

Full Paper

ENGINEERING PROPERTIES OF *MONODORA TENUIFOLIA* SEEDS AS INFLUENCED BY MOISTURE CONTENT

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ABSTRACT

Some engineering properties of *Monodora tenuifolia* seeds were investigated as a function of moisture content. Within the moisture range considered (10.75–16.23% w.b), the major, intermediate and minor diameters of *M. tenuifolia* seeds were in the range of 14.57–14.65 mm, 9.93–10.17 mm and 7.43–7.90 mm, respectively. The geometric mean diameter, unit weight, volume, sphericity and terminal velocity were in the range of 10.21–10.53 mm, 0.43–0.48 g, 560.60–615.12 mm³, 0.70–0.72 and 10.6–12.87 m/s, respectively. Porosity, bulk and true density were in the range of 0.36–0.42, 0.49–0.52 g/cm³ and 0.82–0.85 g/cm³, respectively. The coefficient of static friction varied from 0.33 to 0.43 over four different structural surfaces and the angle of repose of the seed were between 26.65° and 31.37°. Specific heat values were in the range of 12.29–16.07 J/gK, 4.86–5.95 J/gK, and 3.34–4.14 J/gK, for the seeds and 10.43–16.28 J/gK, 4.85–5.66 J/gK, and 3.72–4.37 J/gK, for the kernels at temperatures 40, 60 and 80°C respectively. As moisture content increases, the rupture force, rupture energy and deformation of *M. tenuifolia* seed varied from 47.36–68.40 N, 0.03–0.06 J and 1.01–1.64 mm, during vertical loading and 326.80–469.44 N, 1.69–2.29 mm and 0.30–0.47 J, during horizontal loading respectively. The effect of moisture content on the properties considered was significant ($p < 0.05$) and the regression models adequately expressed the relationships existing between the properties of *M. tenuifolia* seeds and moisture content.

Keywords: *Monodora tenuifolia* seed, Moisture content, engineering properties

1. INTRODUCTION

African nutmeg (*Monodora tenuifolia*) is a medium sized tree in the *Annonaceae* family of plants, native to the West African coasts and especially grown as a botanical and ornamental plant in Nigeria, Cameroon, Guinea and Gabon (Ezenwali *et al.*, 2009 and Quattrocchj, 2000). The spherical fruit is usually suspended on a long stalk; embedding numerous brownish, smooth and glossy seeds inside a non-edible pulpy mass, each seed encasing an edible kernel (Plate 1). Known for different applications in African traditional medicine (Ajayi *et al.*, 2012; Njoku *et al.*, 2012; Ekeanyawu and Njoku, 2013), *M. tenuifolia* seed is a major ingredient in the preparation of certain native potions to relieve tooth ache and cure dysentery, constipation, diarrhea and post-natal uterine hemorrhage in women (Njoku *et al.*, 2012; Iwu, 2002; Udeala, 2000 and Adeoye *et al.*, 1986). The use of *M. tenuifolia* root, bark and leaves for treating different skin-related problems has also been documented (Burkil, 1985). According to Ekeanyawu and Njoku (2013), proximate analysis indicated that *M. tenuifolia* seed contains 16.2, 2.85, 33.91, 32.1 and 5.2% of moisture, ash, protein, crude fat and carbohydrates, respectively; while analysis of the seed oil revealed the main fatty acids as linoleic, 39.37%; oleic, 34.40% and palmitic acid, 12.56%. In addition, *M. tenuifolia* seed contains antioxidants and has shown good antimicrobial activity against a wide range of gram-positive and gram-negative bacteria; hence, commonly used as a substitute for nutmeg in food flavor, spices and condiments preparations (Ajayi *et al.*, 2012; Bele *et al.*, 2011; Eggeling, 2002).

As the search for non-conventional seeds is getting more intensified in the tropics coupled with growing awareness regarding their utilization as food or industrial materials, it is almost certain that production will increase; hence, knowledge of the physical and mechanical properties of these seeds will be important in the imminent need for handling and processing equipment or adaptation of existing ones (Bangboye and Adejumo, 2009). Density characteristics, coefficient of friction and angle of repose are important parameters when determining space requirements for the design of grain hoppers, storage bins, discharge units, and conveying systems. Aviara *et al.* (2013) stated that information regarding porosity of seed is useful in the design of aeration equipment for stored products and in the estimation of the resistance of seed to air flow during drying. For grain cleaning and separation facilities (especially, pneumatic conveying systems), terminal velocity and drag coefficient are the most important properties; whereas, the knowledge of thermal properties useful in modeling the behaviour of seeds during thermal processing (such as

drying and frying) and the development of processes equipment for thermal treatments (Al-Mahasneh *et al.*, 2008). Razavi *et al.* (2007) and Aviara *et al.* (2013) pointed that moisture content is the strongest factor affecting the properties of biomaterials, the efficiency and energy consumption of their processing machines. Some conventional and non-conventional oil bearing seeds in the tropics for which information regarding moisture dependent properties have been widely documented include: moringa (Aviara *et al.*, 2013; Ogunsina, 2014), pistachio (Galedar *et al.* 2009; Razavi *et al.*, 2007; Kashaninejad *et al.* 2004), jatropha (Pradhan *et al.*, 2009), guna (Aviara *et al.*, 2008), olive (Kılıçkan and Güner, 2008), beniseed (Tunde-Akintunde and Akintunde, 2007), flaxseed (Coskuner and Karababa, 2007), safflower (Bauñmler *et al.*, 2006), sunflower (Ince *et al.*, 2005), African star apple (Oyelade *et al.*, 2005), hazelnut (Özdemir and Akinci, 2004), almond (Aydin, 2003), arecanut (Kaleemullah and Gunasekar, 2002), chick pea (Konak *et al.*, 2002), locust bean (Olajide *et al.*, 1999; Ogunjimi *et al.*, 2002) and sorrel (Omobuwajo *et al.*, 2000).

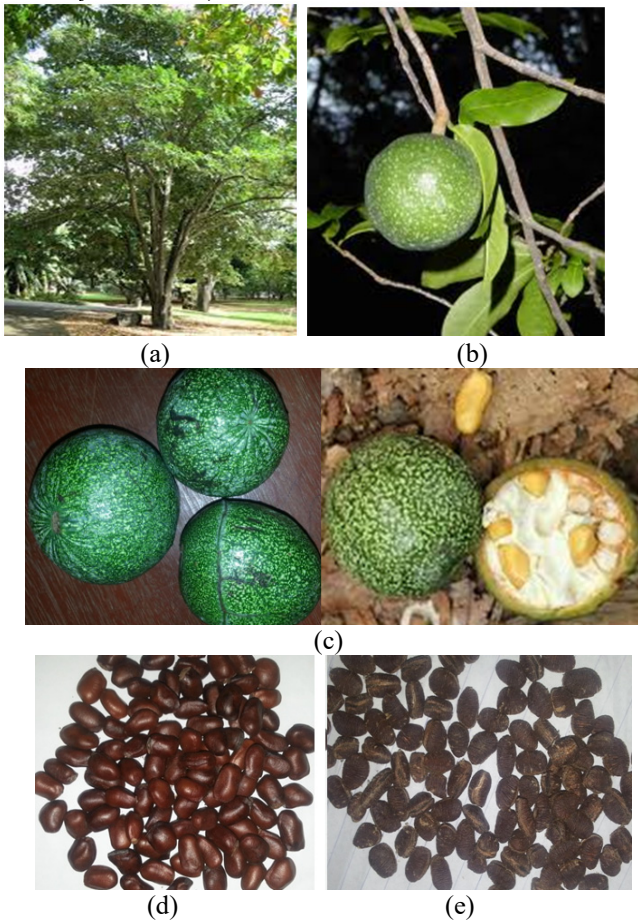


Plate 1. The *Monodora tenuifolia* plant and its products
 a) A cross-section of *M. tenuifolia* trees on Obafemi Awolowo University Campus, Ile Ife, Nigeria
 b) A typical *M. tenuifolia* fruit in its vegetative stage
 c) Mature *M. tenuifolia* fruits showing its internal structure d) *M. tenuifolia* seeds e) *M. tenuifolia* kernels (dehulled seeds)

Despite reports from literatures regarding the medicinal, biochemical and food-related importance of *M. tenuifolia* seeds, there is little or no information about its engineering properties. On the basis of the foregoing, this work focuses on the effect of moisture content on some physical, mechanical, thermal and aerodynamic properties of *M. tenuifolia* seeds.

2. MATERIALS AND METHODS

Freshly harvested *M. tenuifolia* fruits were obtained from ornamental and botanical trees in Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria. The fruits were sun-dried and seeds were extracted from the dried fruits manually. The seeds were dried further and a portion of the dried lot was dehulled manually to obtain the kernels. Moisture content determination was carried out by oven drying at 130±0.1°C for 6 h (using SM 9023 Uniscope Laboratory Oven, Made in England) until no change in weight was observed (ASAE, 2003). The initial moisture contents of the seed and kernel were obtained as 10.75 and 8.10% (w.b) respectively.

Moisture adjustment was carried out according to Balasubramanian (2001). The seeds were divided into four portions; one was retained at the initial moisture level of 10.75% while other three were adjusted to 12, 14 and 16%. This was done by adding a calculated amount of distilled water to the seeds (equation 1). The seeds were put in plastic bottles and kept in a refrigerator for one week to equilibrate. Samples were brought out of the refrigerator 24 h before use to allow thawing. Afterwards their respective actual moisture contents were determined and found to be 10.75, 12.04, 14.18 and 16.23%.

$$Q = w_i \left\{ \frac{m_f - m_i}{100 - m_f} \right\} \tag{1}$$

where, Q = weight of water added (g), W_i = initial weight of the sample (g), m_i = initial moisture content of the sample (%w.b.) and m_f = final moisture content (% w.b.).

For the axial dimensions and shape indices, 100 seeds and kernels were randomly selected from the lot containing about 2500 seeds. For each seed and kernel, the major axis, L; intermediate axis, W and minor axis, T were measured using an Electronic Micrometer Screw Gauge (Model No. 293-832, Made in Mitutoyo, Japan; 0.001 mm accuracy). Values were reported as an average of 100 replications + standard deviation. The ratios of various seed and kernel dimensions were determined and the relationships existing among them were established. The arithmetic mean diameter, D_a ; geometric mean diameter, D_g ; Sphericity, ϕ and the unit volume (mm^3) of the seeds were calculated as follows:

$$D_a = \frac{L+W+T}{3} \tag{2}$$

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

$$\phi = \left(\frac{D_g}{L} \right) \times 100\% \tag{4}$$

$$\text{Volume (mm}^3\text{), } V = \frac{\pi LWT}{6} \text{ (Miller, 1987)} \tag{5}$$

True density was determined by water displacement method (Omobuwajo *et al.*, 1999). One hundred randomly selected seeds were coated with a thin layer of epoxy resin to prevent water absorption. The seeds were placed in a measuring cylinder containing 500 ml of distilled water. The sample was totally immersed in the water using a sinker. Net water displacement by the seeds was recorded and used to calculate the density. This procedure was replicated twice. Bulk density was determined using the mass/volume relationship (Ogunsina, 2014). A measuring cylinder of known volume and weight was filled with the sample, the excess was removed by a strike-off stick without any compaction and the weight of the sample was determined afterwards. The ratio of the weight of sample to the volume it occupied in the cylinder was calculated as bulk density. This procedure was also replicated thrice. Porosity was calculated from the particle and bulk densities using equation 6 (Mohsenin, 1986)



$$P = 100 \left(1 - \frac{\rho_b}{\rho_t} \right) \quad (6)$$

For the angle of repose, a hollow cylinder of known dimensions was placed on a wooden table, filled with the seeds and raised slowly until the bulk assumed its natural slope as a cone of seeds, and the angle made by the slope with the horizontal was obtained as the angle of repose (Amin *et al.*, 2004; Kaleemullah and Gunasekar, 2002). Static coefficient of friction was determined on four different surfaces: mild steel, stainless steel, wood and glass surface. A container without base and lid was filled with sample and placed on an adjustable tilting plate, faced with the test surface; the container was slightly raised so as not to touch the surface. The inclination of the test surface was increased gradually with a screw device until the container just started to slide down and the angle of tilt (θ) was read from a graduated scale; and the static coefficient of friction = $\tan \theta$ (Ogunsina, 2014).

The terminal velocity of seeds at the different moisture contents considered was measured using an air column made of a hollow cylinder of transparent plastic material. A rotary positive displacement blower driven by a variable speed electric motor was used to develop air velocities. The open end of the column was overlaid with wire netting and for each test, and for each experiment, a seed was dropped on the netted surface into the air stream from the opened top of the air column, up which air was blown to suspend the material in the air stream. The terminal velocity of the sample was taken as the air velocity when the sample was just momentarily lifted above the contacting netted surface and suspended in the air stream was measured by an electronic anemometer (Am-4812, N479-296, Made in UK; having 0.01 m/s sensitivity). There were five measurements for each of the three test samples (Akinci *et al.*, 2004; Aydin and Ozcan, 2002).

For specific heat capacity, copper calorimeters were calibrated following the procedure of Aviaara and Haque (2001). A sample of known weight, temperature and moisture content was dropped into the calorimeter containing water of known weight and temperature. The mixture was stirred continuously using a copper stirrer and the temperature was recorded. The final temperature was recorded and the specific heat, C_s was calculated according to equation 7. At each moisture level of the samples, three temperature levels between the ambient and cooking temperatures were used to investigate the effect of temperature on the specific heat of the seed and kernel.

$$\frac{(M_c C_c + M_w C_w)(T_e - T_w)}{M_s(T_s - T_e)} \quad (7)$$

where: M_c = Mass of the calorimeter (g), M_s = Mass of the sample, M_w = Mass of water (g), C_c = Specific heat of the calorimeter ($Jg^{-1}K^{-1}$), C_w = Specific heat of water ($Jg^{-1}K^{-1}$), T_s = Temperature of the sample (K), T_w = Temperature of water (K).

Strength characteristics of the seeds were investigated by subjecting the seed sample to uni-axial compressive loading in the horizontal and vertical axes (Plate 2) at a loading rate of 10 mm/min. Compression tests were carried out on an Instron Universal Testing Machine (Model 3369 model 3369, Instron, Norwood, USA; 50 kN capacity). The rupture force applied in vertical and horizontal directions, deformation and energy at rupture point were measured. Graphs describing the relationship were plotted and regression equations generated. Data were presented as means of three determinations \pm SD. All the data obtained were subjected to analysis of variance and means were separated using Duncan multiple range tests SAS (2002).

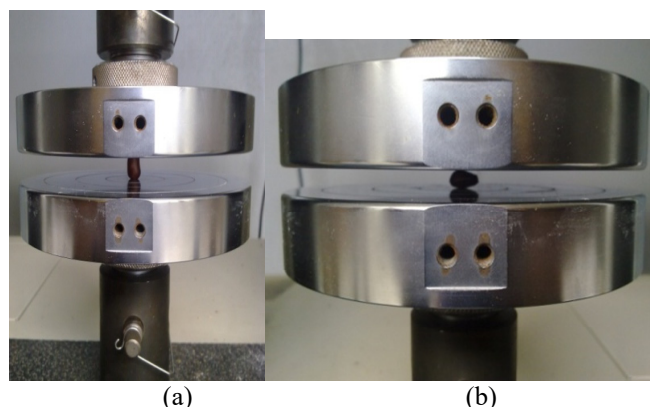


Plate 2. Compression of *M. tenuifolia* seeds on Instron Universal Testing Machine during vertical loading (a) and horizontal loading (b)

3. RESULTS AND DISCUSSION

3.1. Size and shape indices

Table 1 presents the properties of *M. tenuifolia* seeds and kernel at 10.75 and 8.10% respectively. The results show that the major, intermediate and minor axes measurements were 14.57, 9.93 and 7.43 mm for the seeds and 11.95, 7.48 and 6.34 mm for the kernels respectively. These values are slightly lower than 16.68, 11.52, 9.98 mm reported for Calabash nutmeg (*Monodora myristica*) (Omobuwajo *et al.*, 2003; Burubai *et al.*, 2007). Compared with cashew, almond, pistachio and filbert nuts for which length, width and thickness were 32.24, 23.23 and 17.02 mm (Oloso and Clarke, 1993); 25.49, 17.03 and 13.12 mm (Aydin, 2003); 16.86, 12.1 and 11.81 (Kashaninejad *et al.*, 2004) and 25.32, 20.54 and 17.93 mm (Pliestic *et al.*, 2006) respectively, *M. tenuifolia* seed is smaller in size.

Table 1. Physical properties of *M. tenuifolia* seeds and kernels

Parameters	Seeds at 10.75% (w.b)	Kernels at 8.10% (w.b)
Major axis, mm	14.57(1.10)*	11.94(1.25)
Intermediate axis, mm	9.93(0.86)	7.48(0.64)
Minor axis, mm	7.43(1)	6.34(0.55)
Aspect ratio	0.68(0.1)	0.63(0.09)
Arithmetic mean dia., mm	10.64(0.48)	8.59(0.50)
Geometric mean dia., mm	10.21(0.50)	8.25(0.46)
Sphericity	0.70(0.06)	0.70(0.06)
Weight, g	0.43(0.07)	0.29(0.04)
Unit volume, mm ³	560.60(85.46)	296.79(44.66)
Bulk density, g/cm ³	0.52(0.87)	0.57(0.00)
True density, g/cm ³	0.82(0.06)	0.94(0.04)
Terminal velocity, m/s	10.6(0.10)	10.33(0.09)

*Numbers in parenthesis are standard deviation

However, it is bigger in size than sweet corn, moringa, and bambara groundnut for which length, width and thickness were 10.47, 8.33 and 3.83 mm (Coskuner and Karababa, 2007), 10.96, 10.83, 10.24 mm (Ogunsina, 2014) and 10.5, 9.48 and 8.50 mm (Baryeh, 2001) respectively. The ratios of the axial dimensions and weight of the seed to that of the kernel are presented in Table 2; however, the following general expression can be used to describe the relationships.

$$L = 1.48W = 1.99T = 34.50M \quad (8)$$

$$l = 1.61w = 1.90t = 41.98m \quad (9)$$

$$L = 1.23l; W = 1.34w; T = 1.18t \text{ and } M = 1.53m \quad (10)$$

$$M = 0.0092 MC + 0.3303 (R^2 = 0.99) \quad (11)$$

$$m = 0.0068 mc + 0.2233 (R^2 = 0.92) \quad (12)$$

$$V = -1.6596 MC^2 + 55.508 MC + 152.83 (R^2 = 0.97) \quad (13)$$

$$v = -0.0048 mc^2 + 1.7295 mc + 277.07 (R^2 = 0.96) \quad (14)$$

where, L = major axis, W = intermediate axis, T = minor axis and M = weight of the seeds; l = major axis, w = intermediate axis, t = minor axis and m = weight of kernel.

Table 2. Ratios of *Monodora tenuifolia* nuts and kernels dimensions

*Parameters	Moisture content (wet basis)			
	10.75 %	12.04 %	14.18 %	16.23 %
L/W	1.48(0.19)*	1.46(0.17)	1.48(0.14)	1.45(0.21)
L/T	1.99(0.29)	1.96(0.23)	2.03(0.24)	1.88(0.32)
L/M	34.50(4.99)	34.09(6.54)	33.03(2.40)	30.75(4.13)
l/w	1.61(0.23)	1.57(0.18)	1.53(0.18)	1.58(0.20)
l/t	1.90(0.26)	1.83(0.27)	1.77(0.25)	1.84(0.23)
l/m	41.98(4.51)	39.81(23.05)	37.15(5.33)	36.83(5.7)
L/l	1.24(0.19)	1.26(0.12)	1.33(0.95)	1.25(0.14)
W/w	1.34(0.17)	1.36(0.15)	1.35(0.99)	1.36(0.15)
T/t	1.18(0.2)	1.18(0.2)	1.16(0.58)	1.23(0.15)
M/m	1.53(0.33)	1.50(0.79)	1.51(0.83)	1.51(0.30)

*L, W, T, M and l, w, t, m represent the major, intermediate minor diameters and weight of the nut and kernel respectively.

*Values are mean of hundred replicates (standard deviation)

Table 3 presents a summary of the properties of *M. tenuifolia* seeds as affected by moisture content. The results show that only terminal velocity and rupture force indicated major significant differences (p<0.05) as they showed a linear increase with moisture content. In Fig. 1, it is shown that seed and kernel weight increased as moisture content increases. The linear regression equations 11 and 12 describe these relationships. Similarly, it was found that the unit volume of *M. tenuifolia* seed and kernel increased as moisture content increases (Fig. 2); these relationships are best described as polynomial equations 13 and 14.

where, M = 100 seeds weight, MC = Moisture content of seed, m = 100 kernels weight, mc = moisture content of kernel, V = unit volume of seed and v = unit volume of kernel.

3.2. Density characteristics

The true density (ρ_t) of *M. tenuifolia* seed at the different moisture levels increased from 0.82 to 0.85 g/cm³ while bulk density (ρ_b) decreased from 0.52 to 0.49 g/cm³ as moisture content increases (Fig. 3). The values indicated are similar to that of almond and flaxseed (Aydin, 2003; Coşkuner and Karababa, 2007), but higher than that of safflower and sponge gourd which are miniature seeds (Bau'mler *et al.*, 2006; Ogunsina *et al.*, 2010) and lower than that of moringa (Aviara *et al.*, 2013). The decrease in bulk density as moisture content increases indicates that volumetric expansion in the sample is greater than weight. The increase in true density as moisture content increases shows that weight gain in the sample is greater than the corresponding volumetric increase. The polynomial equations 15 and 16 describe these relationships well.

$$\rho_b = 0.0022 MC^2 - 0.607 MC + 0.9172 (R^2 = 0.97) \quad (15)$$

$$\rho_t = -0.002 MC^2 + 0.0589 MC + 0.4188 (R^2 = 0.93) \quad (16)$$

Table 3. Physical and mechanical properties of *M. tenuifolia* seeds at different moisture contents

Property	Mean Value (standard deviation)			
Moisture Content (w.b.%)	10.75	12.04	14.18	16.23
Major axis, mm	14.57 (1.10) ^b	14.61(1.22) ^b	15.15 (1.21) ^a	14.65 (1.87) ^b
Intermediate axis, mm	9.93 (0.86) ^b	10.07(0.73) ^b	10.26 (0.68) ^a	10.17 (1.31) ^a
Minor axis, mm	7.43 (1.0) ^b	7.48 (0.58) ^b	7.52 (0.56) ^b	7.90 (1.12) ^a
Arithmetic mean dia., mm	10.64 (0.48)	10.72 (0.45)	10.97 (0.49)	10.91 (1.21)
Geometric mean dia., mm	10.21 (0.50)	10.30 (0.39)	10.51 (0.41)	10.53 (1.16)
Sphericity	0.70 (0.06)	0.71 (0.05)	0.70 (0.04)	0.72 (0.09)
Weight, g	0.43 (0.07)	0.44 (0.08)	0.46 (0.06)	0.48 (0.08)
Unit volume, mm ³	560.60 ^b (85.46) ^b	574.63 (64.84) ^d	610.82 (72.30) ^c	615.12 (105.86) ^a
Bulk density, g/cm ³	0.52 (0.87)	0.49 (0.01)	0.50 (0.03)	0.50 (0.00)
True density, g/cm ³	0.82(0.06)	0.83 (0.03)	0.85 (0.03)	0.84 (0.00)
Coefficient of static Friction				
Mild steel	0.42 (0.04)	0.38 (0.05)	0.37 (0.01)	0.37 (0.02)
Stainless steel	0.40 (0.06)	0.38 (0.05)	0.37 (0.01)	0.37 (0.04)
Glass	0.32 (0.04)	0.35 (0.04)	0.34 (0.02)	0.32 (0.02)
Wood	0.43 (0.03)	0.35 (0.03)	0.34 (0.01)	0.33 (0.01)
Angle of repose (°)	26.65 (1.3) ^b	31.37 (3.70) ^a	30.52 (2.45) ^a	31.42 (1.13) ^a
Terminal velocity, m/s	10.6 (0.10) ^c	10.87 (0.15) ^c	11.83(0.35) ^b	12.87 (0.31) ^a
Rupture force, N				
Vertical	47.36(15.92) ^c	56.25(28.63) ^b	42.71(16.61) ^d	68.41(19.23) ^a
Horizontal	326.80(31.01) ^d	403.79(27.62) ^c	436.68(66.57) ^b	468.74(83.67) ^a
Deformation at rupture, mm				
Vertical	1.45(0.66)	(0.93)	1. (0.22)	1.64(0.36)
Horizontal	2.29 (0.31)	2.28 (0.08)	2.71(0.28)	1.69(0.44)

^{a,b,c,d}Means with different letters on the same row are significantly different

The porosity of *M. tenuifolia* seeds increased from 0.36 to 0.42 % as moisture content increases from 10.75 – 14.18 % w.b and decreased to 0.40 % as moisture content approaches 16.23% (Fig. 4). Similar trend have been reported for other oil seeds including *Moringa oleifera* (Aviara *et al.*, 2013) and *Monodora myristica* (Burubai *et al.* 2007). This trend is however lower than that of safflower (Bau'mler *et al.* 2006).

The experimental data showed a nonlinear trend with moisture content and can be expressed as:

$$\varepsilon = -0.0052 MC^2 + 0.1468 MC - 0.6187 (R^2 = 0.99) \quad (17)$$

3.3. Coefficient of static friction

Fig. 5 shows the plots of static coefficient of friction (μ) obtained experimentally on four structural surfaces against moisture content for the seed. The coefficient of friction decreased with moisture content and varies with structural surfaces. For glass, the relationship is linear. Wood has the highest coefficient of friction; followed by mild steel, stainless steel and then glass. The variation of coefficient of friction over the structural surfaces with moisture content may be described by the following polynomial equations

$$\mu_1 = 0.0054 MC^2 - 0.101 MC + 1.1043 (R^2 = 0.94) \quad (18)$$

$$\mu_2 = 0.0018 MC^2 - 0.0548 MC + 0.7753 (R^2 = 0.98) \quad (19)$$

$$\mu_3 = 0.4377 - 0.0068 MC (R^2 = 0.92) \quad (20)$$

$$\mu_4 = 0.0059 MC^2 - 0.1747 MC + 1.6183 (R^2 = 0.91) \quad (21)$$

where, subscripts 1, 2, 3 and 4 represents mild steel, stainless steel, glass and wood respectively.

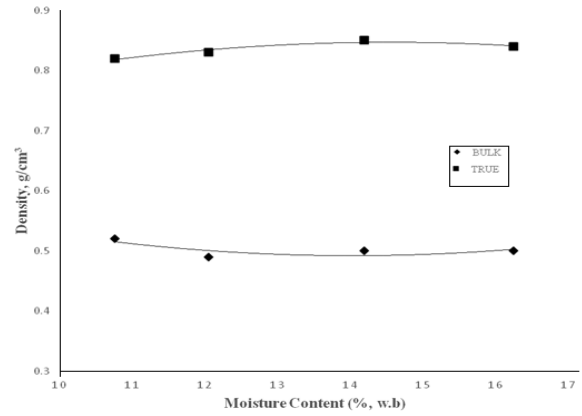


Fig. 3. Effect of moisture content on the true and bulk density of *M. tenuifolia* seeds

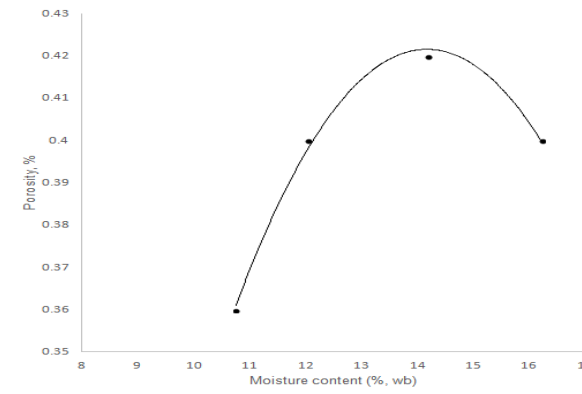


Fig. 4. Effect of moisture content on the porosity of *M. tenuifolia* seeds

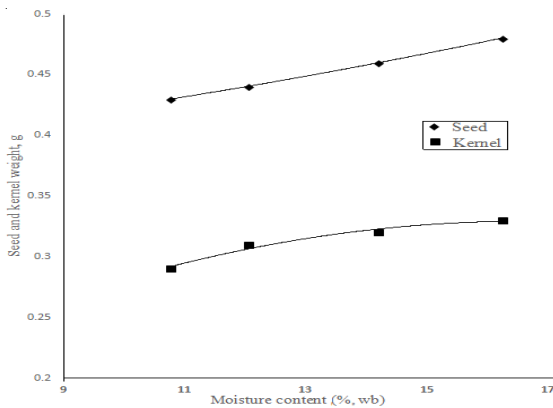


Fig. 1. Effect of moisture content on the weight of *M. tenuifolia* seed and kernel

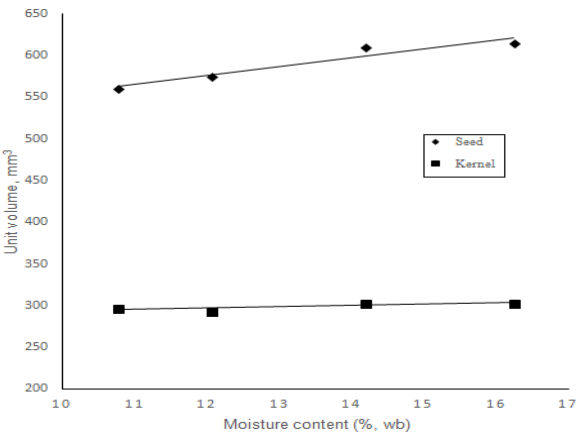


Fig. 2. Effect of moisture content on the unit volume of *M. tenuifolia* seed and kernel

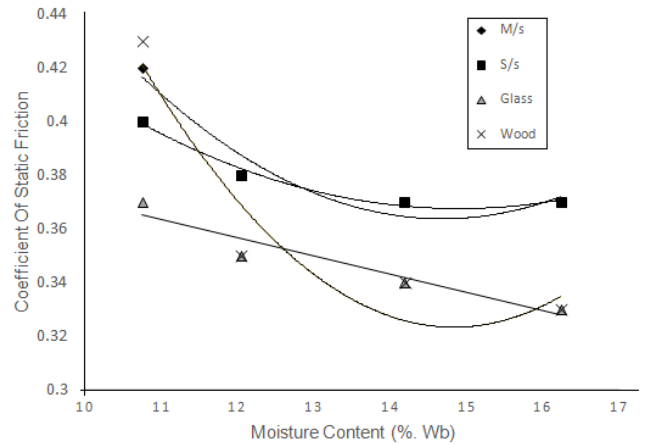


Fig. 5. Static coefficient of friction of *M. tenuifolia* seeds at different moisture contents on different structural surfaces

3.4. Angle of repose

The angle of repose *M. tenuifolia* seed plotted against moisture content is shown in Fig. 6. It could be observed that the angle of repose of the seed increases as a polynomial function of moisture content (equation 22). Such polynomial relationship between angle of repose and moisture content has been reported for many other seeds including calabash nutmeg and moringa (Aviara *et al.*, 2013).

$$\text{Angle of repose, } \Theta = -0.2916 MC^2 + 8.5293 MC - 30.604 (R^2 = 0.89) \quad (22)$$

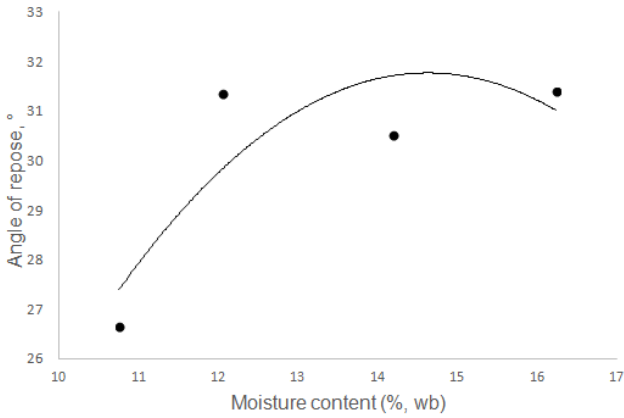


Fig. 6. Effect of moisture content on the angle of repose of *M. tenuifolia* seeds

3.5. Terminal velocity

The terminal velocity of *M. tenuifolia* seed, kernel and hull at various moisture levels are plotted in Fig.7. The trend shows that as moisture content increased, the terminal velocity increases as a linear function of the seed, kernel and hull according to the following equations:

$$V_s = 0.4237 MC + 5.907 \quad (R^2 = 0.99) \quad (23)$$

$$V_k = 0.1452 MC + 8.8183 \quad (R^2 = 0.95) \quad (24)$$

$$V_h = 0.2188 MC + 1.6898 \quad (R^2 = 0.97) \quad (25)$$

where, V_s , V_k and V_h stand for terminal velocities of seed, kernel and hull respectively.

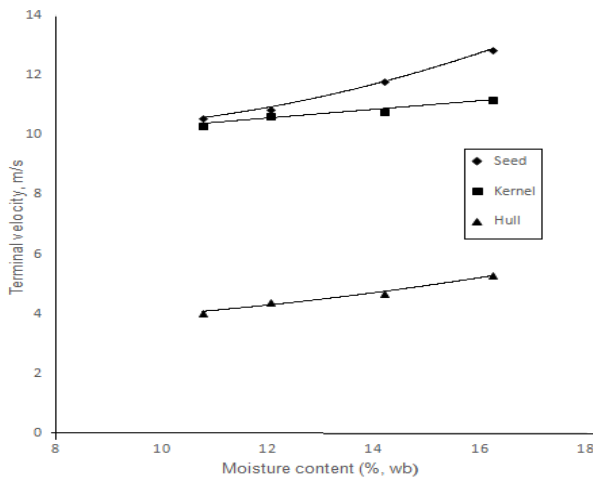


Fig. 7. Effect of moisture content on the terminal velocity of *M. tenuifolia* seeds, kernels and hull

3.6. Specific heat

Changes in the specific heat of *M. tenuifolia* seed and kernel in relation to moisture content at different temperature are presented in Fig. 8. The results show that specific heat increased in the range of 10.75 – 14.10% (w.b) and decreased as moisture content increases towards 16.23% (w.b) for seeds at 40, 60, and 80 °C. For the kernels, at 40, 60 and 80 °C, it was observed that specific heat increased as moisture content increases. The relationships emanating thereof may be described by the following polynomial equations:

$$C_{40^\circ C} = -0.4511 MC^2 + 12.2 MC - 66.742 \quad (R^2 = 0.91) \quad (26)$$

$$C_{60^\circ C} = -0.0977 MC^2 + 2.544 MC - 10.716 \quad (R^2 = 0.85) \quad (27)$$

$$C_{80^\circ C} = -0.0681 MC^2 + 1.9444 MC - 9.5916 \quad (R^2 = 0.86) \quad (28)$$

$$c_{40^\circ C} = -0.4856 mc^2 + 13.829 mc - 82.019 \quad (R^2 = 1.0) \quad (29)$$

$$c_{60^\circ C} = 0.0329 mc^2 - 0.7506 mc + 9.1482 \quad (R^2 = 0.97) \quad (30)$$

$$c_{80^\circ C} = 0.0477 mc^2 - 1.1796 mc + 10.95 \quad (R^2 = 0.96) \quad (31)$$

where, C = specific heat of seed (J/gK), c = specific heat of kernel (J/gK)

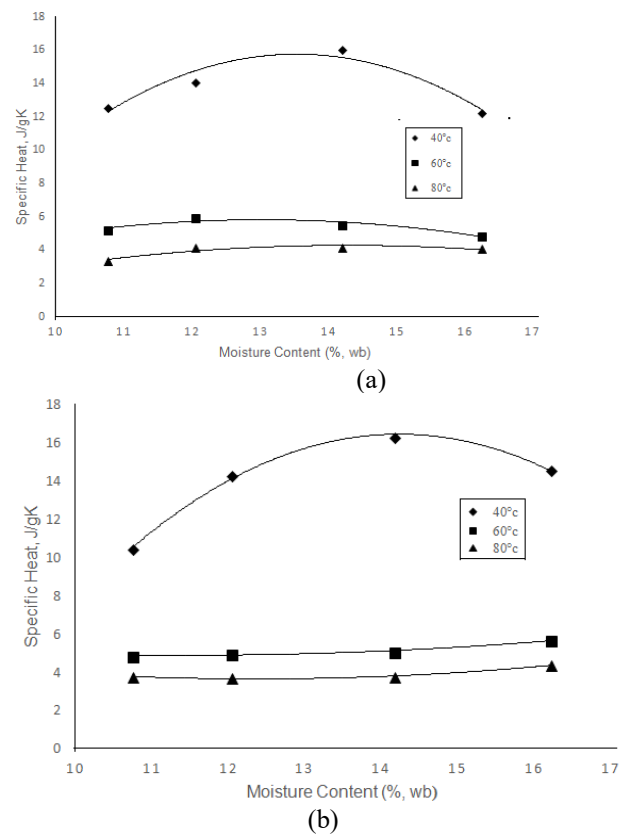


Fig. 8. Variation of specific heat with moisture content at various temperatures (a) Seed (b) kernel

3.7. Strength characteristics

Figs. 9a and 9b describe the relationship between rupture force/energy and moisture content during compression tests when the seed was loaded between two parallel plates at a constant loading rate along the vertical and horizontal axes. The general trend is a decrease in rupture force and an increase in rupture energy as moisture content increases during vertical loading (Fig. 9a); whereas, rupture force and energy increased as moisture content increases during horizontal loading (Fig. 9b).

This implies that more energy was required to achieve seed-hull rupture during compression along the horizontal axis than vertical axis. Some seeds and nuts-in-shell (eg *dika* and cashew



nuts) with fibrous hull and nuts-in-shell usually undergo prolonged elastic deformation when moisture content is high because the ligno-cellulose material that the shell/hull of most seeds and nuts are composed of becomes more fracture resistant as moisture content increases. Similar findings have earlier been documented by Ogunsina and Bamgboye (2013) and Ogunsina *et al.* (2008) for cashew and dika nuts. However, at low moisture content, the shell behaves as a brittle material, requiring minimal energy input for fracture. On the other side, there are some seeds like almond, apricot; macadamia, and shea nuts which require greater force to rupture when moisture content is low but as moisture content increases, the shell gets soft and weak and the force required for rupture reduces (Aktas *et al.*, 2007; Gezer, 2002; Olaniyan and Oje, 2002 and Braga *et al.*, 1997).

loading orientation, respectively. The results show that rupture force and energy along any of the two axes is affected by moisture content in the range considered in this investigation.

Further, in Table 2, it is shown that deformation along the two loading orientations is affected by moisture content within the range considered in this investigation. Deformation values ranged from 1.0 to 1.64 mm and 1.69 to 2.71 mm for vertical and horizontal loading orientations, respectively. Due to increased resistance to fracture, deformation was higher during horizontal loading at all moisture contents than during vertical loading. As deformation progresses to the bio-yield point the material fails and splits into two bilaterally symmetrical parts setting the embedded kernel free. The relationship between moisture content and rupture force of *M. tenuifolia* seed along the horizontal and vertical axes may be expressed by the polynomial equations 31 and 32. In addition, the relationship between moisture content and energy at rupture is given by equations 33 and 34.

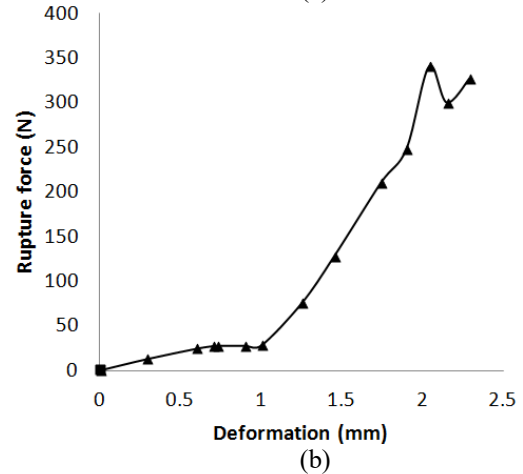
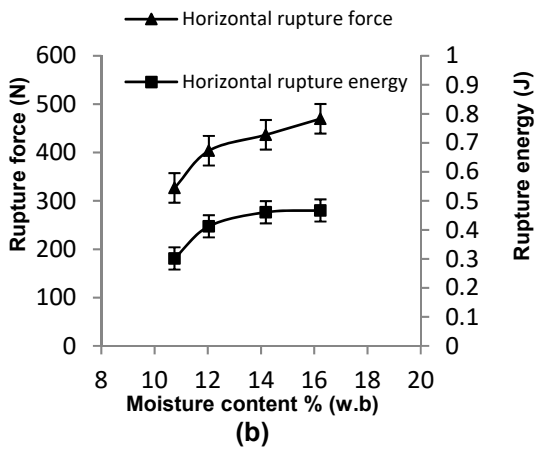
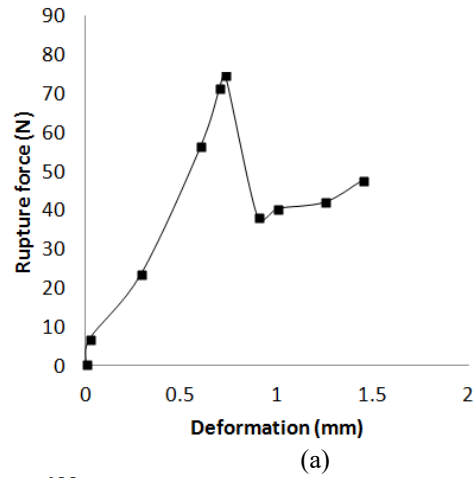
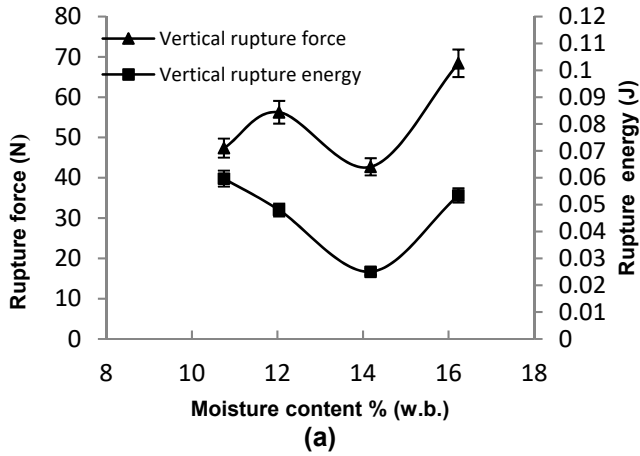


Fig. 9. Effect of moisture content on rupture force and energy absorbed during compressive loading along (a) vertical and (b) horizontal axis

Fig. 10. Force–deformation curves of (*Monodora tenuifolia*) seed during a) Compressive loading along the vertical axis; b) horizontal axis

In this study, statistical analysis indicated that the rupture force along the vertical axis differs significantly from that along the horizontal axis. During vertical loading, rupture force rose initially, then decreased to a minimum value at a moisture content of 14.18% and afterwards increased as moisture content increased from 14.18 to 16.23%. Absorption of water by the shell may have caused the encased kernel to swell until it filled the space between it and the shell; thereby, becoming turgid and requiring higher force to rupture. Similar behaviour were reported for hazelnut (Aydin, 2002), walnut (Koyuncu *et al.*, 2004) and sunflower (Jafari *et al.*, 2011). In Fig. 9b, compression along the horizontal axis, caused an increase in rupture force and energy as moisture content increased from 10.75 - 16.23% (w.b). The rupture force values ranged from 42.36 to 68.41 N and 326.80 to 469.74 N for vertical and horizontal

$$R_H = -4.4605 MC^2 + 144.49 MC - 703.95 \quad (R^2 = 0.96) \quad (31)$$

$$R_V = 1.5413 MC^2 - 38.988 MC - 292.76 \quad (R^2 = 0.90) \quad (32)$$

$$E_H = -0.0096 MC^2 + 0.2862 MC - 1.6623 \quad (R^2 = 0.98) \quad (33)$$

$$E_V = 0.0036 MC^2 - 0.0996 MC + 0.7162 \quad (R^2 = 0.86) \quad (34)$$

where, R_H and R_V are the rupture force along the horizontal and vertical axes respectively; E_H and E_V are the energy at rupture along the horizontal and vertical axes respectively during compression tests of *M. tenuifolia* seeds.

4. CONCLUSION

From this study it was found that the dimensions of the seed and kernel increases with moisture content. One hundred seed and kernel weights, unit volume, true density, porosity, angle of repose, seed terminal velocity, kernel and hull weight of *M. tenuifolia* increased as moisture content increases. The bulk density of the seed decreased as moisture content decreases. The coefficient of static friction decreased as a polynomial function over the four surfaces with corresponding increase in moisture content with the exception of glass in which the relationship was linear. The specific heat of the seed and kernel increased as a polynomial function of moisture content at the observed temperatures. The average force required to crack the seed were found to increase to 68.40 N and 469.74 N for vertical and horizontal loading orientations respectively within the range of adjusted moisture. The average energy at rupture for the seeds was found to decrease in the vertical to 0.053 J and increased in the horizontal to 0.47 J as moisture content increased. The deformation of the seeds were found to increase to 1.64 mm in the vertical and decreased to 1.69 mm in the horizontal loading position within the varied moisture levels. These properties of *M. tenuifolia* seed will lead equipment design or adaptation of existing mechanisms for its processing.

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