Effect of Moisture Content and Loading Orientation on the Mechanical Properties of *Balanites Aegyptiaca* Nuts

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ABSTRACT

Lack of an appropriate equipment to crack *balanites aegyptica* nuts to obtain the kernels, which are rich in oil and proteins, have limited their use and popularity. The manual method, which involves cracking with stone on top of another stone or metal, is slow and risky. In order to design appropriate processing equipment, sufficient knowledge of the mechanical properties of the different varieties is very important. The need to get sufficient information on the mechanical properties of *balanites aegyptiaca* nuts led to the study of the effect of moisture content and loading orientation on six mechanical properties of the one end tapered oblong and spheroidal accessions of *balanites aegyptiaca* (desert date) nuts. Four moisture levels and two compressive loading orientations (axial and longitudinal) were used to test the nuts of the two accessions in a universal-testing machine. The ranges of moisture content used were 4.7–26.4% (d.b.) for the oblong accession and 4.7–24.2% (d.b.) for the spheroidal accession. The six mechanical properties investigated were modulus of elasticity, bioyield point, bioyield stress, compressive strength, rupture strength and modulus of stiffness. Results obtained show that values of all the six properties decreased with increase in moisture content. This inverse relationship between moisture content and the mechanical properties investigated could be attributed to the fact that the nut of *balanites aegyptiaca* is spongy and being a biological material, it becomes weaker and easier to fail as its moisture content increases. Linear and second-order regression equations relating the six properties and moisture content are presented. It was also found that at all the moisture levels considered, the values of all the mechanical properties studied were higher when the nuts were loaded longitudinally for compressive tests than when loaded axially. This means that bonds of the nut cells are weaker to fail, and hence easier to crack when loaded axially. These findings will be useful in the development of processing equipment for *balanites aegyptiaca* nuts.

Keywords: Mechanical properties, *balanites aegyptiaca* nuts, moisture content, loading orientation

1. INTRODUCTION

Balanites aegyptiaca also known as Desert date in English, ‘dattier du desert’ in French, ‘heglig’ in Arabic, ‘mjunju’ in Swahili, ‘tanni’ in Fulfulde, ‘adua’ in Hausa and ‘cungo’ in Kanuri (Hall and Walker, 1991) is one of the most widely distributed trees in Africa. Although found almost everywhere in the continent, very high concentrations of the tree are most prevalent in sahel and sudan savanna zones of West Africa and semi arid regions of East Africa (Shanks and Shanks, 1991). Two accessions of the tree with fruit, nut and kernel shapes that corroborate the findings of Launert (1963) are common in North Eastern Nigeria.

Every part of *balanites aegyptiaca* tree has economic importance. Its roots and bark are used for fishing, the wood as yoke for draught animals and hand implements, while humans eat the leaves and flesh of the ripe fruit because they are very rich in carbohydrates and vitamins. The most important part of the *balanites aegyptiaca* tree is the nut, also called stone (Shanks and Shanks, 1991). The nut is obtained after the removal of the flesh and pulp of the fruit and it contains a kernel with oil and protein contents ranging from 30–60% and 20–30% respectively. The oil is good for cooking as it has an acceptable scent and taste (Hall and Walker, 1991), and does not smoke excessively when heated (Shanks and Shanks, 1991). The kernel meal remaining after oil extraction can be used as livestock feed (Abu-Al-Futuh, 1983). *Balanites aegyptiaca* has been found to have high potential for industrial applications because saponins, which are used as basic raw material in the manufacture of soap, candle, chemicals and cosmetics as well as pharmaceutical products, can be extracted from any part of the tree.

Processing of *balanites aegyptiaca* fruit involves soaking it in cold water for three days or hot water for a day and washing off the pulp to obtain the nut. The nut is sun-dried for two days if cold water was used and for eight hours if hot water was used to soak the fruit. The kernel is obtained from the nut by cracking with stone on top of another stone or metal. Oil is extracted from the kernel by heating its meal in a pan over an open fire or boiling it in a pot containing water.

The most difficult and risky aspect of all the operations is the cracking of the nuts to bring out the kernel. The wide variation in shape and size of the nuts makes it difficult for one to apply uniform force in cracking. If the cracking force is too high, about 40% of the kernels get damaged. Proper understanding of the mechanical properties of *balanites aegyptica* nut is considered necessary in the design of appropriate machines for different postharvest operations such as cracking, cutting, crushing and grinding.

Several investigators have studied the mechanical properties of different agricultural and food materials. Anazodo (1982) reviewed the basic concepts and instrumentation used in studying the mechanical and rheological properties of biomaterials and noted that the universal testing machine is frequently used in compressive loading. Cenkowski *et al.* (1995) studied the effect of moisture sorption hysteresis on the mechanical behaviour of canola and showed that the modulus of elasticity of the product brought into equilibrium through adsorption was higher than that of the one obtained through desorption at the same moisture content. The other products whose mechanical properties have been studied include kiwi fruit (Abbott and Massie, 1995), eggshell (Lin *et al.*, 1995; Dhanoa *et al.*, 1996), apples (Abbott and Lu, 1996), sweet onions (Maw *et al.*, 1996), frozen meat (King, 1996) and sea buckthorn berries (Khazaei and Mann, 2004). Anazodo and Chikwendu (1983) developed equations for the calcualtion of the Poisson’s ratio and elastic modulus of circular bodies subjected to radial compression and Dinrifo and Faborode (1993) applied the Hertz’s theory of contact stresses to cocoa pod deformation.

Anazodo and Norris (1981) noted that the modulus of elasticity, crushing strength and modulus of toughness of corncob all decreased with moisture content. Misra and Young (1981) studied the effect of moisture content on the modulus of elasticity of soybeans under compression in the axial orientation and developed a model that showed the modulus of elasticity decreasing parabolically with increase in moisture content. Similar results have been reported for cowpea (Pappas *et al.*, 1988) yellow dent corn kernels (Waananen and Okos, 1988), cashew nuts (Oloso and Clarke, 1993) and wheat (Kang *et al.*, 1995).

There is no reported information on the mechanical properties of *balanites aegyptiaca* nuts and their relationship with moisture content. The objective of this study was therefore to investigate the mechanical properties of *balanites aegyptiaca* nuts that are relevant to the design of processing machines and determine their variation with moisture content and loading orientation. The mechanical properties include modulus of elasticity, bioyield point, bioyield stress, compressive strength, rupture strength and modulus of stiffness.

2. MATERIALS AND METHODS

2.1 Sample Preparation

Bulk quantities of two accessions of balanites aegyptiaca fruits were obtained from the market in Maiduguri, Borno State, Nigeria. The fruits were soaked in cold water for three days and washed several times to obtain clean nuts. The first accession has nuts that are oblong in shape with one end pointed. It is here referred to as the one end pointed oblong accession (Figure 1a). The second accession has nuts that are spheroidal in shape and is referred to as the spheroidal accession (Figure 1b). The nuts from each accession were sun-dried for two days to reduce the moisture content to a level at which they could be easily cracked to obtain the kernels. The moisture contents at which the nuts could be easily cracked were determined using the method employed by Oje (1993) and Aviara *et al.* (2000) in determining the moisture contents of thevetia nut and shea nut respectively. This involved oven drying of the nut samples at 130°C with the weight loss monitored on hourly basis to obtain the time at which weight began to remain content. Weights of the samples were found to remain constant after six hours of oven drying.

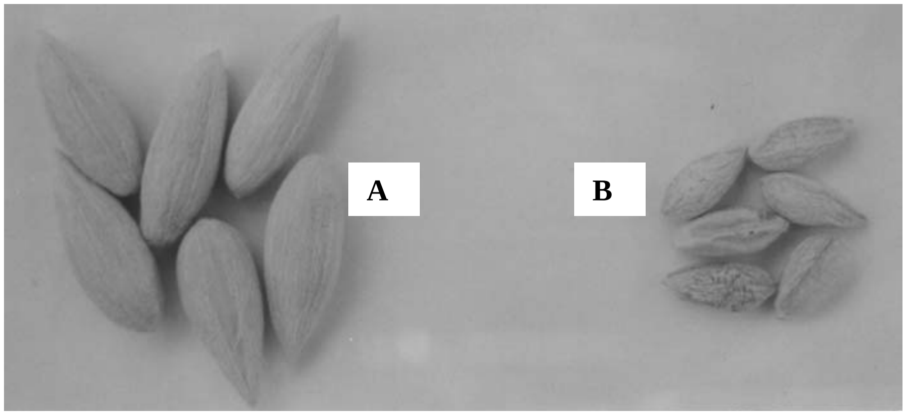

Figure 1a. Photograph of the one end tapered oblong accession of *balanites aegyptiaca* nuts and kernels, A nuts; B kernels

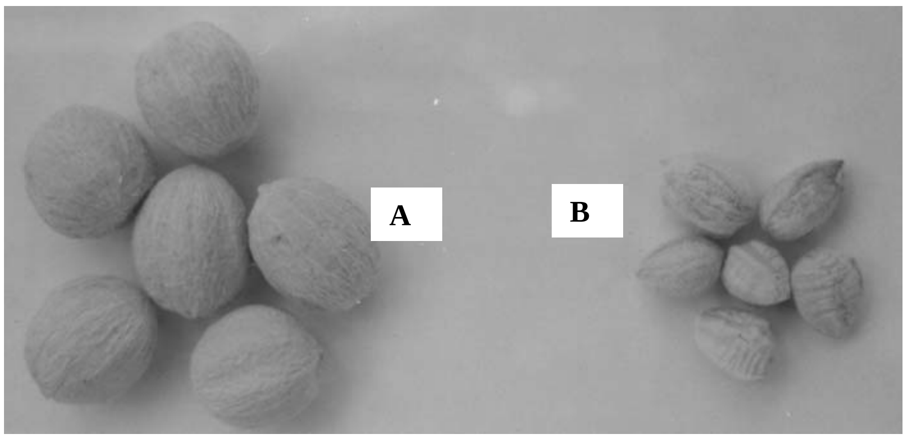

Figure 1b. Photograph of the spheroidal accession of *balanites aegyptiaca* nuts and kernels, A nuts; B kernels

The moisture content of the one end pointed oblong accession was found to be 4.7±0.58% dry basis (d.b.), while that of the spheroidal accession was 4.7±0.10% dry basis (d.b.). In order to determine the effect of moisture content on the mechanical properties of *balanites aegyptiaca* nuts, samples of the nuts at the above moisture contents were conditioned to four different moisture levels ranging from 4.7–26.4% (d.b.) for the oblong accession and 4.7–24.2% (d.b.) for the spheroidal accession. The samples were conditioned by soaking them in clean water for a period of 1–4 hours. Thereafter, the nuts were spread out in thin layer to dry in natural air for about eight hours. The samples were then sealed in marked polythene bags and stored in that condition for a further 24-hour period. This was to achieve stable and uniform moisture content of the samples. The polythene bags were transferred into a refrigerator at 0°C and when needed for experiments, the nuts were allowed to equilibrate in the ambient condition for six hours.

2.2 Experimental Procedure

Compression tests were conducted using a TESTOMETRIC Universal Testing Machine (UTM) controlled by a microcomputer. Test results, statistics and graphs were automatically generated. The machine was programmed to determine six mechanical properties of the *balanites aegyptiaca* nuts.

Two loading orientations were used for all tests. For all levels of moisture content, 25 nuts of each accession were randomly compressed axially (Figure 2a) and longitudinally (Figure 2b) by the UTM. The nuts were compressed at the rate of 25 mm/min. As the compression began and progressed, a load-deformation curve was plotted automatically in relation to the response of each nut to compression. Typical load-deformation curves obtained during the compression tests are presented in Figure 3. The load-deformation curves obtained at each loading orientation and moisture level for the two accessions were analysed for:

i. modulus of elasticity
ii. bioyield point
iii. bioyield stress
iv. compressive strength
v. rupture strength
vi. modulus of stiffness

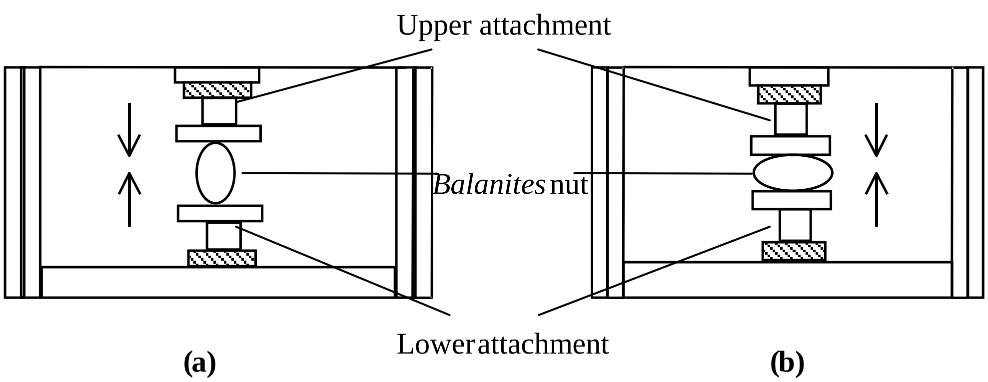

Figure 2. Compressive (a) axial and (b) longitudinal loading orientations of *balanites aegyptiaca* n nuts in the Instron Universal Testing Machine

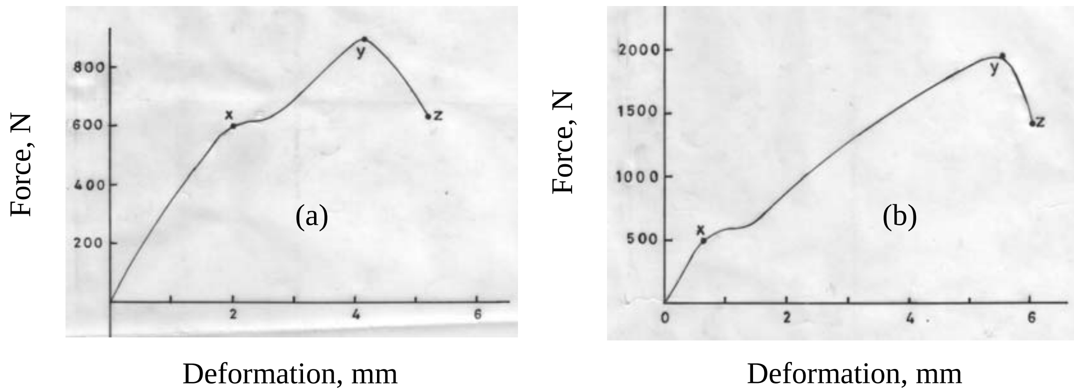

Figure 3. Typical force-deformation curves of *balanites aegyptiaca* nuts during (a) axial and (b) longitudinal compressive loading: *x* – bioyield point; *y* – failure point; *z* – rupture point

The data obtained for each property at each loading orientation was regressed against moisture content to obtain the relationship between the six mechanical properties of the nuts listed above and moisture content.

3. RESULTS AND DISCUSSION

Table 1 presents the regression equations for the plots (Figures 4-9) relating the mechanical properties of *balanites aegyptiaca* nuts to moisture content. The equations are either linear (first-order) or quadratic (second-order). Both linear and quadratic equations have very high coefficients of determination ($R^2 > 0.9$), which indicates that the plots describe the data points reasonably. The linear and quadratic equations are respectively of the form:

$$Y = a + bK \tag{1}$$
$$Y = a + bK + cK^2 \tag{2}$$

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

3.1 Modulus of Elasticity

Figure 4 shows a plot of the modulus of elasticity as a function of moisture content during axial and longitudinal compressive loading for the two accessions of *balanites aegyptiaca* nuts. For axial compressive loading, the modulus of elasticity of the two accessions decreased with increase in moisture content. The modulus of elasticity of the spheroidal accession was slightly higher than that of the oblong accession. However, the difference between values of the two accessions became much less at higher moisture levels.

Table 1. Regression equations for the plots of the mechanical properties of *balanites aegyptiaca* nuts

Property	Accession	Loading orientation	Coefficients			R^2
			a	*b*	*c*	
Modulus of elasticity, N/mm^2	Oblong	Axial	96.556	- 4.473	0.098	0.988
		Longitudinal	105.18	-2.254	-	0.978
	Spheroidal	Axial	110.32	-5.047	0.105	0.981
		Longitudinal	153.33	-8.173	-	0.992
Bioyield point, N	Oblong	Axial	2252.7	-103.09	2.006	0.995
		Longitudinal	2597.2	-67.542	1.374	0.999
	Spheroidal	Axial	1841.5	-87.538	1.608	0.999
		Longitudinal	2496.2	-71.252	1.514	0.999
Bioyield stress, N/mm^2	Oblong	Axial	15.768	-1.059	0.024	0.999
		Longitudinal	18.087	-0.74	0.017	0.998
	Spheroidal	Axial	10.804	-0.523	0.009	0.953
		Longitudinal	20.271	-0.978	0.022	0.998
Compressive strength, N/mm^2	Oblong	Axial	7.993	-0.143	-	0.974
		Longitudinal	11.206	-0.046	-	0.981
	Spheroidal	Axial	7.161	-0.138	-	0.969
		Longitudinal	15.902	-0.251	-	0.983
Rupture strength, N/mm^2	Oblong	Axial	13.388	-0.865	0.021	0.983
		Longitudinal	18.794	-0.887	0.019	0.979
	Spheroidal	Axial	8.979	-0.252	-	0.989
		Longitudinal	21.311	-1.155	0.025	1.000
Modulus of stiffness, N/mm^2	Oblong	Axial	617.43	-7.564	0.028	0.974
		Longitudinal	804.35	-11.69	0.019	0.982
	Spheroidal	Axial	1085.2	-32.915	0.343	0.939
		Longitudinal	1086.0	-23.668	0.187	0.982

For axial loading, the mean values of modulus of elasticity corresponding to the least moisture content for the oblong and spheroidal accessions were 78 and 88.3 N/mm^2, respectively, with a percentage difference of 13%.

The relationship between modulus of elasticity and moisture content during longitudinal compressive loading for the two *balanites aegyptiaca* nut accessions is also inversely proportional (Figure 4). At about 15% moisture content (d.b.), values of the modulus of elasticity of the two accessions were equal. With further increase in moisture content, the modulus of elasticity of the spheroidal accession decreased sharply while that of the oblong accession maintained a gradual decrease.

The mean values of modulus of elasticity obtained at the first moisture level for the oblong and spheroidal accessions during longitudinal compressive loading were 94.9 and 119.2 N/mm^2 respectively, with a variability of 25.6%.

Regression equations of the second-order (Table 1) described the relationship between modulus of elasticity and moisture content for the two accessions of *balanites aegyptiaca* nuts during both axial and longitudinal loadings.

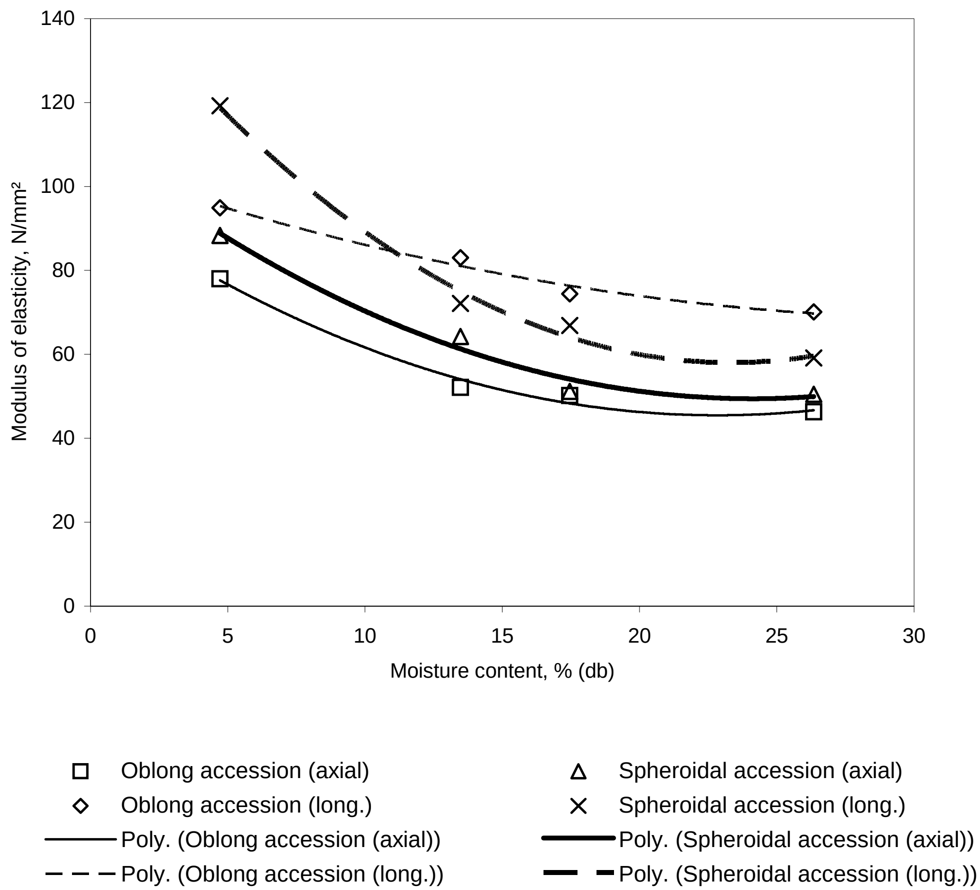

Figure 4. Effect of moisture content on modulus of elasticity of balanites aegyptiaca nuts for axial and longitudinal compressive loading

It could be observed that values of modulus of elasticity of the two accessions were higher when the nuts were loaded longitudinally than when compressed axially. This could be attributed to the fact that *balanites aegyptiaca* nuts are more difficult to crack when they are loaded longitudinally because in this orientation, the ribbed portions of the nuts act as a re-enforcement to the adjacent portions of the shell, hence making it harder to crack.

3.2 Bioyield Point

The relationships between bioyield point and moisture content for the two accessions of *balanites aegyptiaca* nuts when loaded axially and longitudinally are presented in Figure 5. For axial compressive loading, the bioyield point for the two accessions decreased with increases in moisture content.

For axial loading, the mean values of bioyield point obtained at the least moisture content for the oblong and spheroidal accessions were 1817 and 1461 N respectively. These two values gave a percentage difference of 24.4%.

The influence of moisture content on bioyield point for the tapered oblong and spheroidal accessions under longitudinal compressive loading is similar to that of the axial loading orientation (Figure 5). The curves show that bioyield point decreases proportionately with increase in moisture content and the oblong accession recorded higher values than the spheroidal accession.

Quadratic equations (Table 1) gave the best fit between bioyield point and moisture content for the tapered oblong and spheroidal accessions during axial and longitudinal loadings.

The mean values of bioyield point obtained at the first moisture content for the oblong and spheroidal accessions during longitudinal compressive loading were 2309.9 and 2194.3 N respectively, with a variability of 5.3%. Figure 5 also shows that for both the axial and longitudinal loading orientations; the oblong accession nuts had higher values of bioyield point than those of the spheroidal accession.

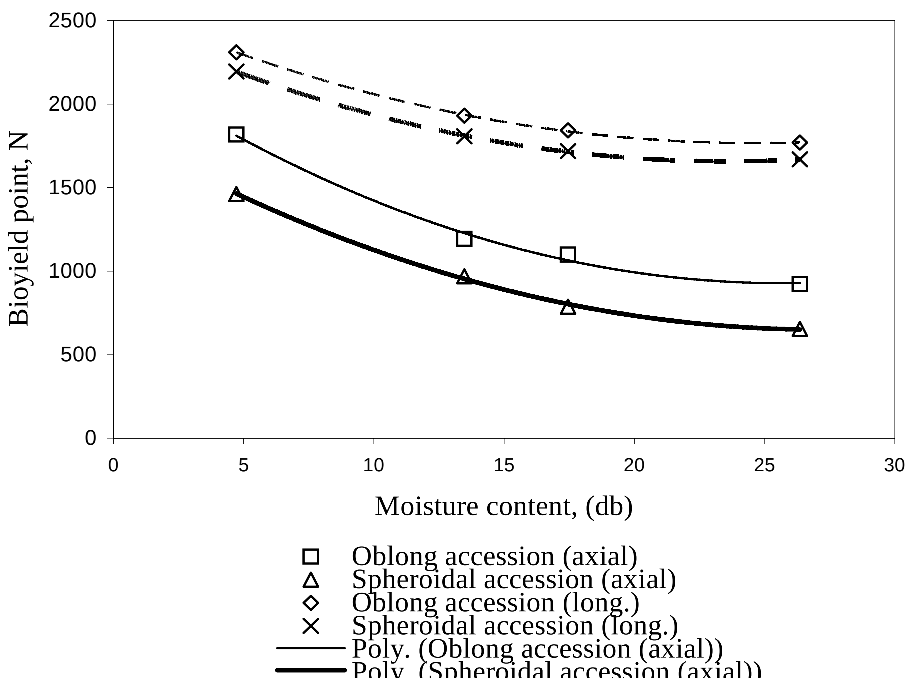

Figure 5. Effect of moisture content on bioyield point of balanites aegyptiaca nuts during axial and longitudinal compressive loading

3.3 Bioyield Stress

The effect of moisture content on the bioyield stress of the two accessions of *balanites aegyptiaca* nuts when subjected to axial and longitudinal loading is shown in Figure 6. The plots show that bioyield stress decreased with increase in moisture content. The decrease in bioyield stress with moisture content is sharper in the tapered oblong accession than the spheroidal accession.

At the first moisture level for axial loading, the oblong and spheroidal accessions had mean values of bioyield stress of 11.3 and 8.4 N/mm^2 respectively. A percentage difference of 34.5% was obtained between these two values.

Figure 6 also describes the relationship between bioyield stress and moisture content for the two accessions under longitudinal compressive loading. Bioyield stress was found to decrease with increase in moisture content. The oblong and spheroidal accessions had the same value of bioyield stress at moisture content of about 13%. Second-order polynomial regression equations (Table 1) gave the relationship between bioyield stress and moisture content for the two accessions under both axial and longitudinal loadings.

The mean values of bioyield stress at the least moisture content for oblong and spheroidal accessions during longitudinal loading were 15 and 16 N/mm^2 respectively, with a variability of 7%.

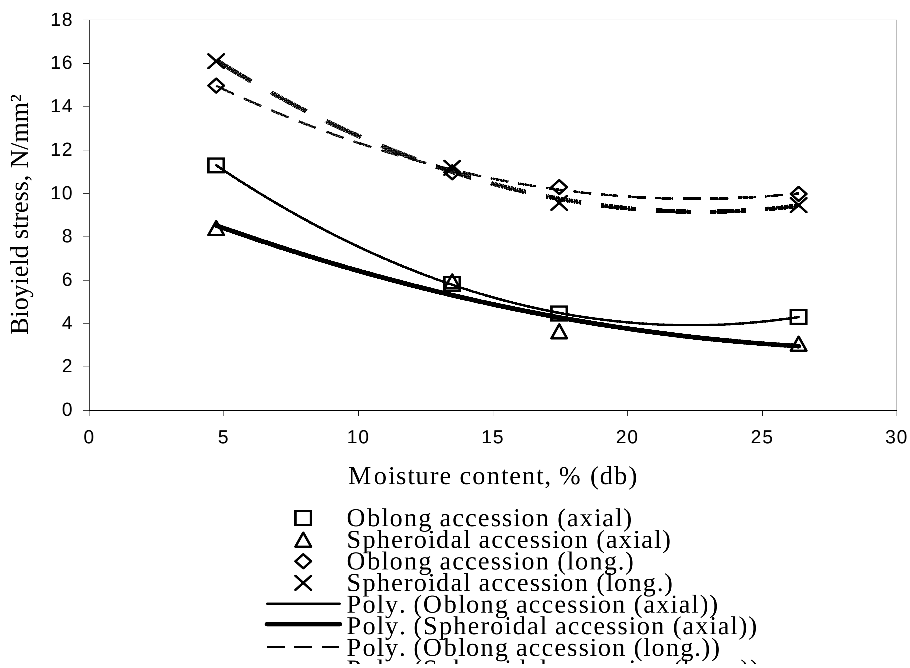

Figure 6. Variation of bioyield stress of balanites aegyptiaca nut with moisture content during axial and longitudinal compressive loading

3.4 Compressive Strength

The compressive strength of the two accessions of *balanites aegyptiaca* nuts as affected by moisture content under axial and longitudinal compressive loading is shown in Figure 7. The compressive strength for the two accessions deceased with increase in moisture content.

The mean values of compressive strength obtained at the first moisture content for the oblong and spheroidal accessions during axial compressive loading were 7.4 and 5.5 N/mm^2 respectively. The difference between these two values represents a percentage difference of 34.5%. An inverse proportional relationship was established between compressive strength and moisture content for the two accessions during longitudinal loading. The curves show that the compressive strength decreased linearly with increase in moisture content. At moisture content of about 22.5% (d.b.), the compressive strengths of the two accessions were equal. Regression equations (Table 1) relating compressive strength with moisture content were best described by equations of the first-order.

During longitudinal compressive loading the mean values of compressive strength obtained at the least moisture content for the oblong and spheroidal accessions were 11 and 13 N/mm^2 respectively, with a percentage difference of 18%.

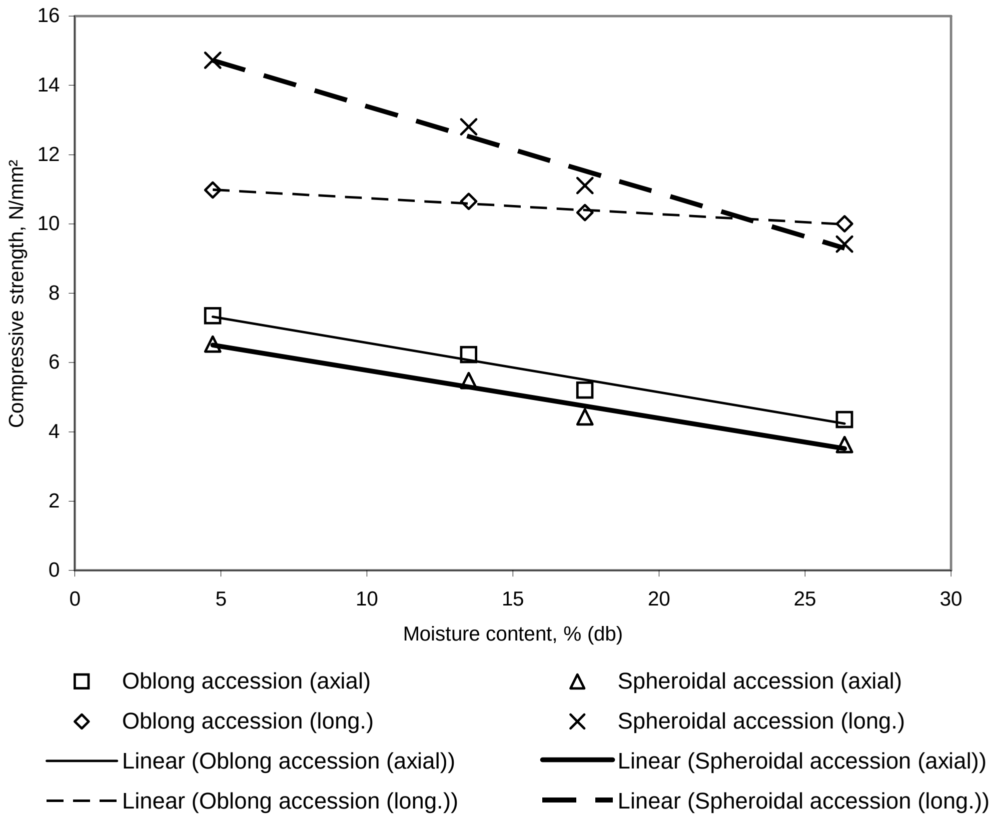

Figure 7. Variation of compressive strength of balanites aegyptiaca nuts with moisture content during axial and longitudinal compressive loading

3.5 Rupture Strength

The rupture strength of the tapered oblong and spheroidal accessions of *balanites aegyptiaca* nuts when subjected to axial longitudinal compressive loading at different moisture contents is presented in Figure 8. During axial loading, the rupture strength of each accession nuts generally decreased with increase in moisture content. For the oblong accession however, rupture strength decreased with increase in moisture content up to about 13% (d.b.) and remained constant thereafter. During axial loading, the mean values of rupture strength at the least moisture content for oblong and spheroidal accessions were 9.8 and 7.7 N/mm^2, respectively, with a variability of 27%. Figure 8 also shows the behaviour of rupture strength of the two nut accessions when loaded longitudinally at different moisture levels. Similar to axial loading, the rupture strength also decreased with increase in moisture content. Regression equations describing the plots for the tapered oblong and spheroidal accessions when subjected to both axial and longitudinal loading are given in Table 1. Quadratic equations of the second order gave the best fit between rupture strength and moisture content for the two accessions and loading orientations.

The mean values of rupture strength at the least moisture content during longitudinal loading of oblong and spheroidal nuts were 15.1 and 16.4 N/mm^2 respectively and this gave a percentage difference of 8.6%.

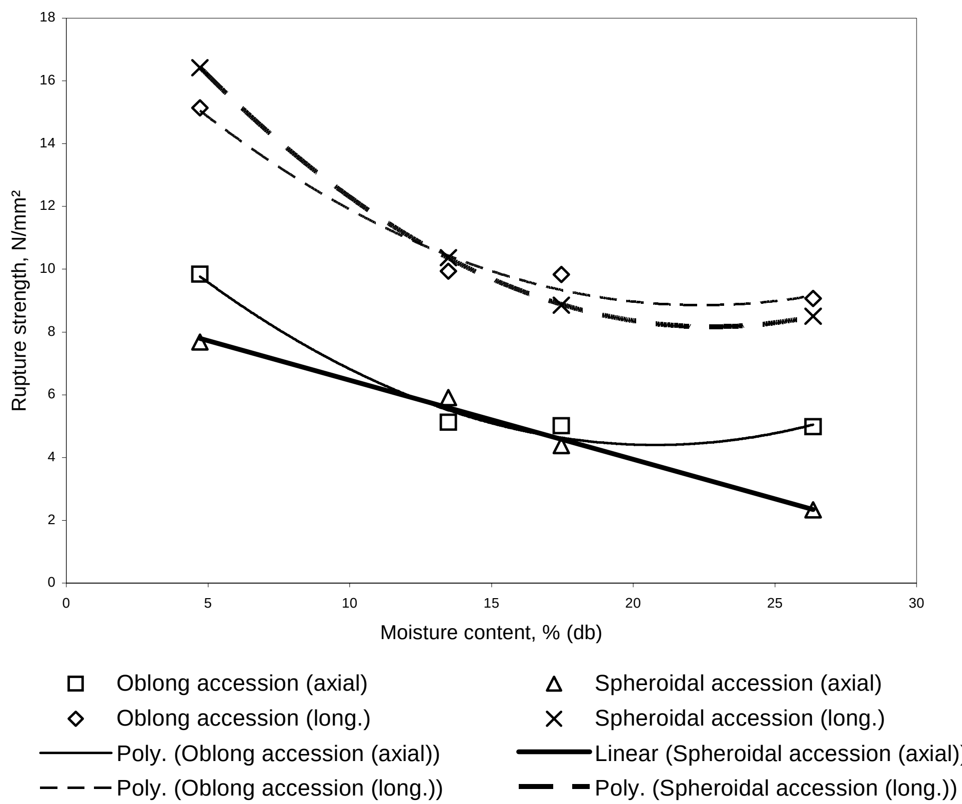

Figure 8. Variation of rupture strength of balanites aegyptiaca nuts with moisture during axial and longitudinal compressive loading

3.6 Modulus of Stiffness

Figure 9 shows the relationship between modulus of stiffness and moisture content of two accessions of *balanites aegyptiaca* nuts under axial and longitudinal compressive loading. The modulus of stiffness of both accessions decreased with increase in moisture content. For axial compressive loading, the spheroidal accession has higher values of modulus of stiffness at lower moisture contents. At moisture contents above 25% (d.b.), the moduli of stiffness of the two accessions were almost equal. For axial loading, the mean values of modulus of stiffness recorded at the least moisture content for oblong and spheroidal nuts were 580.2 and 926.1 N/mm^2 respectively, with a percentage difference of 59.6%.

The modulus of stiffness of the two accessions during longitudinal compressive loading also decreased with increase in moisture content (Figure 9). The spheroidal accession had consistently higher values than the tapered oblong accessions.

Table 1 presents the relationship between modulus of stiffness and moisture content for the oblong and spheroidal accessions subjected to both axial and longitudinal loadings. The best fit for the two accessions and loading orientations are regression equations of the second-order.

The mean values of modulus of stiffness obtained at the least moisture content of oblong and spheroidal accessions during longitudinal compressive loading were 747 and 974 N/mm^2 respectively and this gave a variability of 30.4%. It could be observed from Figure 9 that for both loading orientations, values of modulus of stiffness for the spheroidal accession were higher than those of the oblong accession.

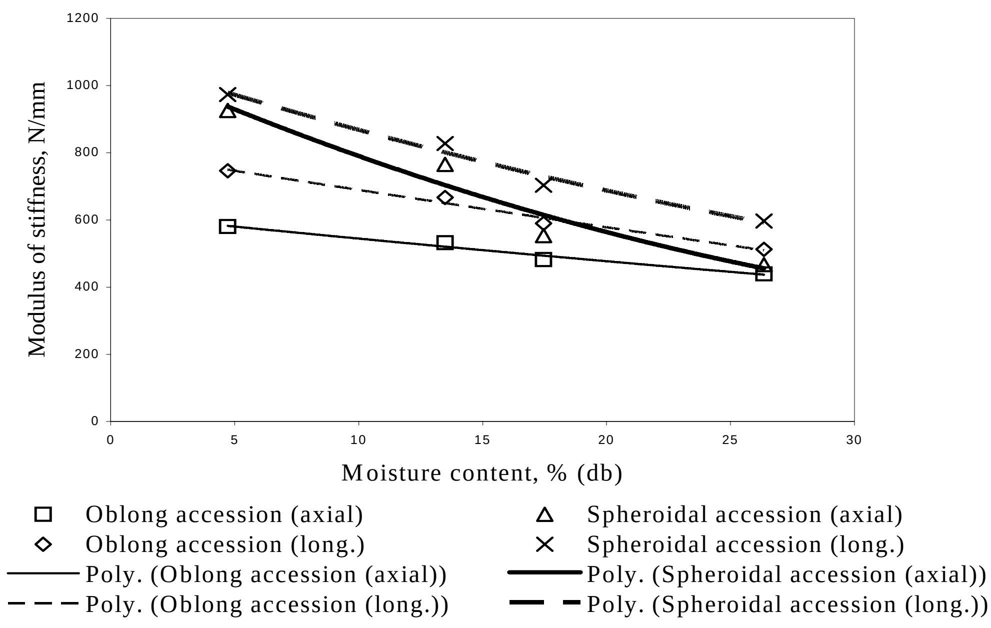

Figure 9. Effect of moisture content on the modulus of stiffness of balanites aegyptiaca nuts during axial and longitudinal compressive loading

4. GENERAL EFFECT OF MOISTURE CONTENT AND LOADING ORIENTATION ON THE MECHANICAL PROPERTIES OF *BALANITES AEGYPTIACA* NUTS

The results presented established that all values of the six mechanical properties of the two *balanites aegyptiaca* nut accessions investigated decreased with increase in moisture content. The linear and quadratic regression models presented relating moisture content and each of the properties confirmed this behaviour of the mechanical properties of the nuts at varying moisture contents during both axial and longitudinal compressive loading. Similar relationships between moisture content and some mechanical properties were reported by Anazodo and Norris (1981), Misra and Young (1981), Oloso and Clarke (1993) and Kang *et al.* (1995) for corn cob, soy beans, cashew nuts and wheat, respectively. The inverse relationship exhibited between moisture content and the mechanical properties investigated could be attributed to the fact that the shell of *balanites aegyptiaca* nuts is spongy and thus as its moisture content increases, the cell bonds become weaker and easier to fail. Consequently, values of the mechanical properties reported were high at low moisture levels and vice versa.

Figures 4–9 show that for all moisture levels, all the six mechanical properties of *balanites aegyptiaca* nuts studied had higher values when the nuts were loaded longitudinally for compressive tests than when loaded axially. This means that bonds of the nut cells are weaker to fail and hence easier to crack when loaded axially.

These two behaviours of *balanites aegyptiaca* nuts (as affected by moisture content and loading orientation) are pertinent for consideration when the development of postharvest processing equipment is envisaged.

5. DESIGN APPLICATIONS

The results reported in this study show that moisture content and loading position have substantial influence on the mechanical properties of the two accessions of the *balanites aegyptiaca* nuts considered. The decrease in the mechanical properties of the nuts with increases in moisture content suggests that, to save energy, the nuts should be cracked at high moisture contents. But cracking at high moisture contents crushes the kernels into small pieces. Since product quality is very important, it is recommended that the nuts be cracked axially at low moisture contents so that kernels that are intact will be obtained.

6. CONCLUSIONS

The effect of moisture content and loading orientation on some mechanical properties of *balanites aegyptiaca* nuts was investigated. Two accessions of the nuts locally available in Nigeria, namely the one end tapered oblong and the spheroidal accessions were used. The mechanical properties considered at four different moisture levels were modulus of elasticity, bioyield point, bioyield stress, compressive strength, rupture strength and modulus of stiffness. The nuts were compressed in the TESTOMETRIC universal testing machine in two loading orientations–axially and longitudinally.

Results obtained show that variation of moisture content affected all the six properties, which decreased with increase in moisture content. This finding corroborates the results of several previous researchers who reported on the relationship between moisture content and some mechanical properties of other agricultural materials. Also, these were found to have higher values when the *balanites aegyptiaca* nuts were loaded longitudinally for compressive tests than when loaded axially. These findings will be useful in the development of processing equipment for *balanites aegyptiaca* nuts.

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