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Research Article

Mechanical Behaviour of Unshelled *Moringa oleifera* Seeds at Varying Moisture Contents

Samson NDUKWE[a*] **Nnaemeka NWAKUBA**[b] **Nkechi NGWANGWA**[b]

[*a] *Department of Agricultural and Bioenvironmental Engineering, Federal Polytechnic, Nekede, NIGERIA*

[b] *Department of Agricultural and Bioresources Engineering, Federal University of Technology, Owerri, NIGERIA*

(*): Corresponding author, *samsonndukwe31@gmail.com*

ABSTRACT

The determination of mechanical properties of unshelled Moringa oleifera seeds was studied under compression test at varying orientations and moisture contents for postharvest equipment design. A completely randomized block design (CRBD) was applied in designing the experiment. The impact of varying moisture content levels of (10.25, 17.33, 24.47, and 32.34% dry basis) on the applied force at bio-yield and rupture, deformation, energy at rupture, crushing strength, and elastic modulus of the seed samples were investigated. Polynomial functions of the 2nd order with coefficients of correlation ranging between $0.642 \leq R^2 \leq 0.999$ gave the best fit and described the resulting relationships between the studied properties with respect to moisture levels at the two loading axes. Results obtained showed that the seed samples had maximum values of 80.3 N, 110 N and 257.2 J, for bio-yield force, rupture and rupture energy respectively at (10.25% d.b., in the horizontal orientation; whereas minimum values of 31.5 N, 54.9 N and 51.3 J for bio-yield force, rupture force and rupture energy occurred at (32.34% d.b.) respectively in the vertical orientation. Also, the maximum compressive strength of 5.8 N mm^{-2} in the horizontal orientation of the seed samples at 10.25% d.b. whereas the minimum compressive strength (2.5 N mm^{-2}) occurred in the vertical orientation at 10.25% d.b. moisture content. The sample exhibited less resistive strength to crushing in the horizontal position as the moisture increased; whereas in the vertical position, the cell's vertical edges provide some form of shield against external pressure which resulted in increased crushing resistance per contact area of the sample.

RESEARCH ARTICLE

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INTRODUCTION

Moringa oleifera (synonymously called *M. pterygosperma* Gaertn) is the widely cultivated species of the genus in Moringa, which is the best genus inside the family of Moringaceae. It has fourteen species (Morton, 1991) which is tremendous all through the tropics. Moringa is a fast-growing, drought-resistant, evergreen, deciduous tree with an open crown of drooping fragile branches, feathery foliage of tripinnate leaves, white plant flowers and long pods, extensively cultivated in farms and compounds (primarily as fence) mainly within the Northern part of Nigeria and many nations in the tropical and subtropical Africa like Nigeria, Ghana, Kenya, Ethiopia, Madagascar, et cetera (Anjorin, 2010; Aviara *et al.*, 2013; Ndukwe *et al.*, 2014). In Nigeria, the plant is popularly known as the "miracle tree" or "tree of life" and it is recognized by way of various names, inclusively of Drumstick tree or Horseradish plant in English, Zogale in Hausa, 'Okwe oyibo' or 'Okwulu oyibo' in Igbo, Ewe Ile in Yoruba and Gawara in Fulani. Research had shown that Moringa was found to contain many essential nutrients that are humanly edible, for instance, vitamins, minerals, amino acids, beta-carotene, antioxidant, anti-inflammatory nutrients, omega 3 and 6 fatty acids which are the raw materials for medicinal, oil, pharmaceutical, cosmetic, food and feed industries in both tropical and subtropical countries (Fahey, 2005; Hsu *et al.*, 2006; Kasolo *et al.*, 2010). The powdered seed is used as an animal feed supplement, as a crop fertilizer and as an effective water purifier and the extracts can produce powerful pesticides that keep other plants healthy. In many communities, where the only drinking water available may come from a polluted lake, the standard of water purification is important (Oloyede *et al.*, 2015). It has been observed that Nigerian Moringa farmers both in the North, South, East and Western regions make do with manual means of processing its seed (Figure 1). This brings about drudgery, low production output and poor-quality product with low income generated at the end. With this hassle in mind, no matter the monetary significance of Moringa seed, no commercial production and industrial usage of the crop takes place in Nigeria. Akani *et al.* (2000), stated that research has been concentrated best on agronomics, while work on the processing of indigenous plants seems to have been neglected. In recent times, greater attention has been given to the use of under-exploited locally available agricultural products and by-products in developing countries for food/fiber processing. Such use would assist these countries, especially African countries, which are currently facing adverse economic problems.

Figure 1. Moringa seeds.

The properties such as size, shape, volume, bulk density, true (particle) density, porosity, angle of internal friction, rupture, arithmetic and geometric diameters, surface areas, sphericity, moisture content, one thousand and unit seed weights, repose angle, deformation energy static coefficient of friction, angle of repose, bio-yield point, bio-yield strength, yield force, rupture point and rupture strength of the seed were obtained by Adejumo and Abayomi (2012); Aviara *et al.* (2013); Ndukwe *et al.* (2014); Oloyede *et al.* (2015); Olayanju *et al.* (2018); Abubakar and Benjamin (2019). These and more data from studies will aid the design and development of machines for processing the seed which will in turn boost massive scale production of the plants by farmers and thereby create jobs and revenue. To design effective machines for handling, conveying systems, separation, processing units, storage facilities, drying, aerating and extracting oil from Moringa seed, there is a need to have more research on its mechanical properties (Ajav and Fakayode, 2013). Agricultural materials do not behave in a purely elastic, plastic or viscous manner due to their structural nature. As a substitute, they possess a blended solid-like and liquid-like behavior and their stress-strain relationship is not only dependent on the magnitude of the stress but also is a function of time. Materials with this type of behaviour are said to be viscoelastic. Studies have shown that agricultural products are viscoelastic and the determination of the engineering properties of biomaterials are difficult and complicated, since the properties are affected by moisture content, temperature and the rate of loading (Nwuba *et al.*, 1994; ASAE, 2004; Ardebili, 2012; Niveditha, 2013). From the data available, it appeared that the viscoelastic behaviour of biomaterial is non-linear (ASAE, 2004; Ardebili, 2012; Niveditha, 2013). Since non-linear viscoelasticity theory has not been well defined in the literature, the linear viscoelastic technique was applied in the study to define the behavior of Moringa seed under the influence of external load.

MATERIALS AND METHODS

Two hundred unshelled Moringa seeds were used for the completely randomized block design experiments and were taken to Civil Engineering Materials Laboratory at the University of Nigeria, Nsukka (UNN), for the compression tests.

Moisture Determination of the Seed

To obtain the moisture in the whole bulk, the quantity was bound and stored in a polyethylene bag for 78 hours. Some samples were taken randomly to determine the initial moisture content of the seed by drying the samples for 24 hours in an air-ventilated oven at 103°C (ASAE, 2001; Ozarslan, 2002). In addition to the initial moisture samples, the remaining mass was split into four parts, which were reconstituted by adding a measured volume of distilled water and sealing them in separate polyethylene bags and storing them in a refrigerator at 5°C for a week to enable the moisture to distribute uniformly throughout the sample (Sacilik, 2003; Garnayak *et al.*, 2008; Aviara *et al.*, 2013). The initial moisture contents (dry basis) of the seed samples were determined by the relationship (ASAE, 2001):

$$\%\ Moisture\ Content\ (d.b) = \frac{\{M_i - M_f\}}{M_f} \times 100 \qquad (1)$$

Where, M_i = initial mass of the seeds/kernels in grams and M_f = final mass of the seeds/kernels in grams when constant mass is detected.

Also, the quantity of distilled water added to the samples, to obtain the required moisture content of study was calculated through Equation 2 below (Tabatabaeefar, 2003; Adejumo and Abayomi, 2012; Ndukwe *et al.*, 2014):

$$W_2 = W_1 \times \left\{\frac{M_2 - M_1}{100 - M_2}\right\} \tag{2}$$

Where, W_2 = the initial moisture content of sample in % dry basis, and M_2 = the desired moisture content of the sample in % dry basis.

Before starting the compression tests, the required quantity of the seed was taken out of the refrigerator and allowed to equilibrate to the room temperature for about 2 hours (Singh and Goswami, 1996; Coskun *et al.*, 2006) and after which the reconstituted samples were checked for the moisture content using the method described by ASAE (2001); Sacilik (2003); Oloyede *et al.* (2015) and values obtained were 10.25%, 17.33%, 24.47% and 32.34% (on dry basis) for the tests. The samples were kept in sealed conditions to attain an ambient environment so that there is no chance of changing moisture.

The compression tests (Figure 2a and 2b) were carried out using Hounsfield Monsanto Tensometer, with a model number of S/W L8889 of ± 0.1% accuracy having a maximum loading rate of 1350 ± 160 N s^{-1} at speed of 2.5 mm min^{-1} to determine the stress-strain graphs of the unshelled seed samples. The test parameters of Moringa seeds were in terms of average force at rupture and bio-yield, deformation at rupture, rupture energy, compressive strength, strain and elastic modulus at two loading positions (horizontal and vertical positions) with varying moisture contents (Adejumo and Abayomi, 2012) of 10.250, 17.329, 24.471, and 32.343% (on dry basis).

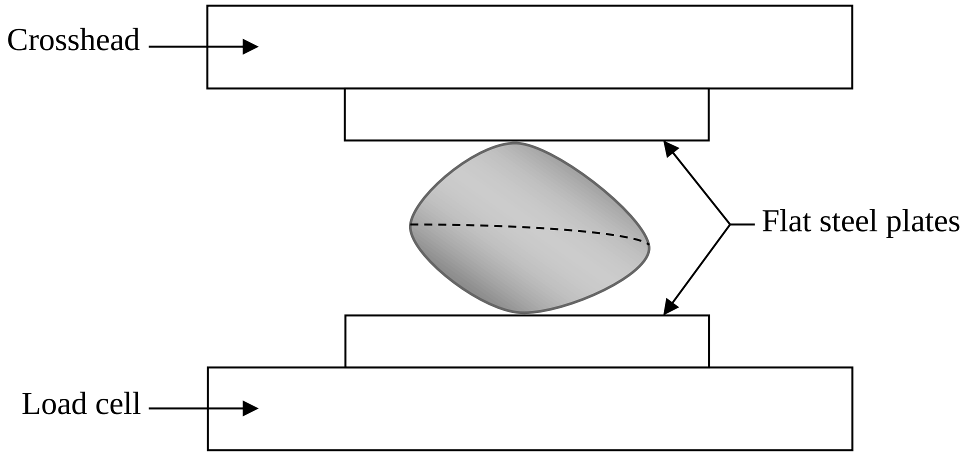

Figure 2a. Uniaxial compression of Moringa seed (Horizontal loading position).

Figure 2b. Vertical loading position.

The Moringa seed samples at the said moistures aforementioned were placed in two loading positions on the compression jaws, thereby making sure that the center of the tool was in alignment with the peak of the curvature of the Moringa seed sample. The loading arm of the tensiometer was spun at 2.5 mm min^{-1} to apply force on the seed to a point of allowable rupture and this was accompanied by the corresponding plot of the force-deformation graph, which was concurrently done by the cursor and its attached needle, which mark the graph sheet at frequent intervals thereby recording the force and the corresponding deformation. The resultant graph produced by joining the successive marks shows the stress-strain curve, which pinpoints bio-yield spot and rupture force spot at the two loading positions and varying moisture levels. The test was repeated 10 times for each parameter at each moisture level under horizontal and vertical loading positions; the results were reported in Table1., for the unshelled seed. The functional relationship existing between the mechanical properties of Moringa seeds and moisture levels was established and expressed using regression equations of the Microsoft Excel 2007 Software package. The accuracy of measurement was 0.01 Newton for force and 0.01 millimeter for deformation (Ahmadi *et al.*, 2009; Niveditha, 2013). The room temperature during the test was 28°C. Experimental data were analyzed using one-way analysis of variance and the means were separated at the 5% significance level applying DMRT (Duncan's New Multiple Range Tests in IBM SPSS software.

Determination of rupture energy of the seed energy for rupture, E_R, is the strength needed to rupture the seed, that is, the product of rupture force and deformation at rupture. Mathematically, the energy for rupture (Nwuba *et al.*, 1994) was computed as:

$$E_R = (\text{Seed deformation, mm}) \times (\text{maximum rupture force, N}) \quad (3)$$

Determination of Seed Deformation at Rupture From Machine Graph

The seed deformation was calculated from the machine graph as follows:

$$\text{Seed deformation, mm} = \frac{\text{Measured deformation, mm}}{4} \quad (4)$$

The graph has a magnification of 4:1

Determination of Seed Bio-Yield Force

From the machine graph plotted during loading, the bio-yield force is the force at a point on the stress-strain curve at which there occurs an increase in deformation with a decrease or no change of force (Nwuba *et al.*, 1994). The presence of bio-yield point is an indication of initial cell rupture in the cellular (micro) structure of the seed.

Determination of Seed Rupture Force

Rupture force is the force at a point on the stress-strain curve at which the axially loaded specimen ruptures or the seed was given complete damage (puncture of shell or skin, cracking or fracture planes) with the kernel exposed under load as obtained from the machine graph plotted (Nwuba *et al.*, 1994). The rupture point on the curve corresponds to a failure in the macrostructure of the seed.

Determination of Degree of Elasticity, $\boldsymbol{\beta}$ and Poisson's Ratio, $\boldsymbol{\mu}$, of Moringa Seed

The degree of elasticity was determined from loading and unloading tests performed for each specimen at the moisture contents of the study. The determination of Poisson's ratio of biomaterials is usually very involving. Trials with available instruments did not yield acceptable results. In the absence of adequate instrumentation, a Poisson's ratio of 0.35 was utilized for Moringa seed in uni-axial compression (ASAE, 2001). The chosen Poisson's ratio of Moringa seed falls within 0.25-0.49 which is the range of Poisson's ratio for agricultural products (Nwuba *et al.*, 1994).

Theoretical Consideration in Uni-Axial Compression of Unshelled Moringa Seed

The following equation from Hertz contact theory obtained from the American Society of Agricultural Engineers (ASAE) Standard: ASAE S368.4 (ASAE, 2004) and Niveditha (2013) was utilized in calculating the elastic modulus of Moringa seeds in uniaxial compression test.

$$E = \frac{0.531}{D^{3/2}} F(1-\mu^2)\left[\left(\frac{1}{R_1}+\frac{1}{R_1^{/}}\right)^{\frac{1}{3}} + \left(\frac{1}{R_2}+\frac{1}{R_2^{/}}\right)^{\frac{1}{3}}\right]^{3/2} \quad (5)$$

Where,

E = modulus of elasticity, N mm^{-2}; F = force, N; $\boldsymbol{\mu}$ = Poisson's ratio, dimensionless

D = deformation, mm; $R_1, R^{/}_1, R_2, R^{/}_2$ are radii of curvature.

It is assumed that for spherical Moringa seed:

$$R_2 = R_1 = R'_1 = R'_2 = \frac{d_e}{2} = \left[\frac{L(W+T)^2}{32}\right]^{1/3} \tag{6}$$

Where, d_e = Equivalent sphere diameter, mm

$$d_e = \left[\frac{L \times (W \times T)^2}{4}\right]^{\frac{1}{3}}$$ (Joshi *et al.*, 1993 and Koochaki *et al.*, 2007)

L = Length of seed, mm; W = width of seed, mm; T = Thickness of seed, mm

Based on this, the Hertz equation is reduced to:

$$\mathrm{E} = 1.502\mathrm{F}(1 - \mu^2)\left(\frac{4}{\mathrm{D}_\mathrm{e}^3 \times \mathrm{d}_\mathrm{e}}\right)^{1/2} \tag{7}$$

It is necessary to limit the deformation to the elastic zone in applying the above formula to biomaterials. Hence elastic deformation, D_e and not the total deformation, D, was used in calculating the elastic modulus of Moringa seeds. But for the application of Hertz contact theory, elastic deformation D_e, and not total deformation, D is required. Thus, the elastic deformation is calculated as:

$$D_e = \frac{\beta D}{100} \tag{8}$$

Where, β = % degree of elasticity,

Crushing strain, ε_c, is given as:

$$\varepsilon_c = \frac{D_e}{2R} = \frac{\beta D}{100(2R)} \tag{9}$$

Z is then estimated from:

$$\varepsilon_c = \frac{\left(\ln(2Z) + \frac{1}{2}\right)}{2Z^2} \tag{10}$$

Using Z, the half contact width, b, mm can be obtained.

$$Z = \frac{R}{b} \tag{11}$$

The maximum contact pressure, q_o, at the center of the contact surface is given by Hertz as the crushing strength, σ_c:

$$\sigma_c = q_0 = \frac{2F_c}{\pi l b} \tag{12}$$

Where, F_c = maximum crushing force, N; l = length of the cylindrical body in y-direction, mm.

RESULTS AND DISCUSSION

Results of the mechanical properties of unshelled Moringa seed were as shown in Table 1. The values of the mechanical properties of Moringa seed had been seen to be a feature of moisture content. The relationships existing between the parameters and moisture content at horizontal and vertical loading positions had been greatly expressed in the polynomial equations of the second order.

Table 1. Table of mean comparison using DMRT for unshelled Moringa seed in the two principal axes at different moisture contents.

Property	Seed horizontal loading orientation				Seed vertical loading orientation			
	Moisture content (percent dry basis)							
	10.250	17.329	24.471	32.343	10.250	17.329	24.471	32.343
Bio-yield force (N)	80.297d ±4.728	51.022c ±7.722	34.666a ±4.476	44.127b ±0.499	36.116f ±0.151	42.958g ±7.715	38.215f ±0.248	31.294e ±0.332
Rupture force (N)	110.037b ±0.784	59.941a ±3.564	60.016a ±4.806	60.658a ±0.614	57.245ef ±1.837	59.334f ±1.713	65.793g ±0.463	54.925e ±5.664
Deformation (mm)	2.337c ±1.045	1.662b ±0.314	0.911a ±0.103	1.220ab ±0.042	1.736g ±0.425	1.151f ±0.185	0.868e ±0.042	0.935e ±0.080
Energy for rupture (J)	257.185b ±115.020	100.101a ±22.478	54.444a ±5.305	72.802a ±3.168	99.469g ±25.144	68.128f ±9.964	57.119ef ±3.0172	51.303e ±6.287
Compressive strength (N mm^{-2})	5.838b ±1.097	2.624c ±0.127	3.735d ±0.531	3.186d ±0.070	2.492g ±0.052	2.787g ±0.658	3.415e ±0.023	3.186g ±0.070
Modulus of elasticity (N mm^{-2})	140.295b ±74.797	130.503c ±10.963	53.472a ±11.420	94.191d ±1.720	69.169e ±0.935	102.878f ±53.982	143.188f ±6.031	135.869f ±53.539

*Means in rows with the same superscript are similar to each other at $p \leq 0.05$ using Duncan's Multiple Range Test mean comparison technique.

The equations had very high coefficients of determination ($r^2 > 0.9$), which indicates that they described the relationships reasonably. These equations are of the form:

$$Y = a \pm b(MC) \pm c(MC)^2 \quad [\mathrm{R}^2 - \text{value}] \tag{13}$$

Where: Y= mechanical property; a, b, c= regression coefficients; MC= moisture content (% d.b.)

The variations of the bio-yield force of Moringa oleifera seed with moisture content under horizontal and vertical orientation are respectively presented in Fig.3. This force decreased polynomially from 80.3 N to a minimum of 35.5 N (which is at 25.94% d.b) with increasing moisture content (from 10.25- 25.94% d.b) and then increased with more moisture (above 25.94% d.b) under horizontal loading orientation. But in a vertical position, the bio-yield force increased from 36.1 N to a maximum of 40.8 N (at 19.11%, d.b) as the moisture content increased from 10.25 to 19.11% (d.b) and decreased with similarly increase in moisture (above 19.11% d.b). This behaviour indicates an increase in intra-cellular resistance to applied pressure beyond the optimum moisture level. The minimum bio-yield force of *Moringa oleifera* seed was better at the vertical loading and occurred at a lower moisture level (at 19.11%, d.b) than that obtained under horizontal loading (at 25.94%, d.b). Table 1 showed that the bio-yield force at 10.25% MC (d.b) is significantly different from with that at 17.33%, 24.47% and 32.34% MC (d.b) in the horizontal loading orientation as well as the vertical loading orientation, bio−yield force at 10.25% and 24.47% MC (d.b) were not significant at 5% level of probability but significantly different at the moisture of 17.33% and 31.29%.

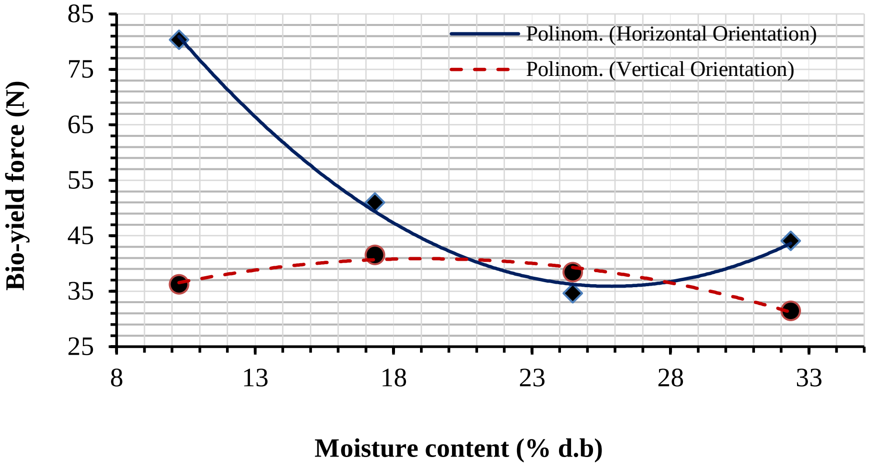

Figure 3. Effect of moisture content on bio-yield pressure of Moringa seed beneath compression test at the horizontal and vertical loading orientations.

When the moisture is above that at which the minimum values occur within the positions, the bio-yield force turned into a higher value at the vertical than on the horizontal position, but lower at moisture levels below that at which the minimum happened. The above result implies that the stress needed at the compressive cracking of unshelled Moringa oleifera seed to bring about the failure of the seed shell at the microscopic stage is moisture and loading orientation dependent. The minimal stress needed would be lower at the horizontal loading position but would require higher moisture than that, at the vertical position. The decrease in bio-yield force at the horizontal position with moisture may be due to the effect of moisture on the intercellular structure of the seed shell whereas its increase at the vertical position might be as a result of the seed shell structural arrangement of the three vertical edges running from one end of the nut to the other which constitutes reinforcement for the shell. The bio-yield force equation at varying sample moisture contents and loading orientations was described by 2nd order polynomial functions (Eqs. 14 and 15) with high R^2-values (0.994 and 0.968), which indicate that the mechanical property had a close correlation with sample moisture content.

$$Y_h = 159.3 - 9.544MC + 0.184MC^2 [\mathrm{R}^2 = 0.994] \tag{14}$$

$$Y_v = 20.76 + 2.102MC - 0.055MC^2 [\mathrm{R}^2 = 0.968] \tag{15}$$

Where: Y_h, Y_v= Bio-yield forces in the horizontal and vertical orientations (N), respectively, *MC* = moisture content (%d.b).

The varied rupture force of *Moringa oleifera* seed with moisture contents in compression under horizontal and vertical loading orientations is as shown in Fig. 4. At the horizontal orientation, the force at the rupture point dropped from 110 N to at least 52.4 N (25.79% d.b) as the moisture increased from 10.25 to 32.34% (d.b). Thereafter, it increased from 52.5 N with a similar boom in moisture level. Likewise, it surged from 57.2 N to an upmost value of 64.2 N (20.85% d.b) as moisture rose from 10.25 to 32.34% (d.b) and reduced with further growth in moisture content at the vertical loading orientation. The drop in the force at rupture with a rise in moisture become unexpected as the shell of the seed became anticipated to emerge as much less brittle as the moisture content increased.

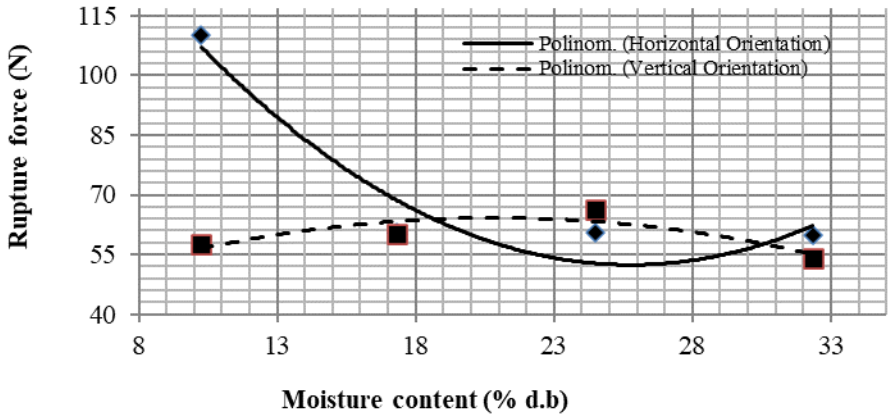

Figure 4. Effect of moisture content on force at rupture of Moringa seed underneath compression check on the horizontal and vertical loading positions.

The decrease in force at rupture of the seed at the horizontal position can be because of the moisture impact on the intercellular structure of the shell whereas the increase in rupture force at the vertical position might be as a result of the vertical bonds within the three edges running from one end of the nut to the other as seen on the shell. A similar trend was observed by Olaniyan and Oje (2002); Tavakoli *et al.* (2009); Aviara and Ajikashile (2011) for the rupture force of soybean, shea nut and conophor nut respectively concerning moisture levels. The minimum rupture force of *Moringa oleifera* seed was observed to be higher at the vertical position than at the horizontal position and this occurred at lower moisture. Moisture above that at which the minimum force at rupture occurred, rupture force was higher underneath vertical loading than on the horizontal position. The rupture force equation at varying sample moisture contents and loading orientations was described by 2nd order polynomial functions (Equations 16 and 17) with high R^2-values (0.925 and 0.751).

$$Y_h = 203.4 - 11.71MC + 0.227MC^2 \qquad [R^2 = 0.925] \tag{16}$$

$$Y_v = 34.21 + 2.877MC - 0.069MC^2 \qquad [R^2 = 0.751] \tag{17}$$

Where: Y_h, Y_v = Rupture forces in the horizontal and vertical orientations (N), respectively, MC = Moisture content (%d.b).

Subjecting the seed to compressive loading underneath horizontal and vertical position, deformation at rupture of seed with respect to moisture content is as shown in Figure 5. This depicts that the deformation at rupture of Moringa seed reduced from 2.3 mm to at the very least 1.1 mm as the moisture content elevated from 10.25 to 32.34% (d.b) and thereafter upsurge with a similar rise in moisture content under horizontal loading orientation. At the vertical loading position, it is observed that the deformation at rupture of seed reduced from 1.7 mm to a minimum of 0.9 mm as the moisture elevated from 10.25 to 32.34% (d.b) and thereafter upsurge with further rise in moisture. The deformation at rupture of seed at each moisture point was larger at the horizontal position than that on the vertical position. This means that the seed has a better capability to deform beneath compressive loading on its horizontal position than on vertical orientation. The deformation at rupture equation at varying sample moisture contents and loading orientations was also described by 2nd order polynomial functions (Eqs. 18 and 19) with high R^2-values (0.958 and 0.999).

$$Y_h = 4.598 - 0.266MC + 0.005MC^2 \quad [\mathrm{R}^2 = 0.958] \tag{18}$$

$$Y_v = 2.831 - 0.144MC + 0.002MC^2 \quad [\mathrm{R}^2 = 0.999] \tag{19}$$

Where: Y_h, Y_v = Deformation at rupture in the horizontal and vertical orientations (N), respectively, MC = moisture content (%d.b).

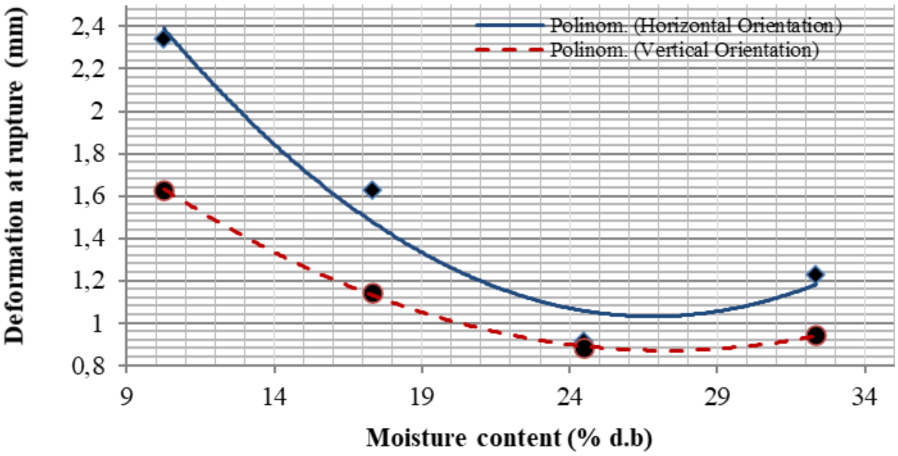

Figure 5. Influence of moisture on deformation at rupture of Moringa seed underneath compression test at the horizontal and vertical loading orientations.

The rupture energy of moringa seed with respect to moisture in a compression test underneath horizontal and vertical loading positions is shown in Fig. 6. It is observed that the work done for rupture of the seed decreased from 257.2 J to a minimum value of 54.4 J because the moisture content increase from 10.25 to 32.34% (d.b) and thereafter rose with more moisture at the horizontal loading orientation. It additionally shows that energy for rupture underneath vertical position decreased from 99.5 J to a minimal of 57.1 J as moisture increase from 10.25 to 32.34% (d.b) after which there is a surge with similar rise in moisture of the seed. Minimal work done for rupture of seed became higher at vertical loading than at horizontal loading position but dropped at higher moisture. The energy for rupture was higher at a horizontal position at moisture levels above 26% d.b than a vertical position. At a higher moisture content level, the turgidity of the sample seeds increased, which resulted in a diminutive amount of energy to completely break-up the seeds. Reduction in moisture content shrinks the intercellular shells, thus more energy required to break the shell. The energy for rupture equation at varying sample moisture contents and loading orientations was also described by 2nd order polynomial functions (Eqs. 20 and 21) with high R^2-values (0.993 and 0.990).

$$Y_h = 613.1 - 43.48MC + 0.831MC^2 \quad [\mathrm{R}^2 = 0.993] \tag{20}$$

$$Y_v = 144.6 - 5.875MC + 0.092MC^2 \quad [\mathrm{R}^2 = 0.990] \tag{21}$$

Where: Y_h, Y_v = Energy for rupture in the horizontal and vertical orientations (N), respectively, MC = Moisture content (%d.b).

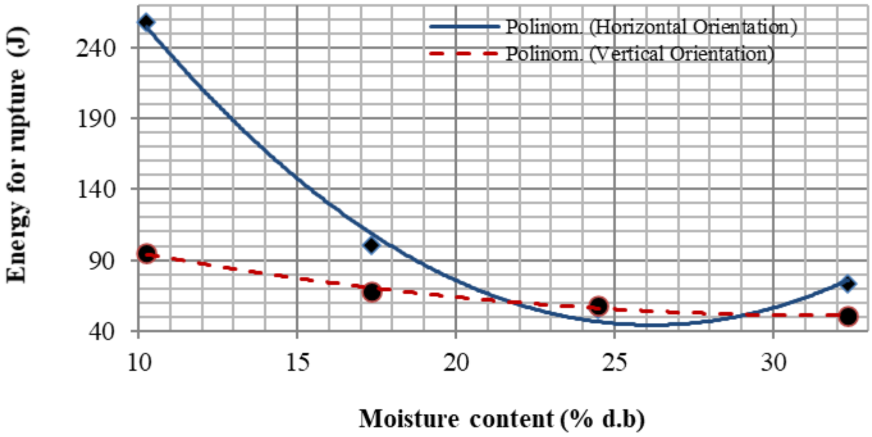

Figure 6. Influence of moisture content on rupture energy of Moringa seed beneath compression test at the horizontal and vertical loading positions.

The variation of Moringa oleifera seed compressive (crushing) strength with respect to moisture under the compression test in the horizontal and vertical positions is shown in Figure 7. The crushing strength of the seed was observed to reduce from 5.5 N mm^{-2} to a low value of 2.8 N mm^{-2} at 25.38% d.b as the moisture surged from 10.25 to 32.34% (d.b) as seen from the regression equation and thereafter increased with further moisture increment when the seed was in the horizontal position. But, in the vertical position, it increased from 2.5 N mm^{-2} to a maximum of 3.9 N mm^{-2} at 31.67% d.b and then reduced with higher moisture increment. The decreasing trend of compressive strength of the seed in the horizontal position might be due to the presence of moisture contained in the intercellular structure of the seed shell whereas its increase at the vertical position might be as a result of the seed shell structure of the three vertical edges running from one end of the nut to the other which constitutes reinforcement for the shell. The pattern exhibited less resistive strength to crushing in the horizontal position as the moisture content became higher; whereas in the vertical position, the cell's vertical edges provide some form of shield against external pressure which resulted in increased crushing resistance per contact area of the sample.

The compressive (crushing) strength equations at varying sample moisture contents and loading orientations were described by 2nd order polynomial functions (Equations. 22 and 23):

$$Y_h = 10.48 - 0.609MC + 0.012MC^2 \qquad [\mathrm{R}^2 = 0.681] \qquad (22)$$

$$Y_v = 0.871 + 0.190MC - 0.003MC^2 \qquad [\mathrm{R}^2 = 0.771] \qquad (23)$$

Where: Y_h, Y_v = Energy for rupture in the horizontal and vertical orientations (N), respectively, MC = moisture content (% d.b).

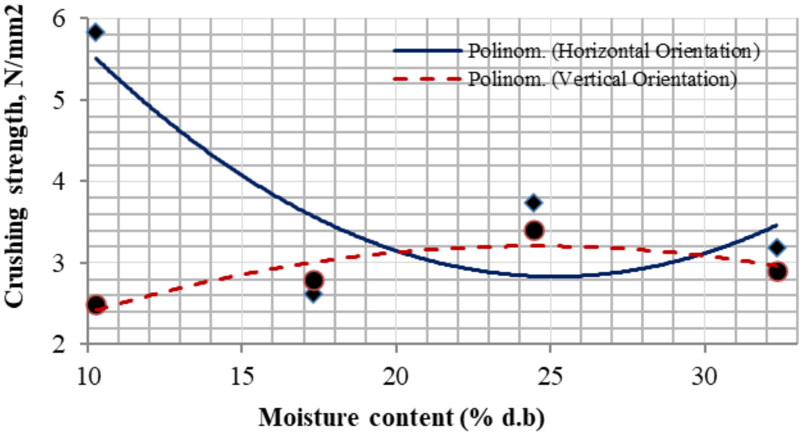

Figure 7. Impact of moisture content on crushing (compressive) energy of Moringa seed underneath compression at the horizontal and vertical loading orientations.

The elastic modulus of Moringa seed with respect to moisture beneath compressive loading at the two-loading orientations is provided in Figure 8. It shows from the graph that, the elastic modulus reduced from 125.8 N mm^{-2} to at least 78.7 N mm^{-2} at 26.96% d.b and thereafter became larger with more moisture increment under horizontal loading orientation. Additionally, for the vertical loading orientation, the elastic modulus surged from 66.38 N mm^{-2} to 140.5 N mm^{-2} (at 29.36% d.b). This depicts that the elastic modulus was larger at the vertical position than at the horizontal position and this indicates that the seed has a high affinity to go back to its natural form after compressive loading is removed from its vertical position compared to the horizontal position. The modulus of elasticity equation at varying sample moisture contents and loading orientations was described by 2nd order polynomial functions (Equations 24 and 25) with high R^2-values (0.642 and 0.959), which indicate that the mechanical property had a close correlation with sample moisture content.

$$Y_h = 264.1 - 13.75MC + 0.255MC^2 \qquad [\mathrm{R}^2 = 0.642] \qquad (24)$$

$$Y_v = -34.47 + 11.92MC - 0.203MC^2 \qquad [\mathrm{R}^2 = 0.959] \qquad (25)$$

Where: Y_h, Y_v = Energy for rupture in the horizontal and vertical positions (N), respectively, MC = Moisture content (%d.b).

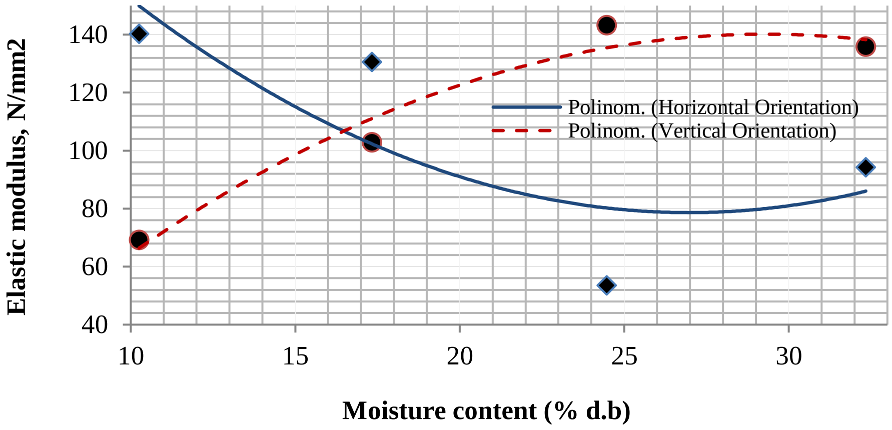

Figure 8. Effect of moisture on elastic modulus of Moringa seed underneath compression test on the horizontal and vertical loading orientations.

CONCLUSION

The subsequent conclusions were drawn from the results of the experimental study:

i. The bio-yield and rupture force of *Moringa oleifera* seed reduced with rise in moisture content to minimal values and increased with a further rise in moisture of the seed but the trend at the vertical position behaved differently. There were lower deformation and energy properties of the seed with a surge in moisture till certain values were reached before incremental changes occurred with further rise in moisture. The minimum values of these properties had been higher beneath vertical loading orientation than at horizontal loading orientation except for the deformation at rupture of the Moringa seed.

ii. The seed is easily cracked at a moisture content of approximately 25.38% d.b (at 2.8 N mm^{-2}). They did not readily crack at higher moistures above the optimum. When the moisture content was about 30% d.b, the *Moringa oleifera* seed did not crack but tended to crush when the force was applied.

iii. The elastic modulus of the seed was lower on the horizontal orientation (78.7 N mm^{-2} at 26.96% d.b) than that at the vertical loading (140.5 N mm^{-2} at 29.36% d.b). This implicates that with immediate removal of the applied compressive force; the seed gets to its original shape more at the vertical than the horizontal position. This decrease in the mechanical behaviour of the seeds with a surge in moisture suggests that energy is saved when seeds are cracked at high moisture but cracking at high moisture crushes the seeds into small pieces. For the fact that product quality is very important, it is agreed that the seeds be cracked horizontally (natural rest position) at low moisture contents so that kernels that are intact and whole could be obtained.

iv. Similarly, studies at the viscoelastic and aerodynamic residences of *Moringa oliefera* are of extraordinary importance for the ultimate layout and development of processing equipment.

DECLARATION OF COMPETING INTEREST

The author(s) have no conflict of interest.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

The authors declared that the following contributions are correct.

Samson Ndukwe: Conceptualization, writing of original draft, methodology, data collation, formal analysis, and editing.

Nnaemeka Nwakuba: Methodology, review, editing, Investigation, methodology, formal analysis.

Nkechi Ngwangwa: Data collation, visualization, data collation, validation, formal analysis and review.

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