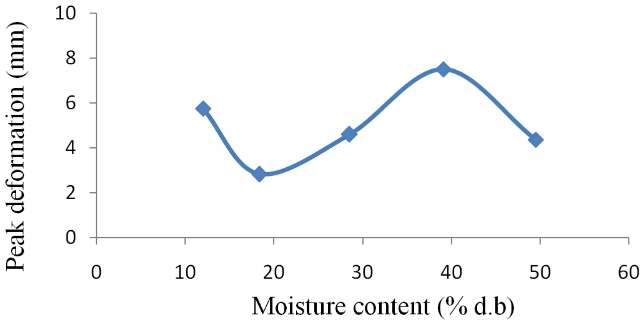

Figure 17. Effect of moisture content on bioyield deformation of *Moringa oleifera* pods under compression in natural loading.

be seen that the bioyield deformation, bioyield energy, rupture force, and rupture energy of the pods decreased with increase in moisture content to a minimum point, then increased with a further increase in the moisture content. The yield force of the pods increased to a maximum value and then decreased as the moisture content increased while the bioyield force decreased with an increase in moisture content to a minimum value and then increased with further decrease inthe moisture content range.

Figures 22 to 27 show the variation of the above strength properties for moringa seeds with moisture content under both lateral and longitudinal loading.

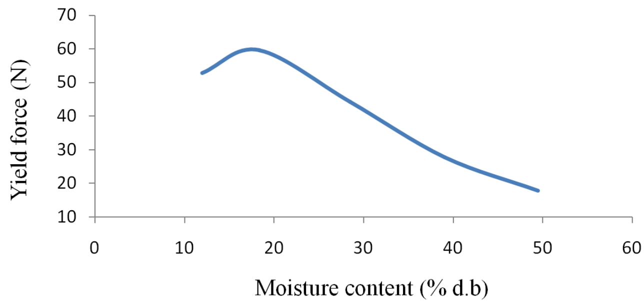

Figure 18. Effect of moisture content on yield force of *Moringa oleifera* pods under compression in natural loading.

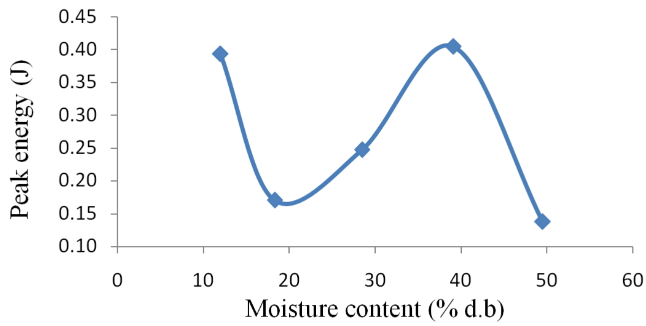

Figure 19. Effect of moisture content on bioyield energy of *Moringa oleifera* pods under compression in natural loading.

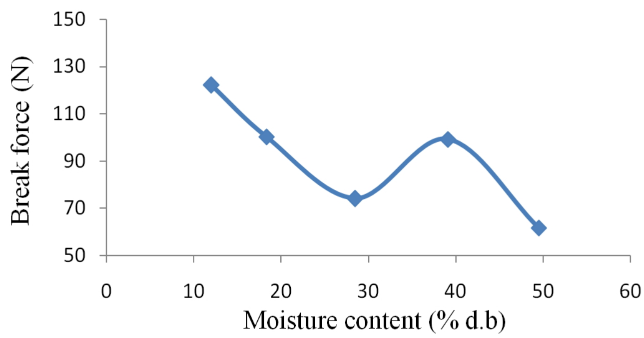

Figure 20. Effect of moisture content on rupture force of *Moringa oleifera* pods under compression In natural loading.

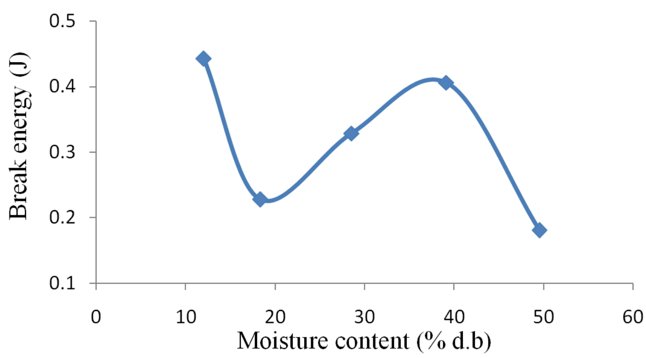

Figure 21. Effect of moisture content on rupture energy of *Moringa oleifera* pods under compression in natural loading.

From these figures, it can be seen that loading on the transverse axis, or lateral orientation, caused all the properties to decrease with increasing moisture content to a minimum value, after which further increase in moisture content resulted in an increase in the property value. For seeds loaded in the longitudinal orientation, all the properties with the exception of bioyield deformation increased with an increase in moisture content to a maximum value, and thereafter decreased with a further increase in moisture content.

The bioyield deformation of the seeds decreased with an increase in moisture content to a minimum value, and then increased with a further increase in moisture content. It was observed that the rupture force was significantly higher for the pods than the seeds. The pods are larger and heavier than the seeds, thus requiring a higher rupture force. Preliminary efforts to rupture the pods in a vertical orientation failed; rupture was determined only in a natural position. The force required to rupture the seeds in the lateral orientation was significantly higher than in the longitudinal orientation: 22.94 and 15.36 N, respectively. A similar trend was observed for the bioyield force and yield force.

Comparison of physical properties of moringa pods and seeds

The values of the linear dimensions of the pods (311.15, 22.79, and 22.24mm) and their corresponding values for seeds (15.06, 12.01, and 11.19mm) are presented in Table 4. This result shows that the pods are longer and broader than the seeds. This factor should be considered when designing a hopper, bunker, silo, or other bulk solid storage and handling structure. The average mass of 1000 moringa pods and seeds was 13636.67kg and 273.333kg, respectively. This depicts the fact that moringa pods are much heavier than the seeds. The surface area of the pods

Table 4. Strength properties of *Moringa* seeds at a moisture content of 6.3% (d.b.)

Measurement	Lateral loading		Longitudinal	
	Mean	Std. Dev.	Mean	Std.Dev.
Bioyield force (N)	48.072	14.1696	40.508	5.4592
Deformation (mm)	1.6581	0.4210	2.8163	0.6614
Bioyield energy (J)	0.04086	0.01579	0.0438	0.0061
Yield force (N)	28.148	18.213	20.616	11.150
Rupture force (N)	22.944	8.5816	15.36	2.2303
Rupture energy (J)	0.0449	0.0164	0.0469	0.0063

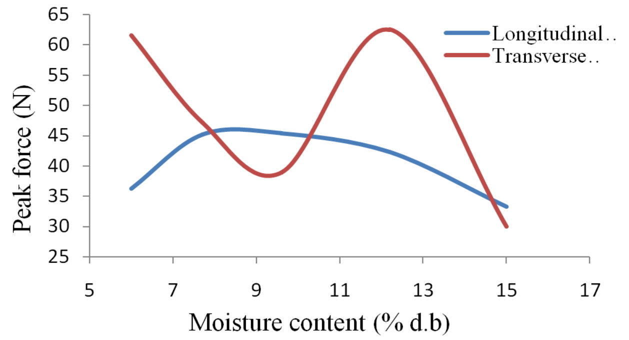

Figure 22. Effect of moisture content on bioyield force of *Moringa oleifera* seeds under compression in lateral and longitudinal loading.

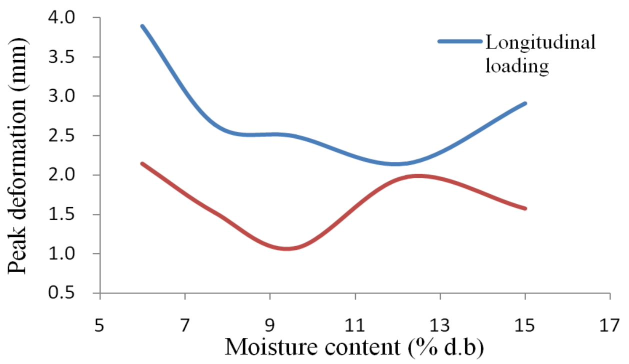

Figure 23. Effect of moisture content on bioyield deformation of *Moringa oleifera* seeds under compression in lateral and longitudinal loading.

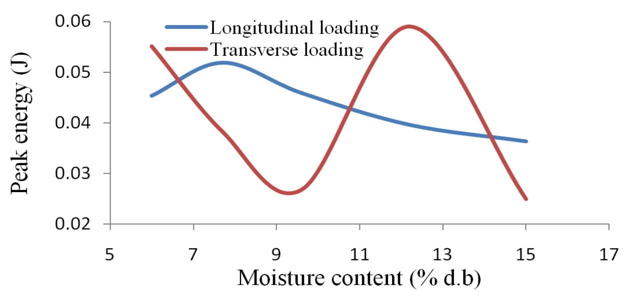

Figure 24. Effect of moisture content on bioyield energy of *Moringa oleifera* seeds under compression in lateral and longitudinal loading.

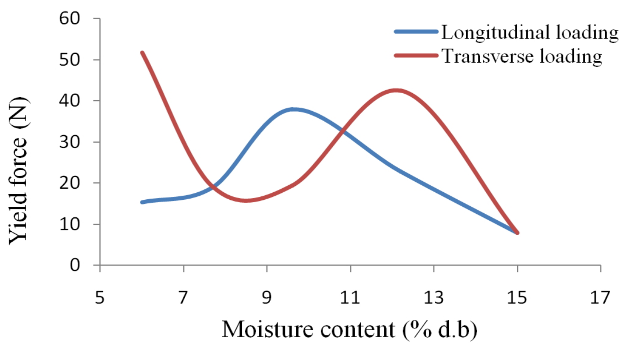

Figure 25. Effect of moisture content on yield force of *Moringa oleifera* seeds under compression in lateral and longitudinal loading.

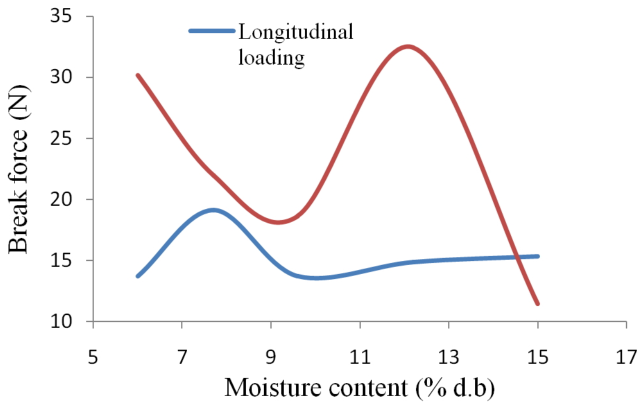

Figure 26. Effect of moisture content on rupture force of *Moringa oleifera* seeds under compression in lateral and longitudinal loading.

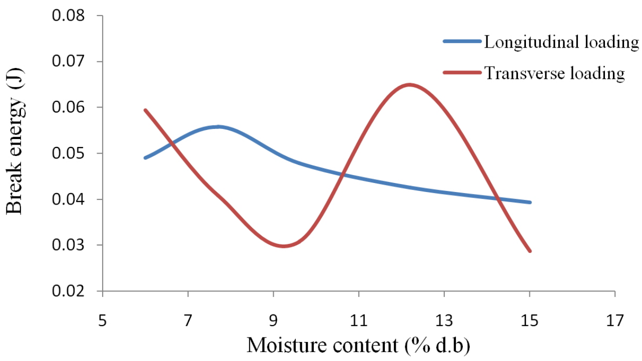

Figure 27. Effect of moisture content on rupture energy of *Moringa oleifera* seeds under compression in lateral and longitudinal loading.

Table 5. Physical properties of *Moringa oleifera* pods and seeds at 12% d.b. moisture content

Property	pods at 12% Mc	seeds at 12% Mc
Length (mm)	311.15	15.06
Width (mm)	22.79	12.01
Thickness (mm)	22.24	11.19
Geometric mean (mm)	53.87	12.58
Surface area (mm^2)	9131.82	503.02
Porosity (%)	68.14	81.28
Angle of repose (°)	31.1	32.5
Mass (kg)	13636.67	273.333

and seeds averaged 9131.82 mm^2 and 503.02 mm^2. The pods have a larger surface area compared to the seeds. The coefficient of friction for the pods is higher than that of the seeds. The angle of repose of the pods and seeds are 31.1° and 32.5°, respectively. Any machine designed for processing the pods should take into consideration the wide difference in the angle of repose of the pods and seeds. This information is very useful in the design of processing equipment for the pods.

Conclusions

The investigation of select physical properties of *Moringa Oleifera* revealed the following:

(1) The physical properties of the pods determined as a function of moisture content varied significantly with increase in moisture content.
(2) The principal dimensions, mass, surface area, sphericity, bulk density, angle of repose, and coefficient of friction increased with an increase in moisture content in the range of moisture content investigated.
(3) The bioyield, yield, and rupture forces of moringa pods decreased with an increase in moisture content to a minimum value, and then increased with a further increase in moisture content.
(4) The bioyield and rupture energies of the pods decreased with an increase in moisture content to a minimum value, and then increased with a further increase in moisture content, with a final decrease as the moisture content continued to increase.

Conflict of Interest

The authors have no conflicting financial or other interests.

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