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Moisture-dependent Physical Properties of *Detarium microcarpum* Seeds

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Abstract

Purpose: Physical properties of *Detarium microcarpum* seeds were investigated as a function of moisture content to explore the possibility of developing bulk handling and processing equipment. **Methods:** Seed size, surface area, and 1,000-seed weight were determined by measuring the three principal axes, measuring area on a graph paper, and counting and weighing seeds. Particle and bulk densities were determined using liquid displacement and weight in a measuring cylinder, respectively. Porosity was computed from particle and bulk densities. Roundness and sphericity were measured using shadowgraphs. Angle of repose and static and kinetic coefficients of friction were determined using the vertical cylindrical pipe method, an inclined plane, and a kinetic coefficient of friction apparatus. **Results:** In the moisture range of 8.2%–28.5% (db), the major, intermediate, and the minor axes increased from 2.95 to 3.21 cm, 1.85 to 2.61 cm, and 0.40 to 1.21 cm, respectively. Surface area, 1,000-seed weight, particle density, porosity, and angle of repose increased from 354.62 to 433.19 cm^2, 3.184 to 3.737 kg, 1060 to1316 kg/m^3, and 30.0% to 53.1%, respectively, whereas bulk density decreased from 647.6 to 617.2 kg/m^3. Angle of repose increased from 13.9° to 28.4°. Static and kinetic coefficients of friction varied between 0.096 and 0.638 on different structural surfaces. **Conclusions:** Arithmetic mean, geometric mean, and equivalent sphere effective diameters determined at the same moisture level were significantly different from each other, with the arithmetic mean diameter being greatest. Surface area, 1,000-seed weight, particle density, porosity, and angle of repose all increased linearly with moisture content. Bulk density decreased linearly with moisture content. The coefficients of friction had linear relationships with moisture content. The highest values of static and kinetic coefficients of friction were observed on galvanized steel and hessian fabric, respectively, whereas the lowest values were observed on fiberglass.

Keywords: Angle of repose, *Detarium microcarpum*, Particle and bulk densities, Static and kinetic coefficients of friction

Introduction

Detarium microcarpum, commonly known as sweet detar, is an African food crop tree belonging to the Fabaceae family. The fruit is fleshy and edible (Keay et al., 1964). In southeastern Nigeria, *D. microcapum* is locally known as "Ofor" and flour made from its seed is popularly used as a thickening agent for soup. Its high carbohydrate content and ability to form a viscous gum at low concentrations in sauce indicate it belongs to the class of food ingredients known as hydrocolloids (Ihekoronye and Ngoddy, 1985). The fruit is rich in vitamin C (3.2 mg), with 4.8 g of protein and 64.5 g of sugar per 100 g, and can be eaten raw or cooked. It had the highest total phenolic, flavonoid, and antioxidant value among 14 wild edible fruits studied in Burkina Faso (Abdalbasit et al., 2009). The seed (Figure 1) yields 7.5% oil and the predominant fatty acid is linoleic acid. Hulled seed flour contains 3.5~6.5 g water, 3 g crude fiber, 13~15 g crude fat, 13.5~27 g of crude protein, and 39 g carbohydrate per 100 g.

D. microcarpum is usually harvested during the dry season. A long pole is used to knock the fruits from the tree, and fruits may fall to the ground on their own. In order to obtain the seed, a stone or knife is used to break

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Figure 1. *Detarium microcarpum* seeds.

the fruit and a sharp object is used to remove the seed. Typically, there is one seed per fruit. The coat or hull of the *D. microcarpum* seed is brown in color and hard. The edible kernel inside the seed is milky white, and both seed and kernel are disc shaped. The seed is typically processed further to release the kernel.

Processing the seed may involve such operations as boiling, roasting, or frying for variable periods. Afterwards, the seeds are dehulled using a rubbing action made by moving a cylindrically shaped stone with slight shear pressure over a thin layer of seeds on a flat surface. The kernels obtained are washed 3~4 times and soaked in water overnight. The water is then drained off, and the kernels are sundried and milled. The seed kernel flour is used as a traditional emulsifying and thickening agent in soup, baby food, and local beer.

The process described above not only leads to quantitative and qualitative losses of the finished product, but also are laborious and time consuming. As such, there is a need to develop more efficient methods for processing and storing *D. microcarpum* seeds and their by-products. The development of such methods and equipment requires knowledge of the physical properties of the seed. Mieszkalski (1997) and Aviara et al. (1999) reported that the moisture content of agricultural crops influences the adjustment, performance efficiency, and energy consumption of processing machines. Therefore, physical properties of seeds with different moisture content are important considerations in the design and development of equipment for the processing and storage.

Numerous studies (Dutta et al., 1988, Singh and Goswani 1996, Aviara et al., 1999, Ogunjimi et al., 2002, Tabatabaeefar 2003, Aviara et al., 2005a, 2005b, Burubai et al., 2007, Simonyan et al., 2007, Tunde-Akintunde *et al.*, 2007, Zewdu and Solomon 2008, Bamgboye and Adejumo 2009, Shafiee et al., 2009, Simonyan et al., 2009, Aviara et al., 2010, Shafiee et al., 2010, Gholami et al., 2012, Gebreselassie 2012, Satimehin and Philip 2012, Aviara et al., 2013, Aviara et al., 2014a, 2014b) have documented the physical properties of different agricultural products for this purpose. Important physical properties at different moisture levels include axial dimension, size distribution, surface area, 1,000-seed weight, roundness and sphericity, aspect ratio, particle and bulk densities, angle of repose, static and kinetic coefficients of friction on different structural surfaces, and coefficient of restitution. No study, however, has been conducted on the physical properties of *D. microcarpum* seed and the dependence of their values on seed moisture content. Therefore, the purpose of our study was to determine the physical properties of *D. microcarpum* seeds and investigate variation in the properties associated with seed moisture content.

Materials and Methods

Detarium microcarpum seeds used for this study were obtained from the Eke-awgbu market in Awgbu town of Orumba North Local Government Area, Anambra State, Nigeria. The seeds were cleaned and broken and immature seeds were removed. Seeds were preserved by storage in airtight polyethylene bags.

The moisture content of *D. microcarpum* seeds was determined using the method of Aviara *et al.* (2010). Samples of seed were dried in an oven at 105°C to a constant weight while weight loss was monitored hourly to determine the time at which weight loss began to approach zero. The samples reached a constant weight at 6 h. To determine the effect of moisture content on physical properties of the seed, five moisture levels were used. Seed samples moisture levels higher than the initial moisture content, were prepared using the method of Ezeike (1986) as employed by Aviara et al. (2010) and Aviara et al. (2013). Briefly, seeds were soaked in water for 30 min to 2 h and were then spread in thin layer to air dry for 8 h. For the moisture levels below the initial moisture content, triplicate samples of seed were sun-dried at ambient temperature for 3 h, and were then sealed in marked polyethylene bags and stored for 24 h. The storage period resulted in stable and uniform moisture content.

To determine the seed size, 100 seeds were randomly selected from each moisture level following Dutta *et al.* (1988). For each seed, the three principal axial dimensions, (major, intermediate, and minor axes) were measured using Vernier calipers read to the nearest 0.05 mm. The arithmetic mean, geometric mean, and equivalent spherical diameter were calculated using the following equations:

$$AMD = \frac{(a+b+c)}{3} \tag{1}$$

$$GMD = (abc)^{1/3} \tag{2}$$

$$ESD = \left(\frac{6\,W_{1000}}{1000_{\rho t\pi}}\right)^{1/3} \tag{3}$$

where AMD is arithmetic diameter (cm), a, b, and c are major, intermediate, and minor axial dimensions (cm) respectively, GMD is geometric mean diameter (cm), and ESD is equivalent spherical diameter (cm).

Because the size of seed is an important parameter in processing (Teotia and Ramakrishna 1989, Joshi *et al.*, 1993, Suthar and Das 1996), our seed sample at initial moisture content was classified into three categories: large (a > 3.07 cm), medium (2.53 cm ≤ a ≤ 3.07 cm), and small (a < 2.53 cm) based on the length of the major axis. Seed surface area was determined using the coating method described by Mohsenin (1986) with modifications. Thirty *D. microcarpum* seeds at specified moisture content were randomly selected. Each seed was carefully wrapped foil. Excess foil was cut off and that covering the seed was carefully unwrapped and spread out on graph paper. The outline of the foil was traced and the surface area was determined by counting the squares. One thousand-seed weight at each moisture level was obtained using an electronic balance weighing 1,000 seeds to the nearest 0.001 g. Particle density was determined using the water displacement method. Thirty seeds were coated with thin layer of epoxy resin to prevent the absorption of water. Bulk density was determined using the AOAC (1980) method. Briefly, we filled a 500-ml cylinder with seeds to a height of 15 cm and weighed the contents. Porosity was calculated from particle and bulk densities using the relationship given by Mohsenin (1986).

$$P = \left(1 - \frac{\rho_b}{\rho_t}\right) \times 100 \tag{4}$$

where P is porosity (%), ρ_b is bulk density (kg/m^3), ρ_t is particles density (kg/m^3).

Roundness and sphericity were determined by tracing shadowgraphs of the seed at its natural position of rest on graph paper. Next, inscribing and circumscribing circles were constructed. The projected area was determined by counting squares, and the diameter and area of the smallest circumscribing circle, as well as the diameter of the largest inscribing circle were measured. Thirty shadow graphs were constructed for each moisture level and the seed roundness and sphericity were calculated using the following equations:

$$R = \frac{A_p}{A_c} \times 100 \tag{5}$$

where R is Roundness (%), A_p is Projected area (cm^2), A_c is Area of smallest circumscribing circle (cm^2)

$$\varphi = \frac{D_i}{D_c} \times 100 \tag{6}$$

where φ is Sphericity (%), D_i is Diameter of the largest inscribing circle (cm), D_c is Diameter of the smallest circumscribing circle (cm).

To determine the angle of repose, the cylindrical pipe method was used. We filled an open-ended cylinder with seeds. The cylinder was slowly raised from a flat surface until it left the seeds forming a cone. The base diameter and height of the cone was measured to calculate the angle of repose.

The static coefficient of friction was evaluated on five structural surfaces: hessian fabric, fiberglass, galvanized steel, plywood with wood grain parallel to the direction of movement, and plywood with wood grain perpendicular to the direction of movement. We used the inclined plane method as described by Dutta *et al.* (1988) and Suthar and Das (1996). Briefly, this involved placing an open-ended box (150 × 150 × 150 mm) on an adjustable tilting surface, upon which the structural surface was placed. The box was filled with seeds and the structural surface was gradually raised until the box began to slide. The angle of tilt was read from a graduated scale and the tangent of this angle was the static coefficient of friction of the seeds at the specified moisture level.

To determine the kinetic coefficient of friction, the open-ended was placed on a horizontal surface. Four different surfaces were used at each moisture level and these included hessian fabric, fiberglass, plywood with wood grain parallel to the direction of movement, and plywood with wood grain perpendicular to the direction of movement. The box was filled with seeds and connected by a string, to a pulley system parallel to the surface of the table. A pan hung from the pulley into which, weights were placed until the box moved uniformly when lightly pushed. The kinetic coefficient of friction of the seeds on a given structural surface was determined using the following expression:

$$\mu = \frac{W_p + W_m}{W_b + W_s} \tag{7}$$

where W_p is mass of pan (g), W_m is total weight placed in pan (g), W_b is mass of box (g), and W_s is mass of sample (g).

All the experiments were repeated five times and frequency distributions of axial dimensions were determined and plotted. Data obtained on surface area, 1,000-seed weight, particle and bulk densities, and angle of repose were subjected to one way analysis of variance (ANOVA) and least square difference (LSD) in a completely randomized block design to determine the significance of variation within these properties with moisture content. Variation of seed size, average diameter, and static and kinetic coefficients of friction were analyzed using a two-way ANOVA and LSD in a split plot design. The relationships between the physical properties of *D. microcarpum* seed and moisture content were expressed using regression equations. All statistical analyses were conducted with SPSS version 20 for Windows.

Results and Discussion

Seed moisture content

The initial moisture of *D. microcarpum* seed was 14.1% dry basis (db). The four moisture levels obtained after conditioning the seeds were 8.2%, 21.9%, 25.8%, and 28.5% (db). Measurements were taken using seeds with the above moisture levels to determine the effect of moisture content on the physical and frictional properties of the seeds.

Seed size and size distribution

The size of *D. microcarpum* seed, measured in terms of axial dimensions and average diameters, at different moisture levels are presented in Table 1. Table 1 shows that the axial dimensions, and the arithmetic and geometric mean diameters increased with moisture level in the range of 8.2%–28.5% (db), whereas the equivalent spherical diameter decreased. Moisture content significantly affected seed size (F = 22.725, df = 4, P < 0.001), and size characteristics of *D. microcarpum* seeds (F = 214.491, df = 5, P < 0.001). The major, intermediate, and minor axes of the seed increased significantly from 2.95 to 3.21 cm, 1.85 to 2.61 cm, and 0.40 to 1.21 cm respectively, from 8.2% to

Table 1. Axial dimensions of *Detarium microcarpum* seeds with different moisture contents

Moisture content % (db)	Major diameter (cm)	Intermediate diameter (cm)	Minor diameter (cm)	Arithmetic mean diameter (cm)	Geometric mean diameter (cm)	Equivalent sphere effective diameter (cm)
8.2	2.95 (0.14)[a]	1.85 (0.13)	0.40 (0.11)	1.73	1.30	1.79
14.1	3.03 (0.27)	2.1 (0.203)	0.65 (0.11)	1.97	1.67	1.78
21.9	3.1 (0.21)	2.27 (0.204)	0.90 (0.14)	2.09	1.85	1.77
25.8	3.18 (0.31)	2.47 (0.215)	1.1 (0.145)	2.25	2.05	1.76
28.5	3.21 (0.28)	2.61 (0.193)	1.21 (0.138)	2.34	2.16	1.75

[a]Numbers in parentheses are standard deviations

Table 2. Size distribution of *Detarium microcarpum* seed at the initial moisture content of 14.1% (db)

Size[a)]	% of sample		Averages ± SD						
	#	Mass	a (cm)	b (cm)	c (cm)	a/b	a/c	M (kg)	a/M
Ungraded	100	100	3.03 ± 0.27	2.1 ± 0.2	0.65 ± 0.11	1.43 ± 0.12	4.66 ± 0.19	3.6 2± 0.53	0.84 ± 0.02
Large	48	51.6	3.28 ± 0.15	2.4 ± 0.17	0.72 ± 0.11	1.40 ± 0.09	4.61 ± 0.63	4.01 ± 0.46	0.82 ± 0.07
Medium	48	45.0	2.70 ± 0.12	2.13 ± 0.2	0.74 ± 0.19	1.38 ± 0.12	4.06 ± 0.62	3.29 ± 0.23	0.89 ± 0.06
Small	4	3.4	2.33 ± 0.11	1.86 ± 0.19	0.65 ± 0.10	1.25 ± 0.13	3.68 ± 0.43	2.75 ± 0.17	0.85 ± 0.09

[a)]Size class by major diameter a (cm): Unclassified, 2.0–3.6; Large, a > 3.07; Medium, 2.53 ≤ a ≤ 3.07; Small, a < 2.53

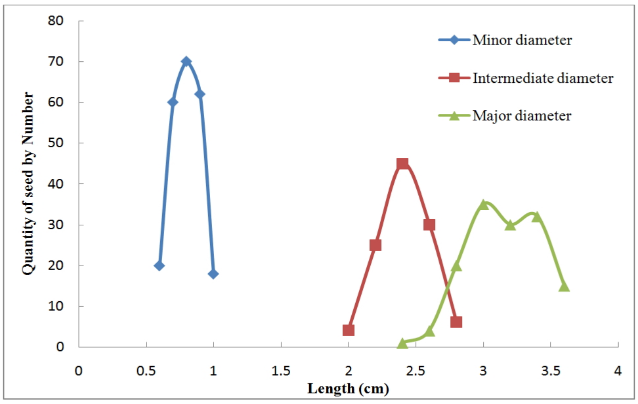

Figure 2. Frequency distribution of *Detarium microcarpum* seed axial dimensions at 14.1% (db) moisture content.

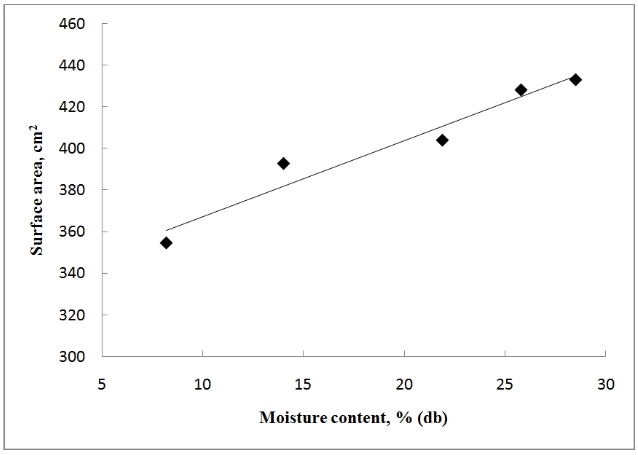

Figure 3. Effect of moisture content on surface area of *Detarium microcarpum* seeds.

28.5% moisture content. The arithmetic and geometric mean diameters of seeds increased as moisture content increased, whereas the equivalent spherical diameter decreased with increasing moisture. These proxies of size were significantly different, with the arithmetic diameter being greatest. The size distribution of *D. microcarpum* seeds at the initial moisture content of 14.1% (db) is presented in Table 2, and the frequency distribution curves of the major, intermediate, and minor axial dimensions of seeds are presented in Figure 2. At the initial moisture level, average major, intermediate and minor axial dimension were 3.03, 2.17, and 0.71 cm, respectively (Table 2). Approximately 48% and 51.6% of the seeds were large (a > 3.07 cm), 48% and 45% were medium (2.53 cm ≤ a ≤ 3.07 cm) and 4% and 3.4% by number and mass, respectively, were small (a < 2.53 cm). The intermediate and minor axes of the seed had a normal distribution, whereas the major axis had a bimodal normal distribution (Figure 2). This is in agreement with the finding of Lawal et al. (2014).

Surface area

The effect of moisture content on the surface area of *D. microcarpum* seeds is presented in Figure 3. Surface area increased from 354.62 to 413.19 cm^2 in range of 8.2% to 28.5% (db). Increase in the surface area of the seed with moisture content can be attributed to the increase in its axial dimensions. This may have been occurred because of swelling caused by the moisture imbibed by the hydrocolloids contained in the seed. Seed surface area was significantly affected by moisture (F = 220.582, df = 4, $P < 0.001$). The relationship between moisture content and surface area of the seed was linear and is expressed by the following equation:

$$S_a = 3.646M + 330.8,\ R^2 = 0.95 \quad (8)$$

where S_a is surface area (cm^2) and M is moisture content (%, db).

One thousand-seed weight

The variation in 1,000-seed weight with moisture content of *D. microcarpum* seeds is presented in Figure 4. The 1,000-seed weight increased from 3.184 to 3.737 kg as the moisture content increased from 8.2% to 28.5% (db).

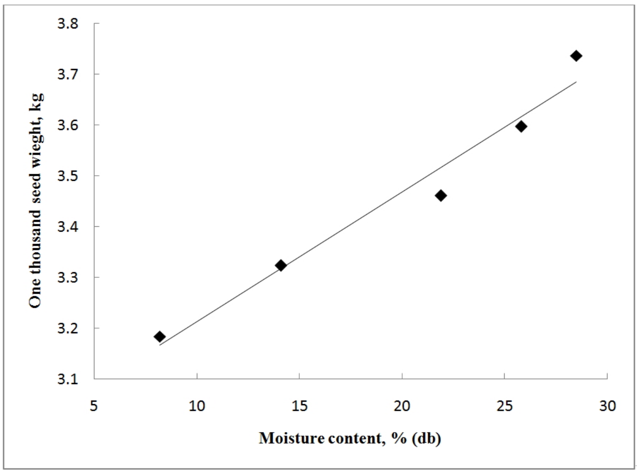

Figure 4. Effect of moisture content on 1,000-seed weight of *Detarium microcarpum* seeds.

Increase in 1,000-seed weight with moisture content has been caused by the contribution water mass to the mass of the individual seed. The 1,000-seed weight differed significantly with moisture content (F = 4.858, df = 4, P = 0.019). The trend in 1,000-seed weight with moisture content may be attributable to an increase in weight caused by water content at higher moisture levels. The relationship between moisture content and mass of 1,000 seeds of *D. microcarpum* was linear and is represented by the following equation:

$$W_{1000}=0.026M + 2.96, R^2 = 0.97 \quad (9)$$

where W_{1000} is the 1,000-seed weight (kg) and M is the moisture content (%, db).

Particle density

The effect of moisture and particle density is presented in Figure 5. Particle density increased from 1,060 to 1,316 kg.m^{-3} as moisture content of the seed increased from 8.2% to 28% (db). The contribution of moisture to increased seed mass may have been greater than that of the swelling of hydrocolloids to the increase in seed volume. The increase is seed mass and volume together caused an increase in the particle density of the seed. Particle density differed significantly by seed moisture content (F = 2.288E3, df = 4, P < 0.001). The relationship between particle density and moisture content was linear and is represented by the following regression equation:

$$\rho_t = 11.97M + 951.72, R^2 = 0.96 \quad (10)$$

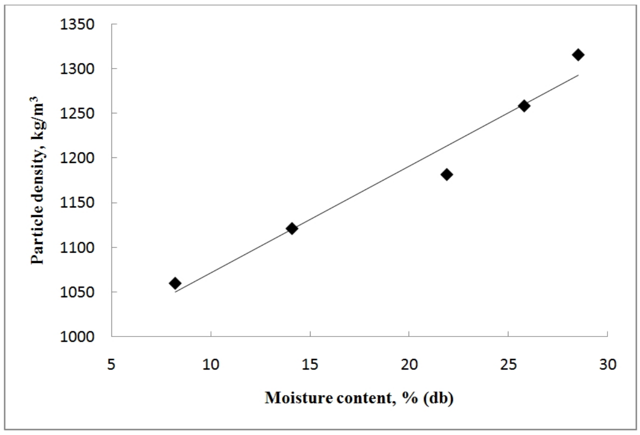

Figure 5. Effect of moisture content on particle density of *Detarium microcarpum* seeds.

where ρ_t is particle (kg/m^3) and M is moisture content (%, db).

Increased particle density with seed moisture content has also been reported by Gupta and Das (1998) for sunflower seeds (*Helianthus annuus*), Chandrasekar and Visvanathan (1999) for coffee beans (*Coffea* sp.), Singh and Goswani (1996) for cumin seeds (*Cuminum cyminum*), Tunde-Akintunde and Akintunde (2007) for beniseeds (*Sesamum indicum*), Aviara *et al.* (2010) for *Mucuna flagellipes* nuts, Aviara *et al.* (2013) for *Moringa oleifera* seeds and kernels, and Aviara *et al*. (2014a) for *Brachystegia eurycoma* seeds.

Bulk density

The effect of moisture on bulk density of *D. microcarpum* seeds is shown in Figure 6. The bulk density of the seed decreased from 652.5 to 617.2 kg.m^{-3} as the moisture content increased from 8.2% to 28.5% (db). Bulk density varied significantly with seed moisture (F = 47.767, df = 4, P < 0.001). This could be attributed to the increase in size with moisture content, which would decrease the quantity of seeds occupying the same bulk volume. Furthermore, resistance of the seeds to consolidation may have increased with moisture content because of the increase in internal pressure. The relationship between moisture content and bulk density was linear and is represented by the equation:

$$\rho_b = -1.949M + 670.25, R^2 = 0.95 \quad (11)$$

where ρ_b is the bulk density (kg.m^{-3}) and M is moisture content (%, db). Carman (1996), Gupta and Das (1997),

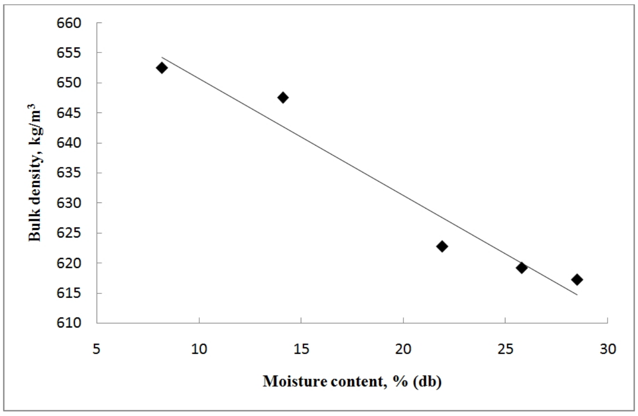

Figure 6. Effect of moisture content on bulk density of *Detarium microcarpum* seeds.

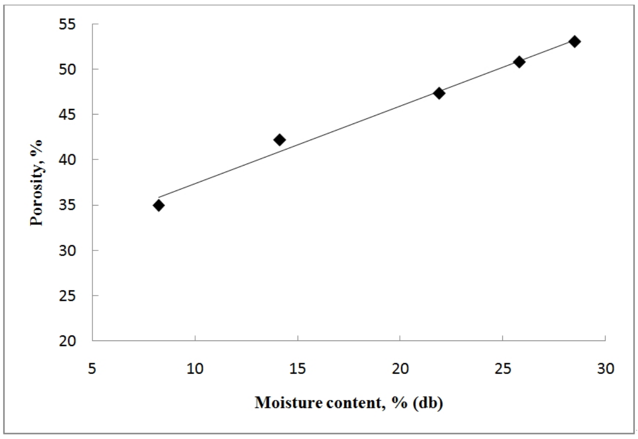

Figure 7. Effect of moisture content on the porosity of *Detarium microcarpum* seeds.

Aviara et al. (2010), Kibar et al. (2010), Visvanathan et al. (1996) and Aviara et al. (2014a) found the bulk density of lentil (*Lens culinaris*) seeds, sunflower seeds, *Mucuna flagellipes* nuts, rice (*Oryza* sp.) seeds, neem (*Azadirachta indica*) nuts, and *Brachystegia eurycoma* seeds, respectively, decreased as the seed moisture content increased.

Porosity

Variation in porosity of *D. microcarpum* seeds with moisture content is presented in Figure 7. The porosity of the seeds increased from 35.0% to 53.1% as the moisture content increased from 8.2% to 28.5% (db). Increase in moisture content may have caused a decrease in the cohesion of bulk seed because of resistance to consolidation. Seed porosity varied significantly with moisture content ($F = 108.886$, df = 4, $P < 0.001$). The relationship between porosity and moisture content was linear and is represented by the following equation:

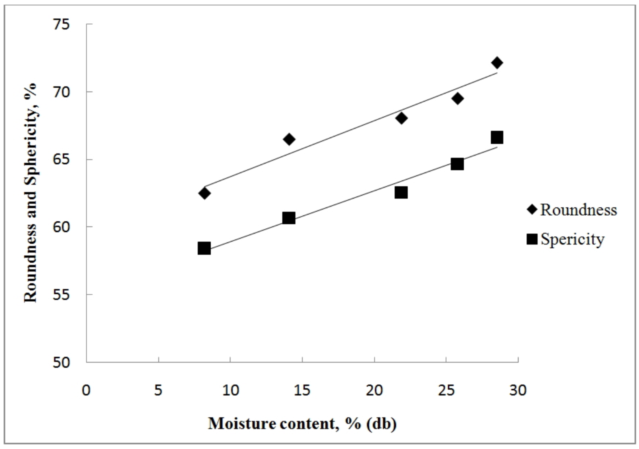

Figure 8. Effect of moisture content on roundness and sphericity of *Detarium microcarpum* seeds.

$$P = 0.857M + 28.82,\ R^2 = 0.99 \tag{12}$$

where P is porosity (%) and M is moisture content (%, db). Increase of porosity with moisture content has been reported for green gram (*Vigna radiata*; Nimkar and Chattopadhyay, 2001), chickpea (*Cicer arietinum*) seeds (Konak et al., 2002), *Balanites aegyptiaca* (Aviara et al., 2005a), watermelon varieties (*Citrullus vulgaris*; Razavi and Milani, 2006), *Mucuna flagellipes* nuts (Aviara *et al.*, 2010), *Moringa oleifera* seeds and kernels (Aviara *et al.*, 2013), dry bean grains (Kibar *et al.*, 2014), and *Brachystegia eurycoma* seeds (Aviara *et al.*, 2014a).

Roundness and sphericity

The effect of moisture content on roundness and sphericity of *Detarium microcarpum* seed is shown in Figure 8. Roundness and sphericity increased linearly from 62.5% to 72.1% and 58.4% to 66.6%, respectively, as the moisture content of the seeds increased from 8.2% to 28.5% (db). The increase in seed dimensions with moisture content was not uniform along the three axes. This may have been caused by the shape of the seed, which was spherical. Roundness and sphericity were significantly affected by seed moisture content ($F = 19.324$ [roundness], $F = 20.665$ [sphericity], df = 4, $P < 0.001$ for both). Because of the high values for roundness and sphericity coupled with a low minor axial dimension the seeds could be described as oval discs. The relationships between moisture content and roundness and sphericity were linear and they are expressed by the following equations:

$$R= 0.415M + 59.6, R^2 = 0.95 \quad (13)$$

$$S= 0.377M + 55.2, R^2 = 0.97 \quad (14)$$

where R is roundness (%), S is sphericity (%), and M is moisture content (%, db).

Increases in roundness and sphericity with moisture content have been reported for pigeon peas (*Cajanus cajan*; Baryeh and Mangope, 2002), Turkish mahaleb seeds (*Prunus mahaleb*; Aydin *et al*., 2002), hemp seeds (*Cannabis* sp. Sacilik *et al*., 2003), red lentil grains (Isik, 2007), sunflower seeds (Isik and Izli, 2007), *Mucuna flagellipes* nuts (Aviara *et al*., 2010), and *Brachystegia eurycoma* seeds (Aviara *et al*., 2014a).

Angle of repose

Variation in the angle of repose of *D. microcarpum* seeds in relation to moisture content is shown in Figure 9. The angle of repose increased from 9° to 28.4° as the moisture content increased from 8.2% to 28.5% (db). The angle of repose of the seeds was significantly affected by moisture content (F = 164.399, df = 4, P < 0.001). At higher moisture contents within the experimental range, the seeds tended to stick together. This resulted in greater particle stability and lower material flowability, which caused an increase in the angle of repose with moisture content. The angle of repose increased linearly with moisture content and is expressed using the equation:

$$\theta = 0.962M + 0.65, R^2 = 0.99 \quad (15)$$

where θ is angle of repose in degree and M is moisture content (%, db).

Linear relationships between the angle of repose and moisture content was also observed for cumin seeds, lentil seeds, coriander (*Coriandrum sativum*) seeds, and *Brachystegia eurycoma* seeds (Singh and Goswani, 1996, Amin *et al.*, 2004, Yalcin and Ersan, 2007, and Aviara *et al.*, 2014a).

Static coefficient of friction

The static coefficient of friction of *D. microcarpum* seeds obtained experimentally on five structural surfaces for seeds in the moisture range of 8.2%~28.5% (db) is presented in Figure 10. The static coefficient of friction of the seed increased linearly with an increase in moisture content and varied according to structural surface. The increase in seed mass resulting from increased moisture content caused an increase in the force of adhesion between the seed and structural surfaces, and this likely increased the coefficient of friction. Among the five structural surfaces considered, the static coefficient of friction was highest on galvanized steel (0.362~0.638), followed by plywood with wood grains perpendicular to the direction of movement (0.292~0.541), hessian fabric (0.238~0.539), plywood with wood grains parallel to the direction of movement (0.256~0.505), and was lowest on fiberglass (0.166~0.395). Moisture content and type of structural surface had significant effects on the static coefficient of friction of the seeds (F = 106.264 [moisture content], F = 72.001 [type of surface], df = 4, P < 0.001 for both). The relationship between the static coefficient of friction and moisture content for the different structural surfaces is expressed by the following equations:

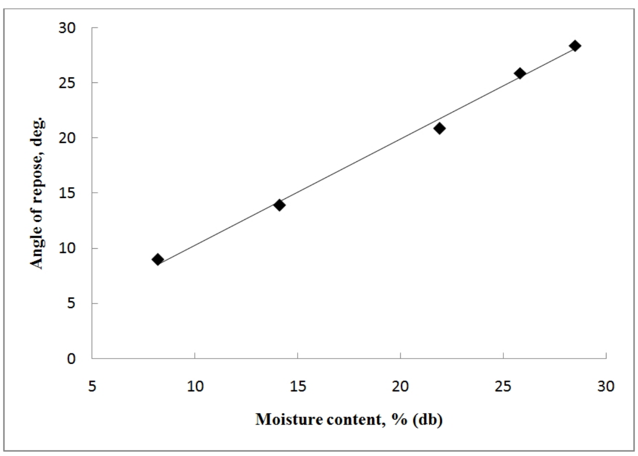

Figure 9. Effect of moisture content on angle of repose of *Detarium microcarpum* seeds.

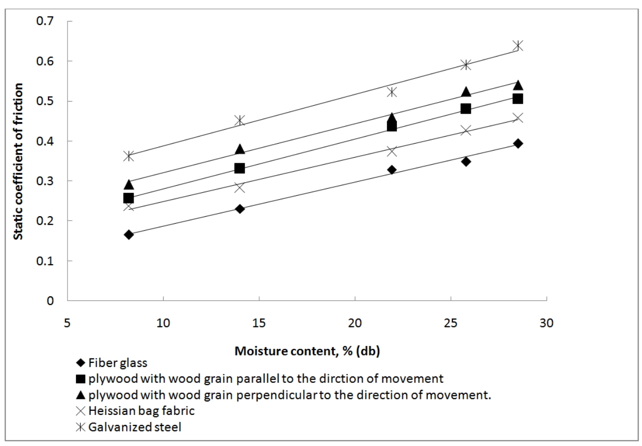

Figure 10. Effect of moisture content on static coefficient of friction of *Detarium microcarpum* seeds.

$$f_{gs} = 0.012M + 0.258, R^2 = 0.99 \quad (16)$$

$$f_{pp} = 0.012M + 0.198, R^2 = 0.99 \quad (17)$$

$$f_{hb} = 0.011M + 0.137, R^2 = 0.99 \quad (18)$$

$$f_{pl} = 0.012M + 0.156, R^2 = 0.99 \quad (19)$$

$$f_{fg} = 0.011M + 0.077, R^2 = 0.99 \quad (20)$$

where f_{gs}, f_{pp}, f_{hb}, f_{pl}, and f_{fg} are static coefficients of friction for *Detarium microcarpum* seeds on galvanized steel, plywood with wood grain perpendicular to the direction of movement, hessian fabric, plywood with wood grain parallel to the direction of movement, and fiberglass, respectively, and M is moisture content (%, db).

Linear increase in static coefficient of friction with moisture content has also been reported by Singh and Goswani (1996); Milani *et al.* (2007); Kheiralipour *et al.* (2008); Aviara *et al.* (2010); Aviara *et al.* (2013) and Aviara *et al.* (2014a) for cumin seeds, cucurbit (*Cucurbita* sp.) seeds, wheat (*Triticum* sp.), *Mucuna flagellipes* nuts, *Moringa oleifera* seeds and kernels, and *Brachystegia eurycoma* seeds, respectively.

Kinetic coefficient of friction

The variation of the kinetic coefficient of friction of *D. microcarpum* seeds with moisture content on five structural surfaces is shown in Figure 11. The kinetic coefficient of friction of the seed increased linearly with increases in moisture content in the range of 8.2%~28.5% (db). Increase in seed mass with increase in moisture content likely increased the drag force between the seeds and the structural surfaces and led to increased kinetic coefficients of friction. Kinetic coefficient of friction was highest on hessian fabric (0.351~0.617), followed by plywood with wood grain parallel to the direction of movement (0.319~0.510), plywood with wood grain perpendicular to the direction of movement (0.255~0.50), galvanized steel (0.162~0.445), and lowest on fiberglass (0.096~0.43). The moisture content, structural surface, and the interaction between these factors all had significant effects on the kinetic coefficient of friction (4 and 16, F = 339.185 [moisture content], F = 244.539 [surface type], df = 4, P < 0.001 for both, and F = 2.959 [interaction], df = 16, P = 0.002).

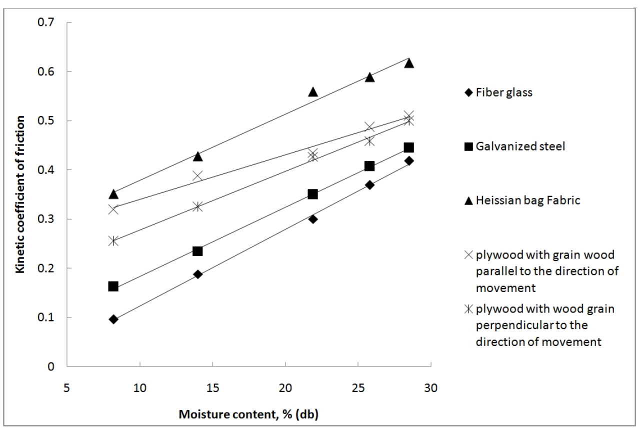

Figure 11. Effect of moisture content on kinetic coefficient of friction of *Detarium microcarpum* seeds.

The relationships between the kinetic coefficients of friction and moisture content are expressed for different structural surfaces using equations as follows:

$$\mu_{hb} = 0.013M + 0.243, R^2 = 0.99 \quad (21)$$

$$\mu_{pl} = 0.009M + 0.249, R^2 = 0.99 \quad (22)$$

$$\mu_{pp} = 0.011M + 0.158, R^2 = 0.99 \quad (23)$$

$$\mu_{gs} = 0.014M + 0.043, R^2 = 0.99 \quad (24)$$

$$\mu_{fg} = 0.015M - 0.033, R^2 = 0.99 \quad (25)$$

where μ_{hb}, μ_{pl}, μ_{pp}, μ_{gs}, and μ_{fg} are the kinetic coefficients of friction of *D. microcarpum* seeds on hessian fabric, plywood with wood grain parallel to the direction of movement, galvanized steel, and fiberglass, respectively.

Carman (1996), Ebubekir *et al.* (2004), Sessiz *et al.* (2007) and Aviara *et al.* (2010) reported a linear increase in the kinetic coefficient of friction for lentil seeds, fenugreek (*Trigonella foenum-graceum*) seeds, caper (*Capparis spinosa*) fruits, and *Mucuna flagellipes* nuts with moisture content, respectively. The value of kinetic coefficient of friction is an essential factor in the determination of the power required for continuous flow of granular or unconsolidated materials.

Conclusions

The study of the physical properties of *D. microcarpum* seeds revealed the following:

(1) In the moisture range of 8.2%~28.5% (db), the major, intermediate, and minor axial dimensions of the seed increased from 3.03 to 3.21 cm, 2.17 to 2.61 cm, and 0.71 to 1.21 cm, respectively. The arithmetic and geometric mean diameters increased from1.97 to 2.34 cm and 1.67 to 2.16 cm, respectively, whereas the equivalent sphere effective diameter decreased from 1.78 to 1.76 cm.
(2) The seed surface area increased from 354.6 to 431.1 cm^2 and 1,000-seed weight increased from 3.184 to 3.737 kg as seed moisture content increased from 8.2% to 28.5% (db).
(3) Particle density and porosity increased with the increase in seed moisture content from 1,060 to 1,316 $kg.m^{-3}$ and 30.0% to 53.1%, respectively, whereas bulk density decreased from 652.5 to 617.2 $kg.m^{-3}$ in the same moisture range.
(4) Roundness and sphericity both increased from 62.5% to 72.1% and 58.4% to 66.6%, respectively, as the seed moisture content increased from 8.2% to 28.5% (db).
(5) Angle of repose increased from 9° to 28.4° and had a linear relationship with moisture content.
(6) Static and kinetic coefficients of friction increased linearly with moisture content and varied with the type of structural surface.

Conflict of Interest

The authors have no conflicting financial or other interests.

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