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Compression Loading Behaviour of *A. squamosa* seeds for Sustainable Biodiesel Synthesis

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Abstract: Due to the increasing demand for sustainable energy, non-edible oilseed crops are being explored as alternatives to traditional edible oils. The *A. squamosa* seeds are rich in oil content (24%/100g), and often discarded as agricultural waste. Determination of mechanical properties of the seeds under compression loading is significant for designing machinery for its handling and processing. Thus, the present study assessed the effect of loading speeds, LS, (5.0-25 mm/min) and moisture contents, ms, (8.0-32.5%, db) on rupture force and energy, bioyield force and energy, deformation, and hardness at the seed's horizontal and vertical orientations using Testometric Universal Testing Machine. The results indicate that both LS, and mc significantly ($p < 0.05$) affect the mechanical properties of the seeds. Particularly, horizontal loading orientations consistently exhibited higher values for the selected compressive properties than vertical orientations, except for deformation at varying LS. The correlations between LS, mc, and the compressive parameters of the seed were mostly linear, at both orientations, with increasing mc from 8.0-32.5%, (db). High correlation coefficients (R^2) were obtained for the relationship between the studied parameters, LS, and mc. The data obtained would provide crucial insights into optimizing oil extraction processes by enabling the design of efficient machinery that accommodates the unique characteristics of the seeds.

Keywords: mechanical properties; compression loading; *Annona squamosa* seed; loading speeds; moisture content; sustainable biodiesel,

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1. Introduction

The universal demand for sustainable and renewable energy sources has grown exponentially due to concerns about environmental degradation, fossil fuel depletion, and greenhouse gas emissions. Among various renewable energy sources, biodiesel has emerged as a promising alternative, offering a cleaner and more sustainable option for powering industries and transportation [1,2]. Biodiesel is primarily produced from vegetable oils, animal fats, and other renewable feedstock. However, the rising demand for edible oils in biodiesel production has raised concerns about food security, necessitating the exploration of non-edible and underutilized oilseed crops [3].

Annona squamosa (*A. squamosa)*, also known as custard apple or sweetsop is a tropical fruit commonly found in regions of Africa, Asia, and the Americas. The fruit is one of the families of *Annonaceae* plant, genus *Annona*, class *magnoliopsida* and, species *Annona* [4]. *A squamosa* has different cultivars like pale-green, red and pink-bluish with similar characteristics [5]. Moreover, the pale-green cultivar which is used in this study is commonly found in the tropical region of Africa and produces seeds rich in oil content (23-25% per 100g) [6]. The prevailing fatty acids present in *squamosa*

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seed oil are oleic with 49.75%, Linoleic, 22.50%, palmitic, 15.06%, and stearic, 4.63%. Thus, makes the seed oil suitable as potential feedstock for biodiesel synthesis [5,7]. Despite the potential of *A. squamosa* seed oil to serve as valuable feedstock for biodiesel production, yet the seeds are often discarded as agricultural waste [6].

In the field of machine design, the study of material properties and their behaviour under various compression loading conditions is crucial for ensuring optimal performance and durability [8]. Agricultural biomaterials, such as seeds, offer a unique perspective due to their complex structure and mechanical responses. Mechanical compression is a widely employed method for extracting oil from seeds due to its simplicity, cost-effectiveness, and eco-friendliness [9]. The effectiveness of this process depends heavily on the mechanical properties of the seeds, such as hardness, deformation, and compressive strength [10]. These properties are influenced by factors like seed moisture content and the speed of compression during the extraction process. Thus, understanding the compression loading behaviour of *A. squamosa* seeds is of particular interest as it can provide insights into the seed structural integrity and potential applications in machine design for maximizing oil yield [11,12]. Furthermore, the loading speed applied to a material and the material moisture level during compression can greatly influence its mechanical response. The rate at which a force is applied can affect the deformation, stress distribution, and failure mechanisms of the material [13]. To improve oil recovery efficiency of *A. squamosa* seed in mechanical screw presses and expellers, it is important to deeply understand how the seed react to compression forces. This involves exploring how the applied force relates to the compression loading speed and moisture content of *A. squamosa* seeds, which can be done using a universal compression testing machine [10].

The mechanical properties of various oil seeds under compression loading in related to varying loading speeds or moisture contents have been studied by different researchers such as [12] for Jatropha seeds, [10] for Soursop seed and kernel, [14] for *Moringa oleifera* seeds, [15] for paddy rice, [16] for myrobalan seed, [17] for plum kernel, [8] for maize grain, and [18] for mucuna bean, among others. However, information on the behaviour of *A. squamosa* seeds under compression loading at varying compression loading speeds and moisture contents seems not to be available in literature. Therefore, the novelty of this study focuses on the compression loading behaviour of *A. squamosa* seeds at varying speeds and moisture contents, aiming to analyze the seeds mechanical response during oil extraction. The findings will not only advance the understanding of *A. squamosa* seed mechanics but also provide critical insights into designing efficient, sustainable, and scalable machinery for handling *A. squamosa* seeds as potential feedstock for biodiesel production systems.

2. Materials and Methods

2.1. Collection and Preparation A. squamosa Seed

The *A. squamosa* seeds (Figure 1) used in this study were sourced from fruits harvested from plants growing in Ogbomoso North Local Government Area, situated at latitude 8.1335°N and longitude 4.2538°E. This region was selected due to its abundant *squamosa* plant population. The seeds were manually separated from the white-pulp and rinsed to remove impurities and foreign materials. The seeds were then sun-dried to reduce their moisture content to a level suitable for storage.

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Figure 1. Image of *A. squamosa* plant, fruits and seeds**.**

2.2. Determination of Initial Moisture Content of A. squamosa Seeds

The initial moisture content of *Annona squamosa* seeds on a dry basis (db) was determined following the American Society of Agricultural and Biological Engineers (ASABE) standard S352.2 (2001), as described by Adeyanju et al. [19], and Oloyede et al. [6]. The procedure utilized the oven-drying method with a laboratory oven (Model: DGH-9101, USA) set at a temperature of 103 ± 2°C. For the analysis, 5.0 g of seed samples (measured in triplicate) were weighed using a digital weighing balance (Model: MP 1001, with 0.1 g sensitivity) and placed in three separate aluminum cans. The cans, containing the seed samples, were then placed in the oven, and the weights of the samples were monitored at three-hour intervals till a constant weight was achieved. The average initial moisture content of the seed samples was calculated using Equation 1.

$$\boldsymbol{mc}\ (\%, \boldsymbol{db}) = {}^{M_w}/_{M_D} \times \mathbf{100} \qquad 1$$

Where $\boldsymbol{mc}$= moisture Content (%, db), $\boldsymbol{M_w}$ = Mass of water (g), $\boldsymbol{M_D}$ = Mass of dry matter (g).

2.3. Conditioning of A. squamosa Seed Moisture Content

The moisture content of *A. squamosa* seeds was adjusted to five predetermined levels (8.0–32.5% dry basis) using the rewetting method, as described by Mousaviraad and Tekeste [20], and Hashemifesharaki [21]. To achieve these moisture levels, a calculated amount of clean water was added to seed samples with known initial moisture content and weight. After adding the water, the samples were sealed in airtight bags, stowed in a refrigerator for at least seven days to ensure uniform moisture distribution thru the samples. Before testing, the essential quantity of the sample was removed from the refrigerator and allowed to equilibrate to room temperature. The amount of water to be added to the samples was calculated using Equation 2.

$$\boldsymbol{Q} = \frac{W(W_d - W_i)}{100 - W_f} \times \mathbf{100} \qquad 2$$

Where $\boldsymbol{Q}$ = Amount of water added (g), $\boldsymbol{w}$ = sample's Initial weight (g), $\boldsymbol{M_d}$ = sample desired moisture level (%, db), and $\boldsymbol{M_i}$ = sample's initial moisture content (%, db).

2.4. Determination of Mechanical Properties of A. squamosa Seed

The mechanical properties of *A. squamosa* seeds, under compression loading which include rupture force, rupture energy, bio-yield force, bio-yield energy, and deformation at the rupture point, were evaluated based on the forces acting on the two major orientations (horizontal and vertical) of

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the seeds. These parameters were measured at different compression loading speeds (5.0-25 mm/min) and moisture contents (8.0-32.5% db) following the recommendations of ASABE S368.4 (2013) for oilseeds, as outlined by Jan [22] and Simbeye et al. [23]. The tests were conducted using a Testometric material testing machine (Figure 2), which has a measurement accuracy of 0.001 N for force and 0.001 mm for deformation. All testing was carried out at the Material Testing Laboratory of the National Centre for Agricultural Mechanization (NCAM) in Ilorin, Kwara State, Nigeria.

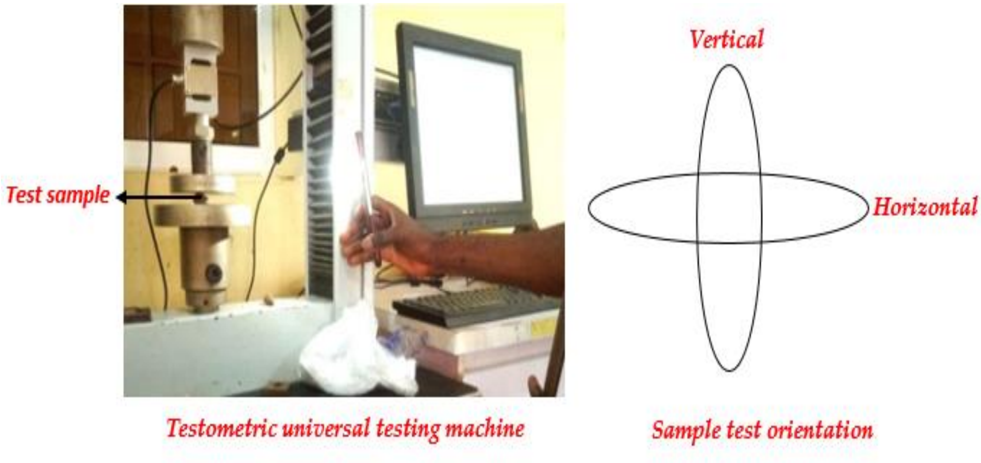


Figure 2. Mechanical analysis of *A. squamosa* seed under compression loading.

2.5. Determination of the Hardness A. squamosa Seed

The hardness of *A. squamosa* seed was determined based on the ratio of rupture force to deformation at rupture point and calculated using Equation 3 [17].

$$H = \frac{F_r}{R_{dp}} \quad (3)$$

Where: H = hardness, F_r = rupture force, R_{dp} = deformation at rupture point.

2.6. Data Analysis

Analysis of Variance (ANOVA) in SPSS software (Version 21) was used to statistically examine the data gathered from the compressive tests. This was carried out in order to assess the noteworthy impacts that different loading rates and moisture concentrations had on the compressive characteristics of *A. squamosa* seeds. Duncan's Multiple Range Test (DMRT) was performed to compare the mean values of the compressive characteristics for the vertical and horizontal loading orientations. A probability level of $p < 0.05$ was used to assess for the significance of the differences.

3. Results and Discussions

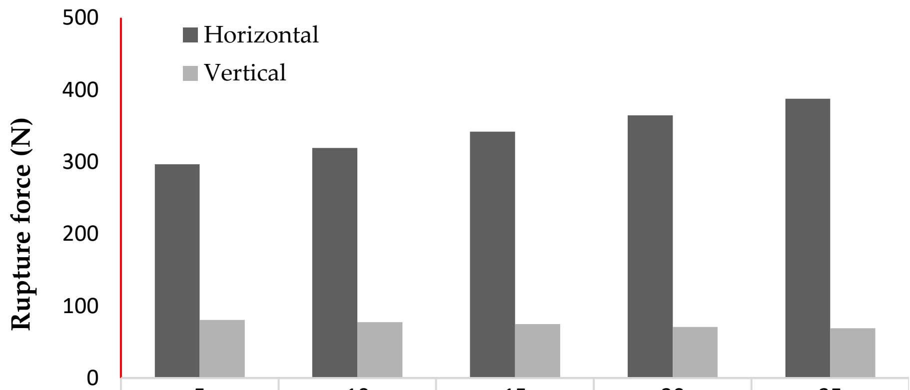
3.1 Moisture Content of A. squamosal Seed

The average initial moisture content of the *A. squamosal* seed samples was obtained to be 8.0% (db) while the moisture levels obtained after conditioning the seed samples were 11.9, 15.4, 22.6 and 32.5% (db). Similar moisture variations have been used for *Annona muricata* seed and kernel, a cultivar of *A squamosa,* and reported by the authors, Oloyede et al. [24], and Jaiyeoba et al. [25], respectively.

3.2. Effect of Loading Speeds on Mechanical Properties of A. squamosa Seed Under Compression Loading Behaviour.

3.2.1. Effect of Loading Speeds on Rupture Force and Energy

The effect of varying loading speeds on mechanical properties of the seed under compression loading was examined at the seed moisture level of 8.0%, db. The horizontal and vertical rupture force and energy of *A. squamosa* seeds at varying compression loading speeds (5.0-25.0 mm/min) at a safe storage moisture level of 8.0% (db) are presented in Figures 3a and 3b. The results show that seed rupture force and energy significantly ($P < 0.05$) increased linearly with increasing compression loading speeds for both loading orientations, except for the rupture force at vertical loading orientation, which significantly ($P < 0.05$) decreased linearly with increasing loading speeds (Figure 3a). Similar behaviour was reported by Chandio [8], and Etim [18] for maize grains and mucuna beans, respectively. The seed rupture force and energy at horizontal loading orientation ranged from 295.86 to 386.11 N and 0.164 to 0.274 Nm, respectively (Table 1). At vertical loading orientation, the rupture force ranged from 81.89 to 69.44 N, and the rupture energy from 0.0483 to 0.104 Nm at loading speeds of 5.0 to 25.0 mm/min. Lower rupture force and energy were observed at the seed vertical orientation. This behaviour can be attributed to the seed's structural anisotropy of *A squamosa* seed [17]. This observation was consistent with the findings of Zareiforoush [26] for paddy grains and Hasseldine et al. [27] for millet. These results indicate that less force is required to break *A. squamosa* seeds in the vertical position compared to the horizontal position. ANOVA results (Table 1) revealed significant F-values for rupture force (893.71 horizontal, 29.15 vertical) and rupture energy (43.49 horizontal, 13.99 vertical). The p-values < 0.05 indicated that compression loading speeds have a significant effect on the seed rupture force and energy. Furthermore, Duncan's multiple range test (Table 2) showed that vertical and horizontal rupture forces and energies mean values were significantly different ($p < 0.05$) for all studied loading speeds. The linear regression models relating the loading speeds to the force and energy required to break the seed on its two major axes are shown in Table 3. A strong positive correlation coefficient (R^2) was obtained for both rupture force and energy at the two major orientations.



	5	10	15	20	25
Horizontal	296.755	319.44	342.105	364.78	387.445
Vertical	80.555	77.695	74.835	71.021	69.115

Compression loading speed mm/min

Figure 3a. Effects of loading speeds on rupture force of *A. squamosa* seed.

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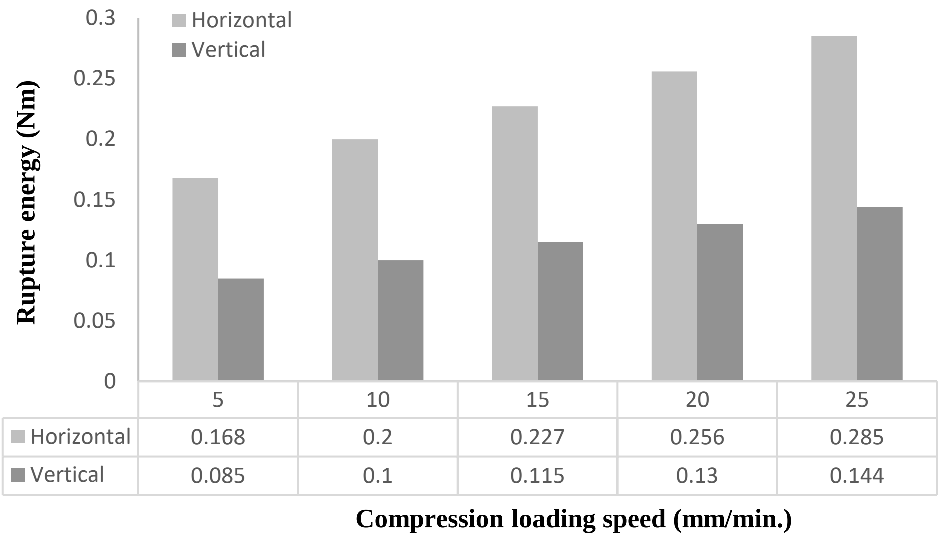

Figure 3b. Effects of loading speeds on rupture energy of *A. squamosa* seed.

3.2.2. Effect of Loading Speeds on Bioyield Force and Energy

The interactions between compression loading speeds, bioyield force, and energy of *A. squamosa* seed at vertical and horizontal orientations are presented in Figures 4a and 4b, respectively. The data showed that the seed bioyield force and energy significantly ($p < 0.05$) increased linearly at horizontal position but decreased linearly at vertical loading position with increasing speeds from 5.0 to 25.0 mm/min. The increase in bioyield force and energy at the seed horizontal orientation, contrasted by a decrease in the vertical orientation, can be attributed to the strain rate sensitivity of the seed [28]. At horizontal orientation, the structural components of the seed may align in a manner that offers greater resistance to deformation thus, resulting in increased bioyield force and energy. However, in vertical orientation, the alignment of structural components may facilitate deformation under rapid loading, leading to decreased bioyield force and energy. These findings align with previous research on bioyield force and energy of pumpkin and sunflower seeds by Fadebiyi and Ozunde [29], and Vasilachi et al. [30], respectively. In horizontal orientation, the mean values for bioyield force and energy ranged from 289.93 to 387.445 N and 0.156 to 0.285 Nm, respectively. At vertical orientation, they ranged from88.29 to 21.33 N and 0.047 to 0.005 Nm (Table 1) with increasing loading speed. The lower bioyield force and energy at the seed's vertical orientation can guide the design of agricultural processing machines to optimize seed oil extraction efficiency with reduced energy consumption [12]. The ANOVA results (Table 2) showed that the model term (loading speeds) had significant ($P < 0.05$) effects on the bioyield force and energy of *A. squamosa* seeds with significant F-values for bioyield force (712.47N horizontal, 723.840N vertical) and bioyield energy (56.68Nm horizontal, 22.75Nm vertical). Duncan's multiple range test (Table 1) revealed that the mean values for bioyield forces and energies were significantly different ($p < 0.05$) for all studied loading speeds, except at 5 and 20 mm/min at the seed vertical orientation for bioyield energy. The linear regression models relating the loading speeds with bioyield force and energy at the two orientations are shown in Table 3. High positive R^2 values were obtained for both bioyield force and energy at the two orientations. This trend aligns with previous findings for soursop seeds by Oniya [10].

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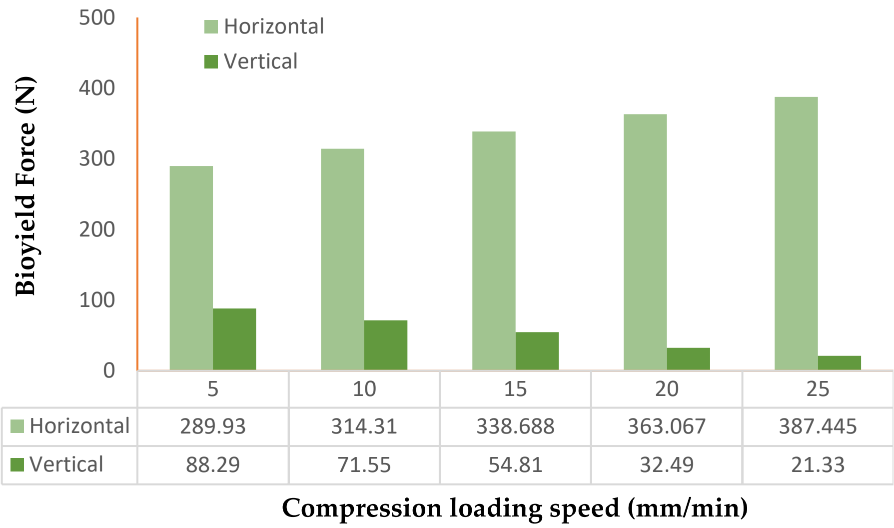

Figure 4a. Effect of loading speed on bioyield force of *A. squamosa* seed.

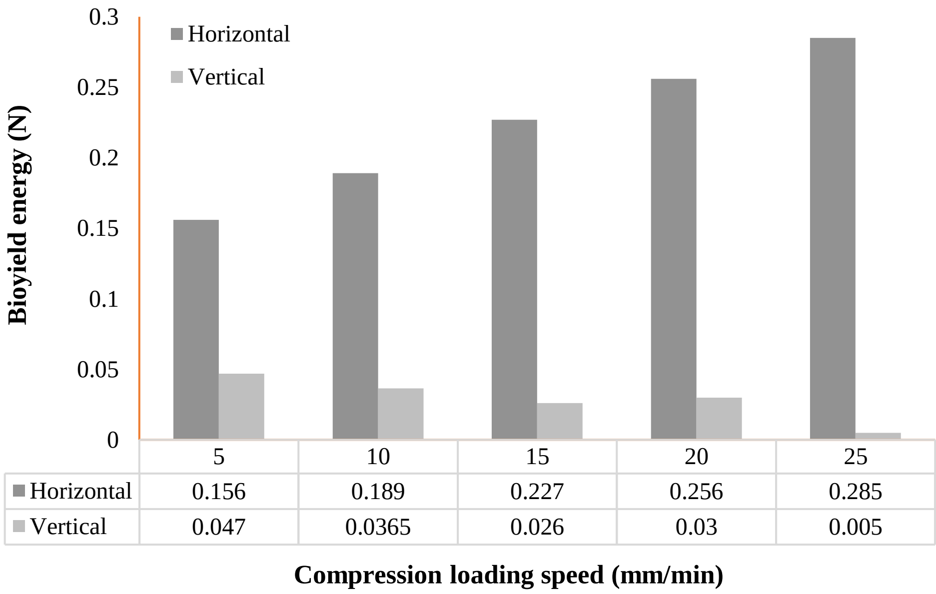

Figure 4b. Effect of loading speed on bio-yield energy of *A. squamosa* seed.

3.2.3. Effect of Loading Speed on Deformation at Rupture Point

The effect of loading speeds on deformation at rupture point (D_{arp}) of *A. squamosa* seed is presented in Figure 5. At the horizontal and vertical loading orientations, the seed deformation ranged from 0.164 to 0.274 mm, and from 1.574 to 2.51 mm, respectively as loading speeds increased from 5.0 to 25.0 mm/min. The results show that the deformation at rupture point of *A. squamosa* seed significantly ($p < 0.05$) increased linearly with loading speeds at both major loading orientations (Figure 5). Higher values of deformation were observed at the seed vertical loading orientation compared to the horizontal orientation. This difference could be credited to the fact that in horizontal orientation, transverse loading causes an earlier failure because of structural buckling and load concentration, whereas the alignment of cells and vascular bundles along the vertical orientation offers greater resistance to axial compression [8]. The highest deformation values were observed at loading speed of 25 mm/mm at both orientations, which implies that the high loading speed offers flexibility and elasticity to *A. squamosa* seed during deformation. similar findings for deformation at rupture point were reported by Chandio [8] for maize grains varieties. ANOVA results showed that loading speeds had a significant effect on deformation at rupture point of *A. squamosa* seed with

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model F-values for of 1.36 (horizontal) and 67.43 (vertical) confirming the significance of the models. The linear regression model relating the loading speed and D_{arp} with high positive R^2 confirming a strong correlation between loading speed and D_{arp} is shown in Table 3.

Table 1. The mean values and standard deviation of compressive properties of *A. squamosa* seed by Duncan's multiple range test ($p \leq 0.05$).

	Compression Loading Speed (mm/min)				
Parameters	**5**	**10**	**15**	**20**	**25**
Compressive test at the seed's horizontal loading position					
Rupture force (N)	295.86±0.01[a]	318.11±0.01[b]	341.11±0.1[c]	363.45.88±0.1[d]	386.11±0.1[e]
Rupture energy (N.m)	0.1643±0.2[a]	0.1733±0.01[a]	0.1977.±0.1[b]	0.2410±0.1[c]	0.2740±0.01[d]
Bio-yield force (N)	286.26±0.01[c]	312.98±0.01[b]	337.35±0.01[c]	362.05±0.1[d]	385.78±0.01[e]
Bio-yield energy (Nm)	0.1593±0.1[a]	0.1957±0.01[b]	0.2337±0.01[c]	0.2627±0.01[d]	0.2950±0.1[e]
Def. at rupture point (mm)	0.1643±0.01[a]	0.1733±0.01[a]	0.1977±0.21[b]	0.2410±0.1[c]	0.2740±0.1[d]
Hardness (N/mm)	192.63±0.01[a]	200.22±0.01[b]	207.14±0.01[c]	213.47±0.01[d]	219.80±0.01[e]
Compressive test at the seed's vertical loading position					
Rupture force (N)	81.89±0.01[d]	78.66±0.1[c]	75.50±0.1[b]	72.02±0.01[a]	69.44±0.01[a]
Rupture energy (Nm)	0.0483±0.1[a]	0.0610±0.1[ab]	0.0687.±0.1[bc]	0.0817±0.01[c]	0.1040±0.01[d]
Bio-yield force (N)	86.95±0.01[e]	70.88±0.01[d]	53.48±0.01[c]	31.49±0.1[b]	20.99±0.01[a]
Bio-yield energy (Nm)	0.0437±0.1[c]	0.0355±0.01[c]	0.0253±0.1[b]	0.0250±0.01[b]	0.0070±0.01[a]
Def. at rupture point (mm)	1.5173±0.01[a]	1.7610±0.01[b]	2.0580±0.1[c]	2.2667±0.1[d]	2.5077±0.1[e]
Hardness (N/mm)	76.56±0.01[e]	64.75±0.01[d]	53.24±0.01[c]	45.43±0.01[b]	38.73±0.01[a]

a, b, c, d, e – implies superscript with different letters of mean in the same row differ significantly, 'ab, bc' and superscript with the same letters of mean indicates not significantly different between that loading speed.

3.2.4. Effect of Loading Speed on Hardness of A. squamosal Seed

The mean value for the seed hardness at the horizontal loading orientation significantly ($P < 0.05$) increased linearly from 193.96 to 221.14 N/mm, while it decreased linearly from 78.23 to 39.93 N/mm at the seed vertical loading position within the loading speed range of 5.0 to 25.0 mm/min (Figure6). At horizontal position, the seed hardness was consistently higher than at vertical loading position across all experimental loading speeds. This behaviour may be due to the loading position of the seed, which allowed easier fracture at vertical position compared to horizontal. The effect of loading speeds on the hardness was found to be significant ($p < 0.05$) (Table 3). More so, the mean values *A. squamosa* seed hardness showed significant ($p < 0.05$) differences at all experimental loading speeds (Table 1). Similar result was reported by Chandio [8] for maize grain whose grain hardness ranged from 711.06 to 381.65 N/mm for vertical hardness and 91.10 to 370.99 N/mm for lateral hardness. The linear regression model relating the loading speed and *A. squamosa* seed hardness is presented in Table 3. The high positive correlation coefficient (R^2) confirmed a strong correlation between loading speed and the seed hardness.

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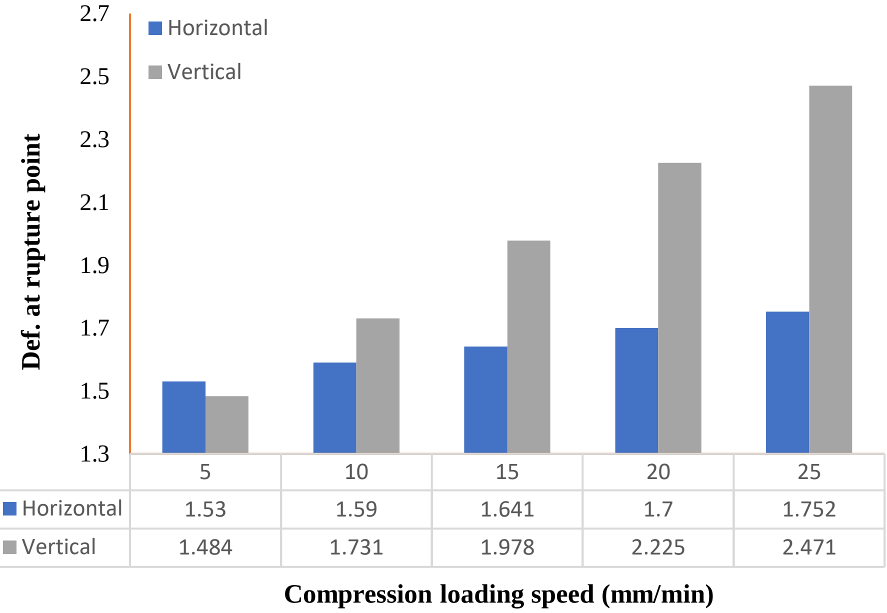

Figure 5. Effect of loading speed on deformation at rupture point of *A. squamosa* seed.

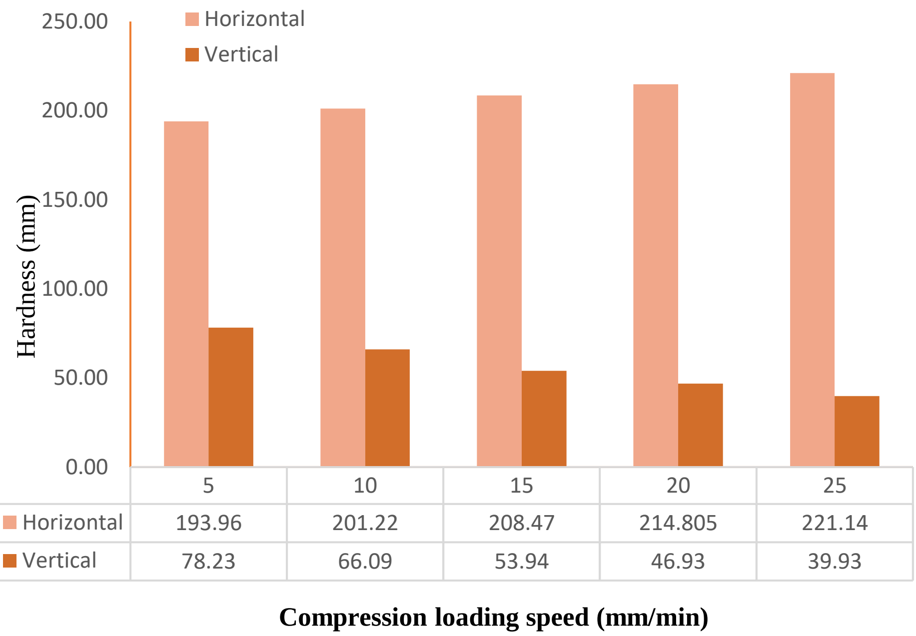

Figure 6. Effect of loading speed on hardness of *A. squamosa* seed.

Table 2. ANOVA shown significant effect of loading speeds on compressive strength of *A.squamosa* seed at $P < 0.05$.

		Sum of Squares	df	Mean Square	F	Sig.
Hrup. force	Between Groups	15302.766	4	3825.691	893.713	.001
	Within Groups	42.807	10	4.281		
	Total	15345.572	14			
Hrup. energy	Between Groups	.026	4	.006	43.485	.001
	Within Groups	.001	10	.000		
	Total	.027	14			
Vrup. force	Between Groups	298.599	4	74.650	29.152	.002
	Within Groups	25.607	10	2.561		
	Total	324.206	14			

Vrup. energy	Between Groups	.007	4	.002	13.996	.001
	Within Groups	.001	10	.000		
	Total	.008	14			
HDat. rupt	Between Groups	.348	4	.087	1.975	.174
	Within Groups	.441	10	.044		
	Total	.789	14			
Hhardness	Between Groups	1373.606	4	343.401	70.562	.003
	Within Groups	48.667	10	4.867		
	Total	1422.272	14			
VDat.rup	Between Groups	1.860	4	.465	67.423	.015
	Within Groups	.069	10	.007		
	Total	1.928	14			
Vhardness	Between Groups	2750.393	4	687.598	131.188	.002
	Within Groups	52.413	10	5.241		
	Total	2802.806	14			
HBio.yield	Between Groups	18475.206	4	4618.801	712.473	.001
	Within Groups	64.828	10	6.483		
	Total	18540.034	14			
VBio.yield	Between Groups	8879.109	4	2219.777	723.840	.010
	Within Groups	30.667	10	3.067		
	Total	8909.776	14			
Hbio.energy	Between Groups	.034	4	.009	58.681	.021
	Within Groups	.001	10	.000		
	Total	.036	14			
VBio.energy	Between Groups	.002	4	.001	22.751	.001
	Within Groups	.000	10	.000		
	Total	.003	14			

Note: V= vertical loading orientation H= Horizontal loading orientation.

Table 3. Regression model shown relationship between loading speed and compressive strength of *A. squamosa* seed.

Regression models	R^2
Horizontal loading position	
$R_f = 4.5344cs + 274.09$	0.999
$R_e = 0.0058cs + 0.1402$	0.999
$B_f = 4.8757cs + 265.55$	0.998
$B_e = -2.527cs + 105.75$	0.964
$D_{rpt} = 0.0494cs + 1.2374$	0.999
$H = 1.359cs + 187.53$	0.999
Vertical loading position	
$R_f = -0.5911cs + 83.51$	0.993
$R_e = 0.003cs + 0.0704$	0.999
$B_f = 0.0065cs + 0.1251$	0.997
$B_e = -0.0018cs + 0.0056$	0.848
$D_{rpt} = 0.0111cs + 1.476$	0.999
$H = -1.9153cs + 85.753$	0.980

R_f: Rupture force, R_e: Rupture energy, B_f: Bioyield force, B_e: Bioyield energy, D_{rpt}: Deformation at rupture point, H: Hardness.

3.3. Effect of Moisture Contents on Mechanical Properties of A. squamosa Seed Under Compression Loading

3.3.1. Effect of Moisture Content on the Seed's Rupture Force and Energy

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The correlation between the mean rupture force of *A. squamosa* seed and moisture content along horizontal and vertical orientations is given in Figure 7a and 7b, respectively. At all moisture levels, the horizontal position exhibited higher rupture force and energy compared to the vertical position of *A squamosa* seed. The force needed to initiate rupture along the horizontal and vertical loading orientations ranged from 296.76 to 179.64 N, and 102.82 to 45.21 N, respectively with an increase in moisture content from 8.0 to 32.5% (db). The energy required to initiate force increased with moisture content from 0.168 to 0.285 Nm, and 0.055 to 0.105 Nm at horizontal and vertical orientations, respectively (Figure 6b). These results indicate that *A. squamosa* seed requires lower compression force to rupture in the vertical orientation compared to the horizontal orientation. This may be credited to the force being applied on the hilum portion of the seed in the vertical position, leading to easier rupture, and differences in the seed surface area [10]. A similar range in rupture force and energy have been reported by Nyorere and Uguru [31] for Beachwood seed. The interaction between the seed rupture force and moisture content in the horizontal position decreased significantly ($p < 0.05$) and linearly with increasing moisture content (Figure6a), while it increased linearly in the vertical position. The reduction in rupture force with increasing moisture content in the horizontal orientation can be attributed to the seed becoming weaker at higher moisture content due to cellular structure modification through water absorption, thus requiring less force to break [18]. Hence, the likely reason for higher rupture energy in the horizontal orientation. Similar trends have been reported for plum kernels by Aaqib [17], and soursop seed by Oniya [10]. The results for both major orientations (horizontal and vertical) were found to be statistically significant at $p < 0.05$. The regression equations showing the relationship between moisture content, rupture force, and energy of *A. squamosa* seed with strong positive R^2 are presented in Table 4. Understanding the mechanical behavior of the seed in relation to moisture content under applied forces is crucial for engineers and scientists. Therefore, when designing equipment for seed handling, both the orientation and moisture content of the seed should be given primary consideration.

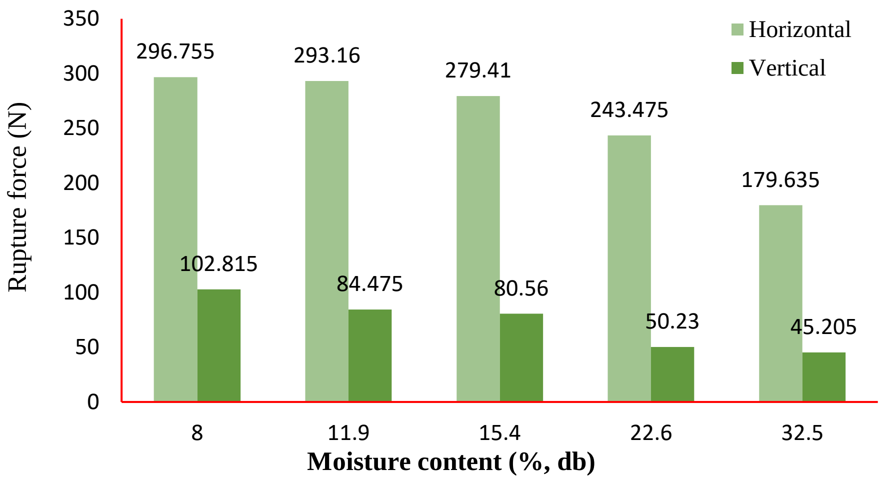

Figure 7a. Effects of moisture contents on rupture force of *A. squamosa* seed.

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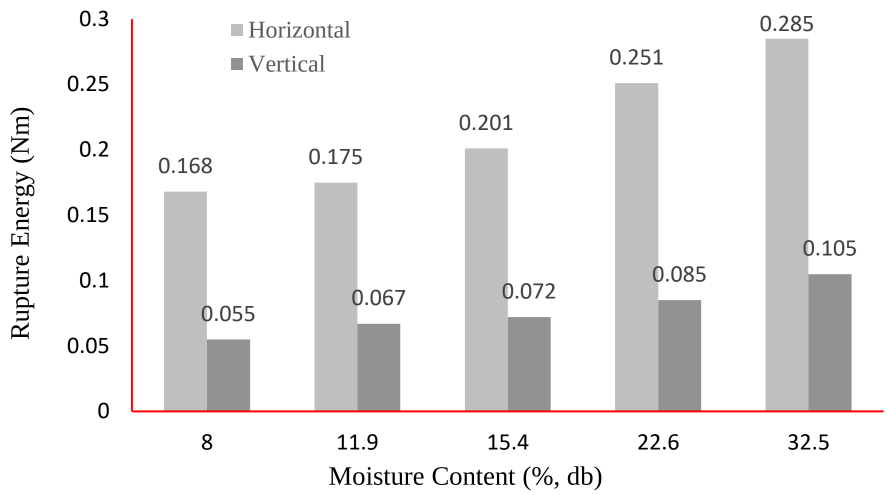

Figure 7b. Effects of moisture contents on rupture energy of *A. squamosa* seed.

3.3.2. Effect of Moisture Content on Bioyield Force and Energy of A. squamosa Seed

The average bioyield force and energy of the seed in both horizontal and vertical loading orientations decreased linearly with increasing moisture content from 8.0 to 32.5% (Figure 8a-b). In the horizontal position, the seed bioyield force and energy ranged from 289.93 to 179.64 N and 0.156 to 0.069 Nm, respectively. In the vertical orientation, these values ranged from 88.29 to 28.04 N and 0.047 to 0.006 Nm, respectively. The bioyield force in the horizontal orientation was consistently higher than in the vertical orientation. This suggests that structural alignment of *A. squamosa* seed in the vertical loading position offers less resistance to applied force, possibly due to structural and mechanical anisotropies within the seed (Mohsenin 1986 in [10]. Similar trends were detailed by Chandio [8] maize grain. The relationship between seed moisture content, bioyield force, and energy was found to be significant at $p < 0.05$ for both loading orientations (Table 5). The mean values for the horizontal bioyield force and energy of the seed showed no significant difference ($p <$ 0.05) except at moisture levels of 8.0, 22.6, and 32.5%. In the vertical loading orientation, no significant difference was observed between the mean values of bioyield force and energy across all moisture levels except at 8.0 and 22.4% (db). These trends align with findings reported for soursop seeds by Oniya et al. [10] High correlation coefficients (R^2) indicate strong relationship between seed moisture contents, bio-yield force, and energy.

Table 4. The mean values and standard deviation of compressive properties of sweetsop seed by Duncan's multiple range test (p<0.05).

	Moisture content (%, db)				
Parameters	**8.0**	**11.9**	**15.4**	**22.6**	**32.5**
Compressive test at the seed's horizontal loading position					
Rupture force (N)	297.74±0.01^{d}	294.37±0.04^{d}	280.41±0.10c	246.88±0.1^{b}	179.97±0.13^{a}
Rupture energy (N.m)	0.1573±0.20^{a}	0.1707±0.1^{a}	0.1977.±0.1^{b}	0.241±0.4^{c}	0.2774±0.1^{d}
Bioyield force (N)	288.26±0.10^{c}	264.62±0.31^{bc}	265.01±0.01^{bc}	242.01±0.1^{b}	178.27±0.01^{a}
Bioyield energy (Nm)	0.1547±0.1^{c}	0.1360±0.01^{b}	0.1360±0.02^{b}	0.1333±0.01^{b}	0.673±0.05^{a}
Def. at rupture point (mm)	1.511±0.01^{c}	1.502±0.41^{c}	1.504±0.11^{c}	1.401±0.12^{b}	1.091±0.03^{a}
Hardness (N/mm)	197.04±0.03^{e}	195.37±0.01^{d}	186.44±0.02^{c}	176.21±0.05^{b}	164.96±0.12^{a}
Compressive test at the seed's vertical loading position					

Rupture force (N)	102.82±0.01c	84.48±0.1ab	80.56±0.1b	50.23±0.14c	45.21±0.2d
Rupture energy (Nm)	0.1573±0.1a	0.1707±0.1a	0.1977.±0.1b	0.913±0.01c	0.1083±0.01 d
Bio-yield force (N)	87.66±0.01c	67.68±0.01b	66.46±0.01b	36.68±0.1a	27.04±0.01a
Bio-yield energy (Nm)	0.503±0.1c	0.383±0.01b	0.413±0.1bc	0.127±0.01a	0.0073±0.01 a
Def. at rupture point (mm)	1.484±0.01d	1.461±0.01d	1.401±0.1c	1.015±0.1b	0.922±0.1a
Hardness (N/mm)	69.47±1.21e	57.86±0.21d	57.50±3.01d	49.45±0.32a	49.03±2.01a

a, b, c, d, e – implies superscript with different letters of mean in the same row differ significantly, 'ab, bc' and superscript with the same letters of mean indicates not significantly different between that moisture levels.

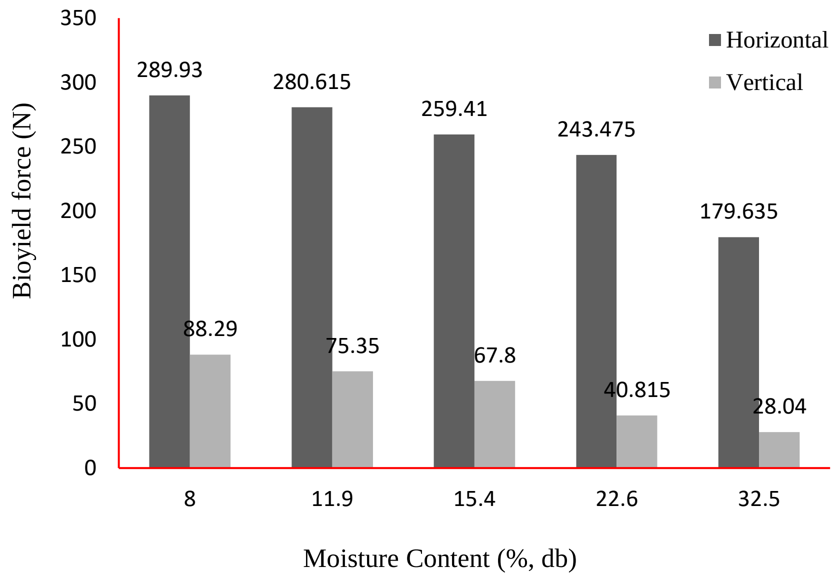

Figure 8a. Effect of moisture content on bio-yield force of *A. squamosa* seed.

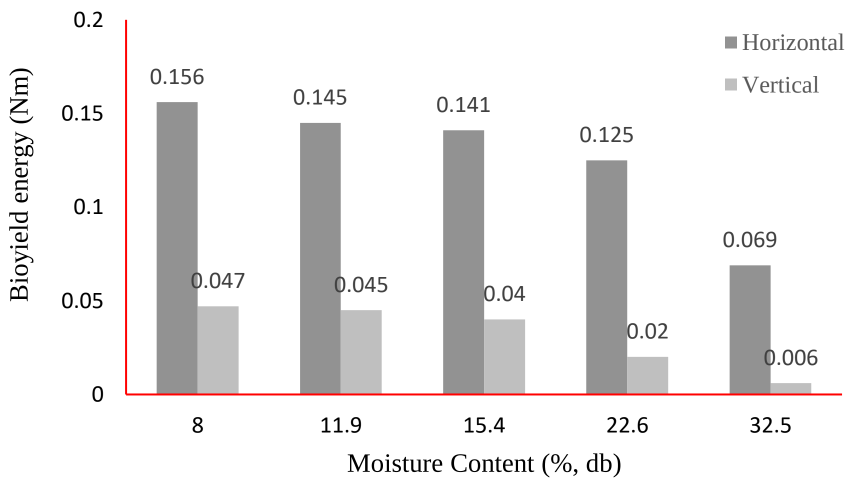

Figure 8b. Effect of moisture content on bioyield energy of *A. squamosa* seed.

3.3.3. Effect of Moisture Content on Deformation at Rupture Point

The mean values of deformation at rupture point for compression via horizontal and vertical loading orientations of *A. squamosa* seed at five moisture contents are presented in Figure 9. At the rupture point, seed deformation decreased non-linearly (with second-order and third-order polynomial relationships in horizontal and vertical orientations, respectively) as moisture content increased from 8.0 to 32.5%. This indicates that the rate of decline was more pronounced at lower moisture levels for both loading orientations. The deformation at rupture point of *A. squamosa* seed compressed along the horizontal orientation was higher at all moisture levels, suggesting that the seed is more resistant and flexible to compression in this orientation. In both orientations, lower moisture contents resulted in more mechanical damage, a trend also reported by Aaqib et al. [17] for plum kernels. The average values for deformation at rupture point ranged from 1.51 to 0.91 mm and 1.48 to 0.49 mm for horizontal and vertical loading orientations, respectively. Along both orientations, statistical analysis revealed that deformation at rupture point varied significantly ($p < 0.05$) with changing moisture content (Table 5). Strong positive correlation coefficients (R^2) described by the regression equations in Table 6 indicate a robust relationship between seed moisture content and deformation at rupture point. According to DMRT, the mean differences across moisture content levels were not statistically significant ($p < 0.05$) for either orientation, except between 22.6 and 32.5% (horizontal), and 15.4 and 32.5% (vertical) moisture levels. This suggests that moisture content changes within these ranges have a notable impact on deformation at rupture point. Similar trends were reported by Lupu et al. (2016) and Chandio et al. [8] for wheat and maize grains, respectively.

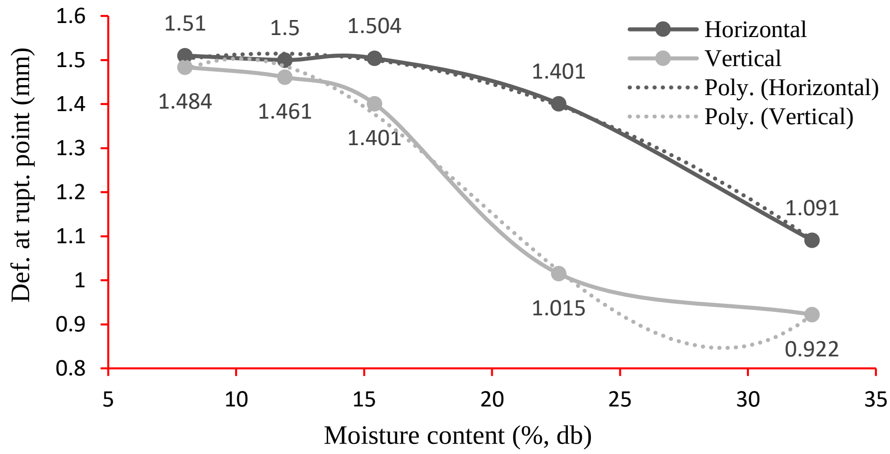

Figure 9. Effect of moisture content on deformation at rupture point of *A. squamosa* seed.

Table 5. ANOVA shown significant effect of moisture content on compressive strength properties of *A. squamosa* seed at $P \leq 0.05$.

		Sum of Squares	df	Mean Square	F	Sig.
Hrup.force	Between Groups	28797.557	4	7199.389	791.297	.005
	Within Groups	90.982	10	9.098		
	Total	28888.540	14			
Hrup.energy	Between Groups	.030	4	.007	41.167	.001
	Within Groups	.002	10	.000		
	Total	.032	14			
Vrup.force	Between Groups	6459.480	4	1614.870	74.810	.025
	Within Groups	215.864	10	21.586		
	Total	6675.344	14			
Vrup.energy	Between Groups	.006	4	.002	33.056	.005
	Within Groups	.000	10	.000		
	Total	.007	14			
HDat.rupt	Between Groups	.894	4	.224	92.893	.013
	Within Groups	.024	10	.002		
	Total	.918	14			
Hhardness	Between Groups	7939.281	4	1984.820	886.756	.002

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	Within Groups	22.383	10	2.238		
	Total	7961.664	14			
VDat.rup	Between Groups	2.017	4	.504	434.675	.001
	Within Groups	.012	10	.001		
	Total	2.028	14			
Vhardness	Between Groups	1947.709	4	486.927	303.861	.030
	Within Groups	16.025	10	1.602		
	Total	1963.733	14			
HBio.yield	Between Groups	21252.799	4	5313.200	29.535	.001
	Within Groups	1798.940	10	179.894		
	Total	23051.739	14			
VBio.yield	Between Groups	7361.889	4	1840.472	62.805	.005
	Within Groups	293.047	10	29.305		
	Total	7654.936	14			
HBio.energy	Between Groups	.014	4	.003	51.947	.010
	Within Groups	.001	10	.000		
	Total	.014	14			
VBio.energy	Between Groups	.004	4	.001	37.471	.003
	Within Groups	.000	10	.000		
	Total	.005	14			

Table 6. Regression model shown relationship between moisture content and compression strength of *A. squamosa* seed

Regression models	R^2
Horizontal loading position	
$R_f - 4.95mc + 348.13$	0.966
$R_e = 0.0051mc + 0.123$	0.974
$B_f = 4.425mc + 330.62$	0.966
$B_e = -2.527mc + 105.75$	0.964
$D_{rpt} = -0.0012mc^2 + 0.024mc + 1.434$	0.978
$H = -8.33mc + 209.00$	0.953
Vertical loading position	
$R_f = -2.835mc + 115.79$	0.902
$R_e = 0.002mc + 0.0413$	0.993
$B_f = 0.0034mc + 0.1892$	0.932
$B_e = -0.0018mc + 0.00645$	0.971
$D_{rpt} = 0.0002mc^3 - 0.0114mc^2 + 1.671mc + 0.741$	0.995
$H = 1.049mc^2 + 11.23mc + 78.79$	0.935

3.3.4. Effect of Moisture Content on A. squamosa Seed Hardness

The hardness of *A. squamosa* seeds exhibited a clear inverse relationship with moisture content, decreasing as moisture contents increased from 8.0% to 32.5% in both horizontal and vertical orientations (Figure 10). The average values for seed hardness ranged from 197.04 to 164.96 N/mm and 69.47 to 49.03 N/mm in the horizontal and vertical orientations, respectively. This reduction in hardness can be attributed to moisture-induced softening of the seed structure, which diminishes its resistance to compressive forces (Oyerere and Uguru, 2018). Similar patterns have been reported for other biomaterials, including plum kernels [17], maize grain varieties [8], and paddy grains [26]. The seed hardness in the horizontal orientation was higher at all moisture levels compared to the vertical orientation. This can be credited to the force application in the horizontal position encountering multiple tissue layers perpendicular to their natural orientation, thus, resulting in greater compression resistance [28]. Statistical analysis confirmed that moisture content significantly ($p < 0.05$) influenced seed hardness (Table 6). Additionally, DMRT analysis showed significant

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differences ($p < 0.05$) in seed hardness at all experimental moisture levels for both orientations (Table 5). Understanding this relationship between hardness and moisture content is crucial for optimizing processing operations and improving energy efficiency in *A. squamosa* seed handling systems. A high positive correlation coefficient confirmed a strong relationship between moisture content and hardness of the seed. Engineers should consider seed hardness data when selecting materials for the design of processing machinery for *A. squamosa* seeds to ensure equipment can withstand potential abrasion without excessive wear.

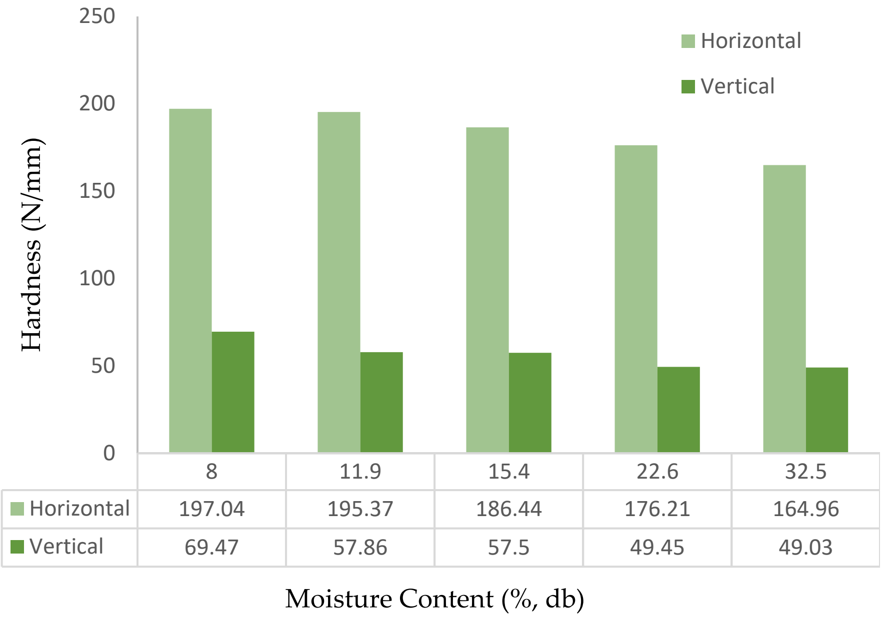

Figure 10. Effect of moisture content on hardness of *A. squamosa* seed.

5. Conclusions

This study examined the mechanical behaviour of *Annona squamosa* seed under compression loading at different compression loading speeds (5.0-25.0 mm/min) and moisture content (8.0-32.5%, db) for sustainable biodiesel synthesis. Based on the experimental results, the following conclusions were drawn:

1. The effect of loading speeds and moisture contents on the rupture force, rupture energy, bioyield force, bioyield energy, deformation at rupture point and hardness was significant at $P < 0.05$ level of ANOVA for the horizontal and vertical orientations.
2. The differences between the mean data of rupture force and energy, bioyield force, and energy, deformation at rupture point and hardness of the seed at all experimental loading speeds and moisture contents for the two loading orientations were found to be statistically significant ($P < 0.05$), except between 22.6 and 32.5% (horizontal), and 15.4 and 32.5% (vertical) moisture levels.
3. The correlations between loading speeds, moisture contents and the parameters under compressive loading behaviour of *A. squamosa* seeds were mostly linear except for deformation (horizontal and vertical), and hardness (vertical) which were polynomial with moisture contents only.
4. The coefficient of correlation (R^2) for the developed regression models, was high for the loading speed and moisture contents of the seed.

Therefore, grasping the impact of loading speeds and moisture content on the mechanical behavior of *A. squamosa* seeds is essential for tailoring equipment to improve oil recovery efficiency in mechanical screw presses and expellers. Hence, this research offers important insights for the biodiesel feedstock processing sector, aiding in the design of machinery that can effectively manage *A. squamosa* seeds, thereby assuring consistent and high-quality oil extraction.

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Abbreviations

The following abbreviations are used in this manuscript:

DB	Dry basis
MC	Moisture content
ASABE	Americal Society of Agricultural and Biological Engineers
ANOVA	Analysis of Variance
SPSS	Statistical Package for the Social Sciences
DMRT	Duncan’s Multiple Range Test

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