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Research Paper

Evaluation of Fracture Resistance of Honey Bean Seed under Quasi Compressive Loading

[*1]Uguru, H., [1]Nyorere, O. and [2]Omotor D. O.

[1]Department of Agricultural and Bio-environmental Engineering Technology, Delta State Polytechnic, Ozoro, Nigeria.
[2]Department of Mechanical Engineering Technology, Delta State Polytechnic, Ozoro, Nigeria.
*Corresponding Author E-mail: erobo2011@gmail.com; +2348039307876

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In this study, some fracture resistance (rupture force and rupture energy) of honey bean seed was investigated, in terms of three seed sizes (small, medium and large), three loading rates (15 mm/min, 20 mm/min and 25 mm/min), and three seed orientations (X, Y, and Z axes). The quasi-static compression of each bean seed was done by using the Universal Testing Machine. The results showed that the force and energy required for fracturing a bean seed is a function of the seed size, seed orientation and compression loading rate. In addition, the seed was generally less flexible in vertical orientation (Y-axis), than in the horizontal orientation (X and Y axes). The analysis of variance showed that the loading rate, seed size and seed orientation significantly ($P \leq 0.05$) influenced the two mechanical parameters studied. Results indicated that rupture force and energy of the seed decreased with increased in the compression loading rate, across the three seed sizes and three seed orientations. In terms of seed size, the fracture resistance decreased with decrease in the seed size. According to the results, the average force and its corresponding energy of the Honey bean seed were found to vary from 118 N, 0.743 Nm in the seed Z-axis, at the loading rate of 15 mm/min to 42.16 N, 0.0213 Nm in the seed Y-axis, at the loading rate of 25 mm/min. The average rupture force of the large seed was about 45 % of that of small seeds, across the three loading rates.

Keywords: Fracture resistance, Honey bean, loading rate, seed size, seed ordination

INTRODUCTION

Common bean (*Phaseolus vulgaris* L) is one of the major leguminous crops cultivated in the world (Leterme and Carmenza, 2002) and widely eaten in Asia and Africa countries. Bean seeds provide nutritional quality and variety of functional properties, such as, desirable structure, texture, flavour and colour characteristics in formulated food products (Oluka and Nwuba, 2001). China (19.3 million tonnes), Indonesia (915,591 tonnes) and India (675,188 tonnes), which are the highest beans production countries, account for over 90 percent of the world's production (24.1 million tonnes) in 2017. Africa accounts for total production of 756,345 tonnes in 2017, with export quality of 217,077 tonnes (FAOSTAT, 2019). Bean seeds come in many colours, sizes, chemical compositions, etc. depending on the cultivar. These differences come from intrinsic factors (e.g. genotype) or extrinsic factors such as farming method, processing method, storage conditions, type of cultivation soil, and technological factors (Gonzalez *et al*., 2005; Aghkhani, *et al*., 2012; Buzera *et al*., 2018).All beans varieties are good source of protein; the seed contains about 26 % of crude protein, significant amount of carbohydrates, and rich micronutrients (e.g. copper, iron and zinc) (Boukar *et al*., 2011; Cowpeas, 2019). Common bean seeds have potential of being used as animal feeds, and incorporating them into animal feeds can reduced feeding cost and improved the animals' health condition (Defang *et al.,* 2008). But some beans varieties contain anti-nutritional agents that negatively affect poultry performances (Kayode and Olorunfemi, 2018). Some common beans varieties grown in Nigeria include; *Iron, Brown*, Kidney, Honey, soya, *Butter*, etc. Honey bean is believed to originate from Africa, sweeter than the black eyed bean with unique taste, even when cooked alone or used to prepared some West African recipes like *Moin-Moin* or *Akara* (AfroFood, 2016)

Engineering properties of agricultural products affect their harvesting, handling, processing, storage and marketing values. For instance, mechanical properties of agricultural materials are important parameter in the analysis and prediction of their failure and breaking behaviours during harvesting, handling and other unit operations (Sadiku and Bamgboye, 2014). In addition, the knowledge of the mechanical properties of bean seeds is essential in the design of beans planters, harvesters, sorters, washers and other postharvest operations machines/equipment (Asoegwu *et al*., 2006; Balasubramanian *et al*., 2012). Processing, handling, transportation and storage of leguminous crops remains a major problem, because of their difference in shape, size, hardness, texture etc.; and any inappropriate method employed can led to destruction and wastage of these materials (Kayode and Olorunfemi, 2018).Mechanical damage of agricultural produce can occur during harvesting, handling, processing, packaging, storage, transportation, etc. (Igwillo, 2018). Presently, most handling and processing operations are done manually; therefore, the design of these machines and equipment without considering their mechanical properties may produce poor results (Asoegwu *et al*., 2006; Polat *et al*., 2006).The mechanical properties of agricultural materials do not only constitute the basic engineering data required for their machine and system design, but also assist in determining the best selection methods in obtaining those data (Bagheri *et al.,* 2011).

Results from previous research had shown that mechanical properties of agricultural materials vary with increased in compression loading rate and material size and loading orientation. According to Olaniyan and Ije (2002), the rupture force of shea nut varied in the different loading orientations (vertical and horizontal). Ogunjimi *et al*., (2002) investigated some mechanical properties of locust bean seed, and reported that the seed orientation significantly influenced the cracking resistance of the seed. According to their results, the highest cracking force was recorded at the vertical axis, and the least at the thickness axis. In the work of (Altuntaş and Karadag, 2006) on the mechanical properties of bitter vetch seed, they reported that the mean rupture force, specific deformation, and rupture energy of the bitter vetch seed were 57.60, 45.00, 87.00 N; 7.60%, 1.62%, 1.93%; 10.14, 4.42, 0.86 N mm, when tested (compressive loading) along the X-, Y- and Z axes. Altuntas *et al*. (2013) investigated the mechanical behaviour (rupture force, specific deformation, rupture energy and toughness) of plum fruits to compression, as affected by different fruit orientation. Altuntas *et al.* reported that the rupture energy and rupture power values of the plum fruits compressed along the Y- axis were higher than the values obtained when tested in the plum fruits in the X- and Z-axis orientations.

In order to design any machine or equipment used in harvesting, handling, processing, and storage of bean seed, it is important to know the effects of loading rate, seed size, and seed orientation on the mechanical properties of the bean seeds. The objective of this study was to investigate the effects of bean seed size, compression loading rate and seed orientation on some mechanical properties (rupture force and rupture energy) of Honey bean cultivar, widely cultivated in Nigeria. These parameters will provide vital data for design of processing and storage systems of Honey bean seeds.

MATERIALS AND METHODS

Study setting

The honey bean seeds were planted at the Research Farm of the Delta State Polytechnic, Ozoro, Nigeria. The area is located at latitude 5.544 N, longitude 6.232 East, altitude 14 M above sea level, and average temperature of 28ºC (Eboibi *et al*., 2018). The physicochemical properties of the area where the honey bean seeds were planted are presented in (Table 1).

Samples collection and preparation

The bean pods were harvested at full maturity age (28 days after peak flowering), sun-dried for five days in a platform before shelling. After which they were air-dried again for another ten days to achieve lower uniform moisture content level. The air-dried seeds were manually inspected to remove premature seeds and other foreign materials, before sorting them into size categories.

Size categorization

The selected Honey bean seeds were categorized into sizes at the Food Processing Laboratory of the Department of Agricultural and Bio-environmental Engineering Laboratory, Delta State Polytechnic, Ozoro, Nigeria. During the process, each bean seed principal dimensions (Length “L”, width “W”, and Thickness “T”) were measured with a digital vernier caliper, having accuracy of 0.01 mm. The geometric mean diameter (GMD) and sphericity of the seed were calculated by equations1and 2 (Mohsenin, 1986).

$$GMD = \sqrt[3]{L \times W \times T} \qquad (1)$$

$$Sphericity = \frac{GMD}{L} x100 \qquad (2)$$

Table 1. Physicochemical properties of the study area soil sample.

Parameter	Level
Particle size distribution	
Sand	40.3%
Silt	35.6%
Clay	24.1%
Chemical analysis	
Soil pH	7.75
Total nitrogen	0.119(mg/kg)
Available Phosphorus	0.337(mg/kg)
Copper	4.911(mg/kg)
Nitrate	0.303(mg/kg)
Sodium	450.748(mg/kg)
Extractable Potassium	687.585(mg/kg)

Source: Eboibi *et al*. (2018)

Table 2. The categorization of *Honey* bean seed based on the seed's GMD and sphericity.

Seed size	L,W,T (mm*)	GMD	Sphericity
Small	9.67, 4.6, 4.1	5.67	58.65
Medium	11.1, 5.7, 5.2	6.90	62.19
Large	12, 6.5, 6.1	7.81	65.05

* = value is based on the mean value of the seeds, L = Length of the bean seed, W = Width of the Bean seed, T = Thickness of the bean seed, GMD = geometric mean diameter.

From the results of the calculations, the seeds were grouped into three size lots, which were large, medium and small seed sizes (Table 2).

Compression test

The quasi-static compression test of the honey bean seeds was done with a Universal Testing Machine (Testometric model, manufactured in England), with 50 KN compression load cell, Integrator, with accuracy of 0.001 N. During the test, each bean seed was loaded in between the loading cell, making sure the bean seed is in alignment with the centre of the loading cell. The compression was done until the bean seed ruptured, with the sensitivity of the machine set at number five. Three loading rates (25 mm/min, 20 mm/min and 15 mm/min), three orientations (X, Y and Z axes), and three seed sizes (large, medium and small) were considered. The X -axis is in the plane containing the seed hilium line; Z-axis is the plane perpendicular to the seed hilium line, while Y-axis is the seed longitudinal axis (Bagheri *et al*., 2011) as shown in (Figure 1).The force and energy required for the rupture of the bean seed were determined electronically by the microprocessor of the machine and read directly from the screen of the machine.

Bean seed like other biological materials has complex biomechanical systems and behaviour; therefore, it cannot be categorized with simple constants (Mohsenin, 1986; Lysiak, 2007), consequently, it is necessary to introduce some concepts such as bio-yield and rupture point (Uguru and Iweka, 2019).The bio-yield point indicates the initial cell (microstructure) rupture in the cellular structure of a bio-material (ASAE Standard, 1980), and occurred at any point beyond the point of Linear Limit (Eze *et al*., 2017). According to (Steffe, 1996; Eboibi and Uguru, 2017) rupture point of the bean seed correlates to the macroscopic failure (breaking point) of the seed. Each test was done in fifteen replications and the average value recorded.

Experimental design

A 3 x 3 x 3 Completely, Randomized Design (CRD) was employed to study the effects of loading rate, seed orientation and seed size on fracture resistance of Honey bean seed under quasi static compressive loading. The loading rate range and loading orientation were selected based on literature review (Bagheri *et al*., 2011; Oghenerukevwe and Uguru, 2018). The statistical analysis of the study was done on randomized complete

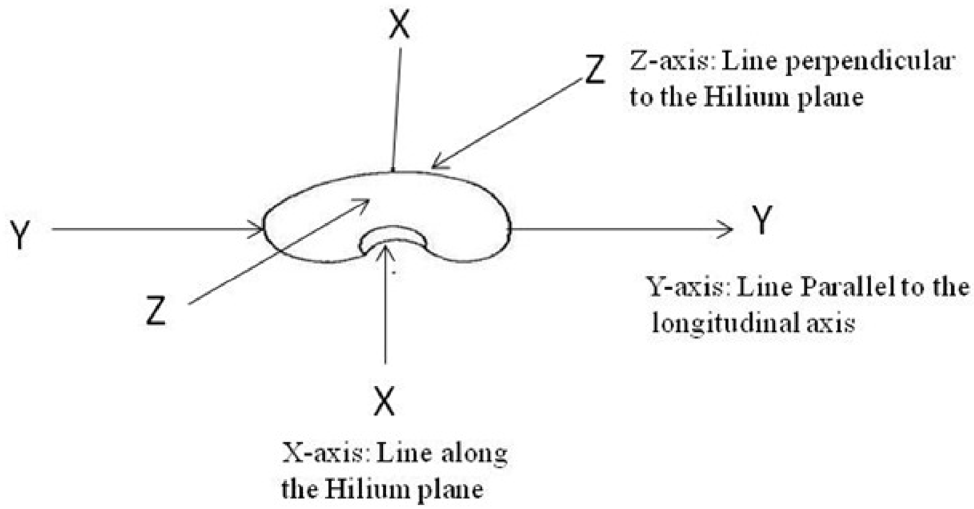

Figure 1. The three orientations of bean seed.

block design, and the analysis of variance (ANOVA) was done by using the SPSS version 20.0 software. The means were separated using the Duncan's multiple ranges test at ($P \leq 0.05$).

RESULTS AND DISCUSSION

The Analysis of Variance (ANOVA) of the data obtained from this study is shown in (Table 3). From the results presented in (Table 3), loading rate, bean size and seed orientation had significant effect ($P \leq 0.05$) on the rupture force and rupture energy of the Honey bean seed. The interaction effect of loading rate and seed size also had significant effect ($P \leq 0.05$) on rupture force and energy of the bean seed. Based on the ANOVA results, interaction effect of loading rate and seed orientation was not significant on rupture force and rupture force of the Honey bean seed. In addition, the interaction of seed size, seed orientation and loading rate, was significant at 5% level on rupture force and rupture energy of the Honey bean seed.

Effect of bean seed size on the fracture resistance

From the results, rupture force of the bean seed increased with increase in the seed size. The average rupture force of the large seed was about 45 % of that of small seeds, across the three loading rates. In addition, the bean seed size had no significant effect on the energy required to fracture the seed, but the energy absorbed by the seed at rupture point increased with increase in the seed size (Figure 2). This may be attributed to the fact the large bean seed is capable of withstanding more deformation under compressive loading, and subsequently yielding an increase in rupture force and energy (Saiedirad *et al*., 2008). Similar trend was reported for Jatropha curcas seed by Karaj and Müller, (2010).

Seed orientation and loading rate on the fracture resistance

The results of the effect of seed orientation on the mechanical properties of bean seed during quasi static compression loading are presented in (Table 4). As shown in (Table 4), Honey bean seed was most flexible in the Z-axis, followed by the X-axis and least in the Y-axis. This shown that during loading, to achieve rupture point under vertical orientation (Y-axis) required lesser force and energy than that under horizontal orientation (X-axis and Z axis). This could be attributed to the cellular arrangement of the bean seed, and possibly due to the smaller surface contact area between the bean seed and the machine loading cell during vertical orientation (Saiedirad *et al*., 2008; Uguru and Iweka, 2019). Similar results were obtained by Altuntaş and Karadag, (2006) when they investigated the mechanical properties (rupture force, specific deformation and rupture energy) of sainfoin, in respect to their loading orientation (X-, Y- and Z-axes). Altuntaş and Karadag results shown that the mean values of the rupture force, specific deformation, and rupture energy for sainfoin seed were 7.40, 9.72, and 4.56 N; 8.94%, 1.71%, and 9.97%; and 1.97, 0.46, and 0.71 N mm along X-, Y- and Z-axes, respectively. Saiedirad *et al*. (2008) investigated the effects of seed size, orientation, and compression loading rate on the rupture force and rupture energy of cumin seed.

Table 3. ANOVA of the parameters investigated on the rupture force and rupture energy of *honey* bean seed.

Source of variation	Rupture force	Rupture energy
Loading rate	2.78E-26*	5.86E-24*
Seed orientation	5.74E-19*	1.13E-20*
Seed size	9.87E-28*	2.36E-28*
Loading rate x seed orientation	0.33375^{ns}	1.61E-04*
Loading rate x seed size	1.07E-05*	1.92E-04*
Seed orientation x seed size	5.83E-05*	7.03E-07*
Loading rate x seed size x seed orientation	0.00726*	0.08210*

* = significant at (P ≤0.05); ns = not significant.

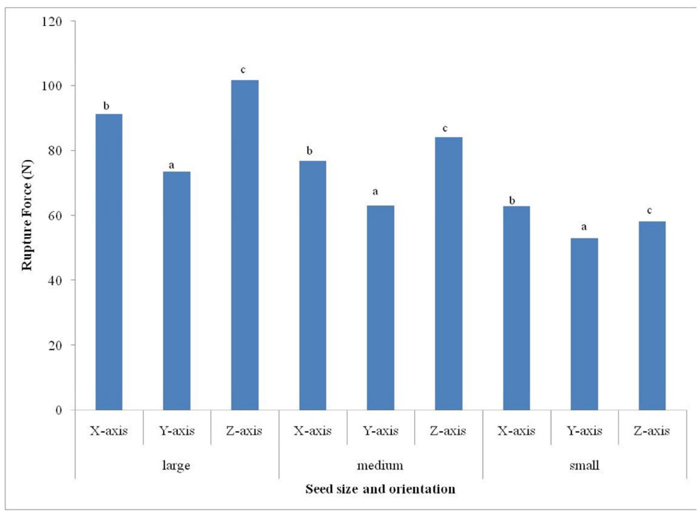

Figure 2a. Rupture force.

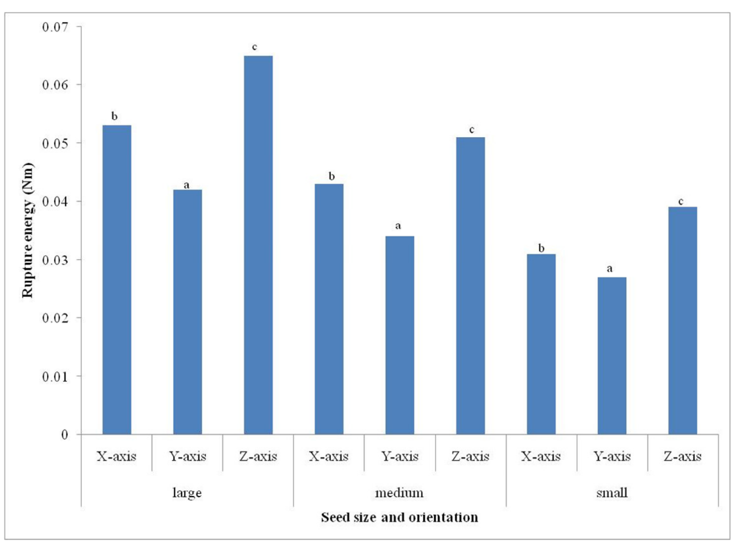

Figure 2b. Rupture energy

Figure 2. Effect of seed size and seed orientation on the rupture force and energy of honey bean seed. Columns with the same common letter not significantly different (P < 0.05) according to Duncan's multiple ranges test.

Table 4. Mean values of the rupture force and rupture energy of honey bean seed, as influenced by interaction of loading rate and seed orientation.

Loading rate (mm/min)	Bean Seed Orientation					
	Rupture force (N)			Rupture energy (Nm)		
	X-axis	Y-axis	Z – axis	X-axis	Y-axis	Z – axis
15	90.01^{a}	76.41^{b}	95.70^{c}	0.0520^{a}	0.0442^{ab}	0.0960^{b}
20	75.93^{a}	63.60^{b}	86.86^{c}	0.0419^{a}	0.0328^{ab}	0.0554^{b}
25	60.15^{a}	49.31^{b}	66.19^{c}	0.0337^{a}	0.0260^{ab}	0.0379^{b}

The means with the same superscript letter, in the same column are not significantly different ($P < 0.05$) according to Duncan's multiple ranges test.

Their results showed that the seed rupture force decreased from 58.2 to 28.8 N for vertical and horizontal loading orientations; while the energy absorbed at the seed rupture decreased from 14.6 to 7.6 mJ, for vertical and horizontal orientations, respectively.

Fracture resistance as a function of loading rate

The results presented in (Table 4) shown that the fracture resistance of Honey bean seed was a function of its loading rate. The rupture force and energy of the seed decreased as loading rate increases from 15 mm/min to 25 mm/min. Similar results were reported by (Uguru and Nyorere, 2019), on SAMNUT 11 groundnut kernels, where the failure force of SAMNUT 11 kernels decreased from 0.068 Nm to 0.028 Nm, as the compression loading rate increased from 15 mm/min to 25 mm/min. Kilickan and Guner, (2008) and Ince *et al.* (2009) investigated the effect of seed orientation and size on its mechanical properties during compressive loading. In their results, Ince *et al.* (2009) recorded the highest rupture force (122.76 N) of peanut kernel at its X-axis; while Kilickan and Guner reported that the rupture force of olive fruit increased with an increase in the fruit size. According to Unal *et al*. (2006), the shelling resistance of black-eyed pea along any of the three major axes was highest while loading along the Z-axis (thickness), whereas loading along the X-axis (width) required the least force to resistance. In similar trend, Niveditha *et al*., (2013) recorded that the force required to rupture *Canavalia cathartica* seeds in the axial orientation was significantly ($p < 0.001$) higher than longitudinal orientation. Rupture force of nuts and kernels is an essential parameter in the design and development of their shelling machines, and their method of shelling

Conclusions

This study was carried out to determine the effects of loading rate, seed size and seed orientation of selected mechanical properties (rupture force and rupture energy) of Honey bean seed. The following conclusions can be deduced from the results obtained from the study.

(i) There was a strong relationship for Honey bean seed fracture resistance as a function of seed size, seed orientation and loading rate.
(ii) The fracture resistance of the bean seed increased with increase in the seed size.
(iii) The force and energy required at rupture point for large-size bean seed were higher in the Z – axis than in the Y-axis and X- axis. The highest rupture energy (0.470 Nm) was obtained at the Z-axis of the seed, when loaded at the rate of 15 mm/min; while the lowest rupture energy (0.213 Nm) was obtained at the Y-axis of the seed, when loaded at the rate of 25 mm/min.
(iv) The results of this study depicted that smaller bean seed was unable to withstand higher compressive, unlike its larger seed counterparts.
(v) The bean seed was less flexible in the vertical loading position (Y-axis) than in the horizontal loading position (X and Z axes), probably due to the buckling of the seed during compression loading.

Authors` Declaration

We declare that this study is an original research by our research team and we agree to publish it in the journal.

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