Mechanical Behaviour of Common Bean (*cv. Butter*) Seeds as Affected by Maturation

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Authors' contributions

This work was carried out in collaboration among all authors. Author HU designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors OIA and SVI managed the analyses of the study. Author AOI managed the literature searches. All authors read and approved the final manuscript.

Article Information

Original Research Article	*Received 01 September 2019* *Accepted 06 November 2019* *Published 22 November 2019*

ABSTRACT

In this study, the effects of maturation of bean seeds on some mechanical behaviours of common bean (cv. Butter) were investigated. The bean seeds were harvested at three maturity stages (15 DAPA, 22 DAPA and 29 DAPA), and their rupture force, rupture energy, specific deformation, toughness and rupture power were test. The bean seeds were quasi-statically loaded in along their three main axes (X-axis, Y-axis and Z-axis), at a loading speed of 25 mm/min. The results obtained revealed that the maturity stage and loading orientation had significant (p ≤0.05) effect on all the mechanical parameters investigated in this study. According to the results, all the parameters investigated increased linearly as the bean seeds matured from 15 DAPA to 29 DAPA. For all the

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mechanical parameters, the highest values were obtained when the seeds were compressed along the Z-axis, while the least values were obtained when the seeds were compressed along the Y-axis. The highest rupture energy (0.064 Nm) was obtained for bean seeds (harvested at 29 DAPA) loaded along the Z-axis, while the bean seeds harvested at 15 DAPA and loaded along the Y-axis required the least energy to rupture (0.028 Nm). From the results, at 29 DAPA, the mean rupture power of 0.277 W, 0.212 W, and 0.314 W were recorded, when the seeds were compressed along the X-axis, Y-axis and Z-axis respectively. These results will be useful in the design and development of bean seeds processing and handling equipment.

1. INTRODUCTION

Common bean (*Phaseolus vulgaris* L.) is one of the leguminous crops extensively grown and consumed in Nigeria. Different cultivars of common bean are cultivated for their edible seeds and leaves. Common bean leaves are rich in vitamins and minerals, and are used as vegetable in soups preparations [1]. The common beans seed is quite rich in vitamins, proteins, dietary fiber, total carbohydrate, and minerals, but very poor in cholesterol and saturated fat; making it one of the best food crops [2-4]. Bean seeds come in different colors, shapes, sizes, nutritional values, engineering properties etc. depending on the cultivar, farming method, soil condition, climatic and technological factors [5-6]. According to Food and Agriculture Organization (FAO) statistics, 24.1 million tons of bean seeds were harvested in the world in 2017, out of which Africa accounts for total production of 756,345 tons with export quality of 217,077 tons [7]. In Nigeria, beans are normally cultivated the North-central and North-western parts of the country. But bean cultivation is not limited to those regions of Nigeria, a good quantity of bean are cultivated in the South-west region of the country.

The knowledge of the mechanical properties (fracture resistance) of agricultural products is essential for the design and development of dehulling and grinding systems [8-9]. This is because these properties not only constituted the basic engineering data required for machine and equipment design, but also they assist the selection of suitable methods for obtaining those data [10-11]. Recently, intensive researchers are been carried out on some engineering properties of agricultural products. Eboibi and Uguru [12] investigated the effects of variety and maturity stage on some physical characteristics of common bean seeds, and observed that maturity of the bean seeds significantly (P≤ 0.05) influenced most of the physical characteristics

investigated. In their results the *Iron* bean seed true density increased from 817.75 kg/m^3 to 1207.0 kg/m^3, while the bulk density increased from 464.5 to 761.75 kg/m^3 as the bean seeds matured. In addition, Akinoso and Raji [13] reported that rupture force of for *Tenera* and *Dura* date palm fruits were 806.1 and 3,924.6 N at 5% wet basis and 40ºC heat temperature, respectively. According to Kilickan and Guner [14] the specific deformation of the olive fruit increased in magnitude with an increase in deformation rate and size. In a research on ground kernel, Uguru and Iweka [15] stated that groundnut kernel size significantly (P ≤0.05) affects the firmness and toughness of SAMNUT 10 groundnut kernel.

Engineering properties of agricultural products (fruits, seeds, roots and tubers) are highly influenced by the farming method, harvesting period, local climate, cultivar, maturity stage, and insect and pests pressure. Iweka and Uguru [16] reported that the rupture energy of okra seed and pod was observed to increase with increase in maturation for okra seed and pod from maturity stage 1 to maturity stage 5. In related development, Demir, et al. [17] observed significant difference on some engineering properties of tomato (*Lycopersicon esculentum*) planted under different environmental conditions. According to Iweka and Uguru [17], maturity stage (mostly at harvest) is one of the vital factors that determine the quantity and quality of seeds produced. Plant growth regulatory substances have been established by Demir, et al. [18] as a factor that influences the physical, mechanical, chemical properties and bioactive compounds in fruits. In a study carried on two groundnut cultivars (SAMNUT 10 and SAMNUT 11), Uyeri and Uguru [11] observed that the force required for initiating the kernel rupture was higher for SAMNUT 10 groundnut (76.10 N) than for the SAMNUT 11 groundnut kernel (64.19 N). Different apple cultivars gave different results when subjected to compression loading, failure

energy of *Redspar* and *Delbarstival* apple cultivars were observed to be 127.59 and 51.06 N mm respectively [19].

Since agricultural materials structures are heterogeneous and anisotropic, mechanical stresses are distributed inhomogeneous within their body [20,21]. Sunflower kernels were reported to have lower rupture force loaded in the horizontal orientation than when loaded in the vertical orientation, implying flexibility in the horizontal orientation [22]. Uguru, et al. [4] reported that the fracture resistance of *honey* bean seed when compressed in the Z-axis was higher (118 N), when compared with the result obtained when the seed was compressed in the Y-axis (42.16 N). Compression orientation and speed affect the amount of force applied to post-harvest applications for plum fruits [23]. The technological characteristics of different biomaterials are closely associated with the development microstructure as a result of deformations in cells and intercellular spaces [24].

Although many researches have been done on the mechanical properties of agricultural products, little information is available on the effect of maturity age on the fracture resistance of Nigeria grown *butter* bean seeds The design and development of a *butter* bean seed dehulling and milling machine require the knowledge of the mechanical properties (e.g. fracture resistance) of the seeds at different maturity age. The objective of this study was to determine some mechanical properties (rupture force, modulus of elasticity, toughness, and rupture energy) of *butter* bean seed as affected by maturity age and loading orientation.

2. MATERIALS AND METHODS

2.1 Experimental Site

The *butter* bean seeds for this study were planted at the Research Farm of the Delta State Polytechnic, Ozoro, Nigeria. The area had an average altitude of 14 m above sea level, and average temperature of 30ºC, during the growing season. Physicochemical analysis of soil samples randomly collected from the study area was done in accordance to standard recommended procedures [25,26].

2.2 Plant Cultivation

A local high yield bean variety, namely; *butter* bean collected from local farmers in Kano State,

Nigeria was used in this study. The obtained seeds were planted in the Research Farm of Delta State Polytechnic, Ozoro, Nigeria under organic farming method. When the bean plants had started flowering, daily observations were conducted on the bean plants and the flowers coded according to their day of anthesis.

2.3 Bean Seeds Sampling Procedure

The bean pods were harvested at three maturity stages of 15, 22 and 29 days after peak anthesis (DAPA) and sun dried (31±3ºC) for seven days. Then the pods were shelled and manually inspected to remove all deformed, pest and disease infested seeds. The seeds were further selected based on uniformity of size and shape. Extremely large or small seeds were discarded from the lot (bean seeds) before there taken to the laboratory for mechanical testing.

2.4 Mechanical Test

Mechanical tests of the bean seeds were carried out by using a Universal Testing Machine (Testometric model, manufactured in England), with 500 N compression load cell, controlled by a microcomputer, with accuracy of 0.001 N. The operating parameters of the machine were as follows: preload speed of 50 mm/min, test-speed of 25 mm/min and sensitivity of 5. During the test, each individual bean seed was placed in between the loading cells, making sure it was in alignment with the loading cells, and compressed quasi statically until the seed ruptured (Fig. 1). As the quasi static compression progressed, a force-deformation curve was plotted automatically by the Universal Testing Machine in relation to the response of the bean seed to the loading (Fig. 2). As soon as the rupture point of the bean seed was detected by the machine, the loading was stopped automatically. At the end of each test, data on the mechanical properties (rupture force, rupture energy and deformation at rupture point) were automatically calculated by the integrator and read from the computer screen.

Butter bean seed has complex non-isotropic system, just like other agricultural products. Therefore, it is practically difficult to characterize by simple constants (e,g. stress) because its size and shape changes continually during compression. Consequently, it becomes necessary to introduce some concepts such as failure and rupture points in characterizing it [27-28]. The American Society of Agricultural

Engineers (ASAE, St. Joseph, MI) has established a standard method for the compression testing of food materials of convex shape (ASAE Standard S368.2) [29]. The bio-yield point also expressed as the failure point indicates the initial cell (microstructure) rupture in the cellular structure of a bio-material (ASAE Standard), and occurred at any point beyond the point of Linear Limit [30,31]. In addition, according to ASAE, rupture point of a bio-material correlates to the macroscopic failure (breaking point) of the bio-material [15,30].

Fig. 1. A bean seed undergoing quasi-compression test

The bean seed was tested in three orientations (axes) as shown in Fig. 3. The X -axis is in the plane containing the seed hilum line; Z-axis is the plane perpendicular to the seed hilium line, while Y-axis is the seed longitudinal axis [4,10]. As recommended by ASABE [29], all the mechanical tests were replicated 20 times, and the mean values were recorded.

Each bean seeds were measured with digital caliper (Model No; Titan 23175) to determine the length, width and thickness of the samples before mechanical test. Toughness of the *butter* bean seed was calculated as the energy absorbed by seed up to the rupture point as shown in Equation 1. The rupture power is powered required to rupture the *butter* bean seed, and it was calculated by using equation 2; while the volume (V) of the *butter* bean seed was calculated using equation 3 [21,32]. In addition, the strain (specific deformation) of the bean seed at rupture point was calculated using equation 4 [33].

$$T_o = \frac{E}{V} \tag{1}$$

$$P = \left(\frac{E \times S}{6000D}\right) \tag{2}$$

$$V = \frac{\pi \times L \times W \times T}{6} \tag{3}$$

$$\varepsilon = \left[1 - \frac{l_i}{l_o}\right] \times 100 \tag{4}$$

Where:

T_o = Toughness (mJ/mm^3),
E = Rupture energy or energy absorbed by the seed (Nm),
V = Volume of the seed (m^3),
P = Power (W),
S = Compression speed (mm/min),
ε = Specific deformation (%),
l_i = Length of deformed bean seed measured in the direction of the compression axis,
l_o = Length of the un-deformed bean seed measured in the direction of the compression axis,
D = deformation at rupture point (m)
L = length of the seed (mm),
W = width of the seed (mm),
T = Thickness of the seed (mm).
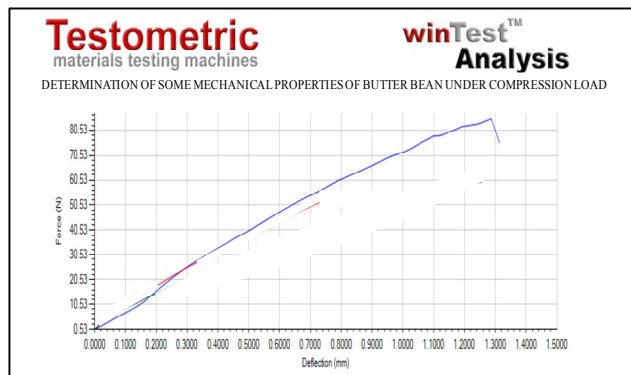
(a)
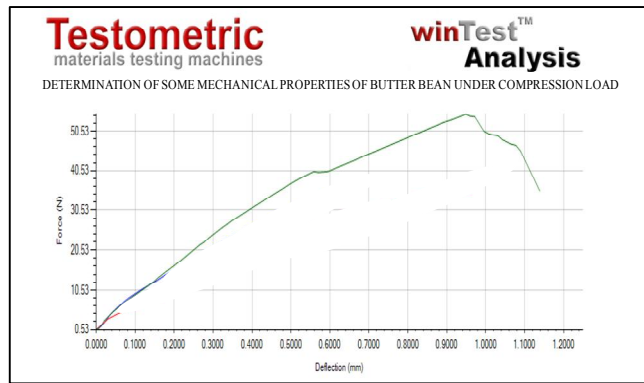
(b)

Fig. 2. A force-deformation curve plotted by the machine.(a)Compression along Z-axis; (b)Compression along Y-axis
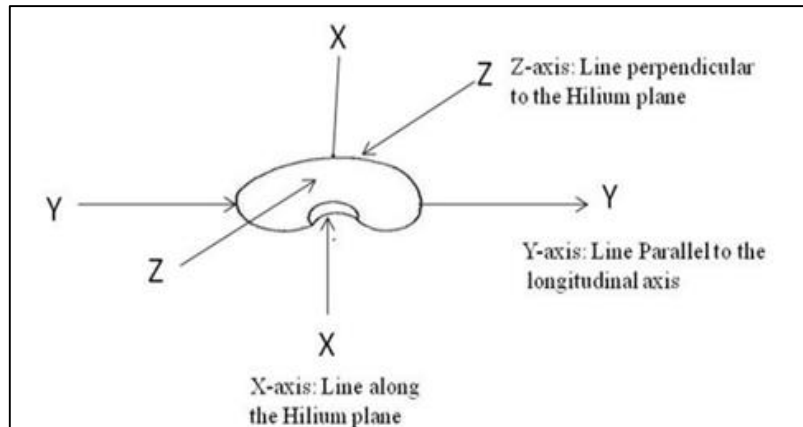

Fig. 3. The three orientations of bean seed [4]

2.5 Statistical Analysis

All data obtained from this study were subjected to statistical analysis using the using the Statistical Package for Social Statistics (SPSS version 20.0) and Duncan's Multiple Range Test (DMRT) was used to compare the mean at 95% confidence level.

3. RESULTS AND DISCUSSION

Results of the physicochemical properties of the soil where the butter bean was cultivated are presented in Table 1 showing that the soil was fairly neutral with appreciable potassium, phosphorus and calcium content.

3.1 Rupture Force

The results of the effects of maturity stage and compression axis on the rupture force of the

butter bean seed are presented in Fig. 4 showing that the effect of compression axis and maturity stage on the rupture force of the *butter* bean seed was statistically significant (p ≤0.05). According to the results, the force required to initiate butter bean seed rupture increased linearly as the seed matured from 15 DAPA to 25 DAPA, across the three axes tested. From the results (Fig. 4) the rupture force required when loading the seed along the Z- axis was the highest (54 N at 15 DAPA which increased to 83 N at 29 DAPA). The Y-axis of the seed recorded the lowest resistance to rupture force during loading. The rupture force measured along the Y-axis was 33 N at 15 DAPA and increased to 45 N at 29 DAPA. This shows that the *butter* bean seeds were most flexible in the Z-axis and least flexible in the Y-axis. Although, maturity stage significantly affects the rupture force of the *butter* bean seeds, no significant difference was observed between the rupture force of the seeds

harvested at 22 DAPA and those harvested at 29 DAPA (Fig. 4). The variation in the rupture force of the bean seed when loaded in the three axes could be attributed to the Non-isotropic nature of a bean seed, and variation in the surface contact area between the bean seed and the machine during loading. Similar results were obtained for honey bean seeds [4] and plum fruits [33]. Uguru, et al. [4] reported that *honey* Z-axis (the plane perpendicular to the seed hilium line) of *honey* bean seed recorded the highest rupture force (95.70 N) during loading, while the Y-axis (the seed longitudinal axis) of *honey* bean seed recorded the lowest rupture force (76.41 N) during loading. Altuntas, et al. (2013) observed that the force require to rupture plum fruits varied significantly (p ≤0.01) when the fruit was loaded

the three axes; the results were 180 N in the X-axis, 243.6 N in the Y-axis and 200.8 N in the Z-axis. Kilickan and Guner [14] reported that the rupture force of the olive fruit varied with the fruit orientation, the rupture force values along the fruit's X-axis and Y-axis were 94.45 N and 57.38 N respectively.

3.2 Relative Deformation at Rupture Point

The result of the specific deformation of the butter bean seed is presented in Fig. 5. As shown in Fig. 5, maturity stage significantly (p ≤0.05) affects the specific deformation of the bean seed. The specific deformation generally decreased along the Z -, X-, and Y-axis as the bean seeds matured. Bean seeds harvested at

Table 1. Physicochemical properties of the study area soil sample

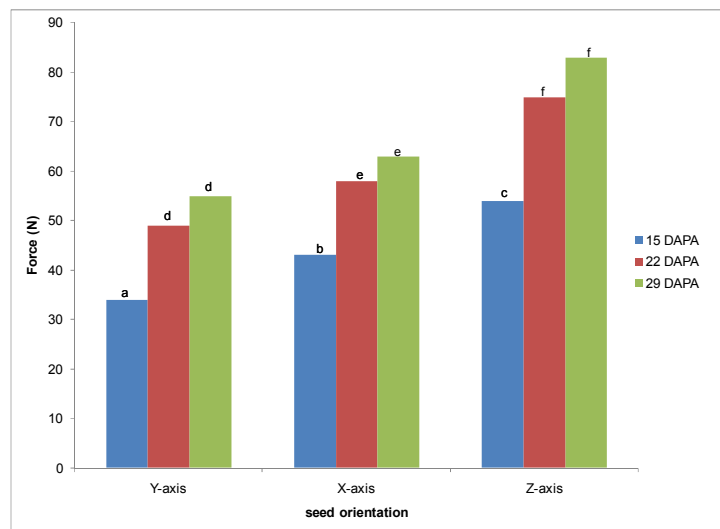| Parameter	Unit	Level
Particle size distribution		
Sand	%	40.1
Silt	%	39.6
Clay	%	20.3
Chemical analysis		
Soil pH (H_2O)		6.75
Total nitrogen	(mg/kg)	4.22
Available Phosphorus	(mg/kg)	15.31
Nitrate	(mg/kg)	8.63
Sodium	(mg/kg)	315.78
Extractable Potassium	(mg/kg)	737.55
Calcium	(mg/kg)	425.82

Fig. 4. Effect of maturity stage and seed orientation on the rupture force of *butter* bean seed
Columns with the same common letter not significantly different (p ≤0.05) according to Duncan's multiple ranges test

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29 DAPA had the least mean specific deformation; when compare with the bean seeds harvested at 15 DAPA, which had the highest mean specific deformation. The specific deformation values of the bean seed decreased from 19.8% to 15.5% as the seed matured from 15 to 29 DAPA through the three bean seed axes tested. This signifies that bean seeds harvested at 15 DAPA were more ductile than those harvested at 29 DAPA. The results further revealed that no significant (p ≤0.05) difference existed between the specific deformation of the bean seeds harvested at 22 DAPA and those harvested at 29 DAPA. For all maturity stages, bean seeds compressed in Z-axis loading position suffered greatest deformation compared with the ones compressed in X- axis and Y-axis loading position (Fig. 5). This could be attributed to the fact that the bean seed Z-axis had the largest surface area of contact with the compression plates compared with seed X- axis and Y-axis. Therefore, the seed will absorbed more energy in Z-axis than in the other two axes before rupture under the same experimental conditions. Altuntas, et al. [33] reported similar result for plum fruits, where the specific deformation of the fruits decreased from 28.13% to 16.84% as the fruits matured. Kilickan and Guner [14] reported that the highest specific deformation of olive fruit was obtained when the fruit was compressed along the X-axis [33]. Similarly, Oghenerukewve and Uguru [34]

observed that fruit axis had significantly (p < 0.05) effect on the mechanical properties *Gmelina arborea* (*Gmelina arboreal* Roxb) fruit, as the force and energy required to initiate failure and rupture of the fruit under axial compression was lower when compare to the longitudinal compression.

3.3 Rupture Energy

The rupture energy of the *butter* bean seeds is presented in Fig. 6. According to the results, maturity stage had significant (p ≤0.05) effect on the rupture energy of the bean seeds. Results obtained from the study (Fig. 6), showed that the rupture energy of the bean seed was generally highly dependent on its maturation and orientation. Rupture energy of the bean seeds increased linearly along the X, Y and Z axes as the *butter* bean seeds matured from 15 DAPA to 29 DAPA. For all cases (maturity stages), the rupture energy of the bean seeds when compressed along the Z-axis were higher than those compressed along the Y- and X-axes. The highest rupture energy (0.064 Nm) was obtained for bean seeds (harvested at 29 DAPA) loaded along the Z-axis, while the bean seeds harvested at 15 DAPA and loaded along the Y-axis required the least energy to rupture (0.028 Nm). The rupture energy measured when the seeds were compressed along the X-axis was found to be 0.038 Nm, 0.047 Nm and 0.051 Nm for the seeds
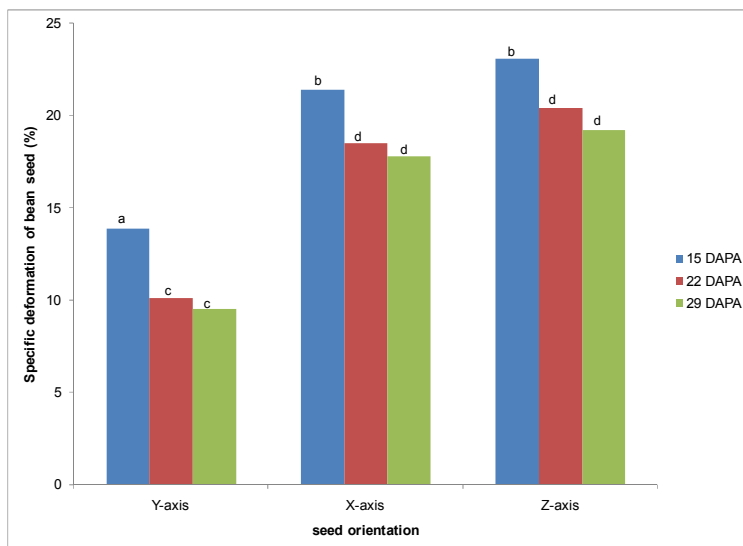

Fig. 5. Effect of maturity stage and seed orientation on specific deformation of *butter* bean seed
Columns with the same common letter not significantly different (p ≤0.05) according to Duncan's multiple ranges test
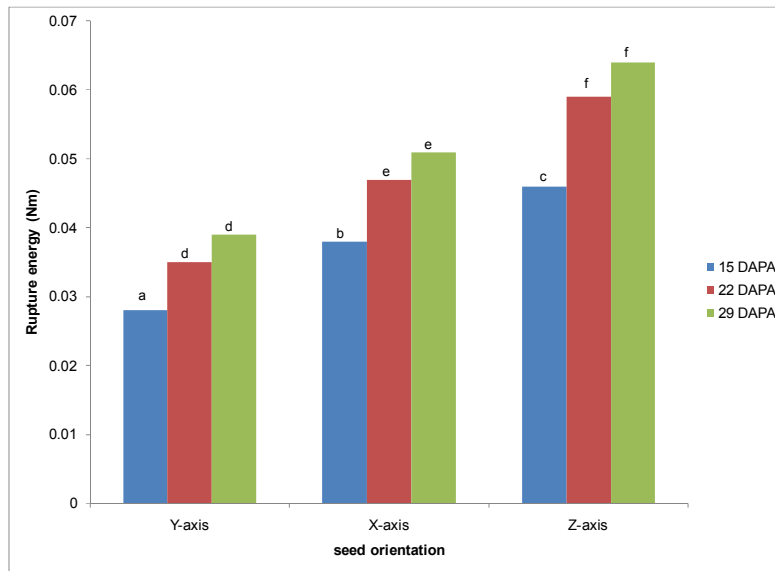
Fig. 6. Effect of maturity stage and seed orientation on the rupture energy of *butter* bean seed
Columns with the same common letter not significantly different (p ≤0.05) according to Duncan's multiple ranges test

harvested at 15 DAPA, 22 DAPA and 29 DAPA respectively. These results showed that the *butter* bean seeds absorbed more energy before rupture when compressed in the Z-axis, and the seeds harvested at 15 DAPA were unable to absorb much energy rupturing. Similar results were obtained for *honey* bean seeds [4] and African nutmeg [35]. Uguru, et al. [4] reported rupture energy values of 0.0520 Nm, 0.0442 Nm and 0.0960 Nm when *honey* bean seed was compressed along the X- axis, Y-axis and Z – axis, respectively. Furthermore, Saiedirad *et al.* [8] investigated the effect of orientation on the rupture force and rupture energy of cumin seeds during compression. They recorded a rupture force and energy of 58.2 N and 14.6 mJ during the vertical compression, which was higher when compare to the rupture force and energy of 28.8 N and 7.6 mJ recorded during the horizontal compression.

3.4 Toughness

Toughness of the bean seeds when tested in the three orientations are presented in Fig. 7. As shown in Fig. 7, maturity stage significantly (p ≤0.05) affects the toughness of the *butter* bean seeds. Generally, the highest toughness was recorded for the seeds harvested at 29 DAPA; while the lowest toughness was recorded for the seeds harvested at 15 DAPA. In both loading orientations, the toughness of the bean seeds increased significantly (p ≤0.05) as the maturity

stage increased (from 15 DAPA to 29 DAPA). For all cases, it was observed that the highest toughness (0.372 mJ/mm^3) was recorded when the bean seed harvested at 29 DAPA was compressed in the Z-axis. In addition, the lowest toughness (0.215 mJ/mm^3) was recorded when the bean seeds harvested at 15 DAPA were compressed in the Y-axis. As seen in the results, significant (p ≤0.05) difference only occurred between the toughness of bean seeds harvested at 15 DAPA and 22 DAPA; in contrast, there was no significant difference between the toughness of the seeds harvested at 22 DAPA and 29 DAPA (Fig. 7). Similar results were obtained for plum fruits [33], when compressed in three axes (X-axis, Y-axis and Z-axis). The higher toughness value obtained in the bean seeds harvested at 29 DAPA when compared to the values obtained in the bean seeds harvested at 22 DAPA and 15 DAPA could be attributed to the differences in their cellular structures. Toughness of seeds and nuts is an essential parameter in the design and development of their milling machines.

3.5 Rupture Power

The results of the study presented in Fig. 8 showed that the average power requirement of the bean seeds were significantly (p ≤0.05) affected by the maturity period and seed orientation. Considering the bean seeds maturation, the bean seeds harvested at 29

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DAPA had highest rupture power compared to their counterparts harvested at 22 DAPA and 15 DAPA. As shown in Fig. 8, the highest rupture power was recorded when the bean seed was compressed along the Z-axis; while the least rupture power was recorded when the seed was compressed along the Y-axis. From the results, at 29 DAPA, the mean rupture power of 0.277 W,

0.212 W, and 0.314 W were recorded, when the seeds were compressed along the X-axis, Y-axis and Z-axis respectively. According to Fig. 8, a rupture power of 0.145 W (15 DAPA), 0.208 W (22 DAPA) and 0.277 W (29 DAPA), was recorded when the bean seed was compressed along X- axis. The study results depicted that more power is consume as the butter bean
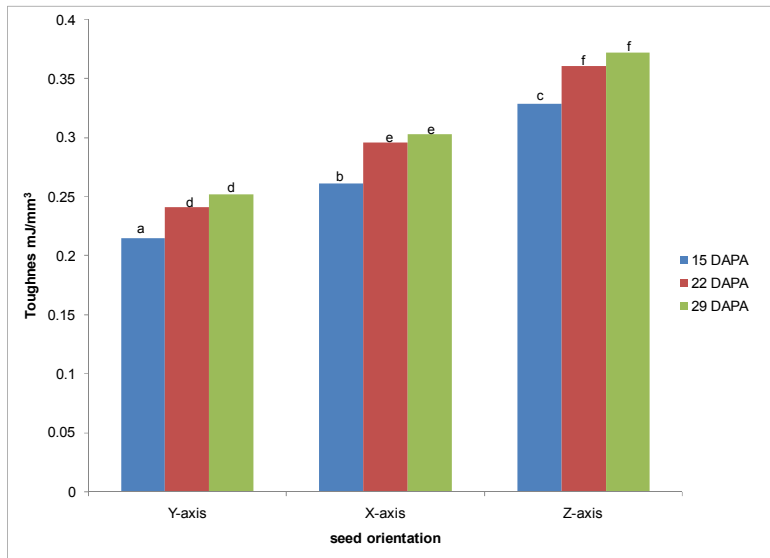

Fig.7. Effect of maturity stage and seed orientation on the toughness of *butter* bean seed
Columns with the same common letter not significantly different (p ≤0.05) according to Duncan's multiple ranges test
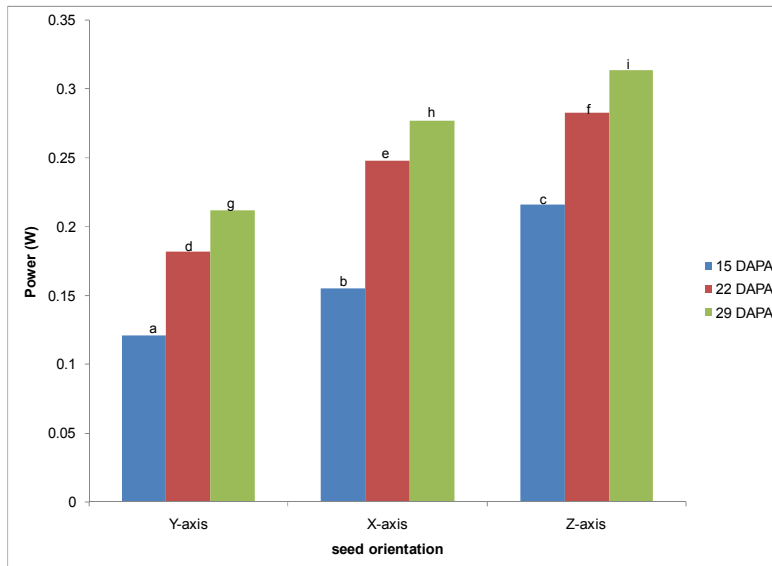

Fig. 8. Effect of maturity stage and seed orientation on the rupture power of *butter* bean seed
Columns with the same common letter not significantly different (p ≤0.05) according to Duncan's multiple ranges test

seeds matured, and if nutritional values of the bean seeds are not affected it is advisable to harvest the bean seeds at a much younger age. Similar results were obtained by Khazaei et al. [36] where the rupture power required to crack an almond and its kernel increased with increasing almond size and the loading speed. The discrepancies in the bean seed rupture power when compressed along its three main axes could be attributed to its heterogeneous cellular structure and anisotropic nature.

4. CONCLUSION

In this study, some mechanical properties (rupture force, rupture energy, specific deformation, toughness and rupture power) of *butter* bean seeds were assessed over the course of three maturity stages (15 DAPA, 22 DAPA and 29 DAPA). The bean seeds were compressed along their three main axes (X-axis, Y-axis and Z-axis), at a loading speed of 25 mm/min. The results obtained from the study indicated that all the mechanical properties were highly dependent on maturity period and the compression axes. From the results, all the mechanical parameters investigated increased as the bean seeds matured from 15 DAPA to 29 DAPA. In addition, compression axis had significant effect (p ≤0.05) on all the mechanical parameters investigated. The results further revealed that the specific deformation, rupture force, rupture energy and rupture power values observed for bean seeds compressed along the Z- axis were highest when compare to the values obtained when they (bean seeds) were compressed along the X- and Z- orientations. Generally, the least mechanical properties were obtained when the seeds were compressed along the Y-axis (longitudinal ordination). The results obtained from this study will be helpful in the design and fabrication of bean seeds processing and packaging systems.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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