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Effect of Fruit Size and Orientation on Mechanical Properties of Gmelina Fruit (Gmelina arborea) Under Quasi-Static Loading

Eng. Oghenerukevwe P.O., Mr. Hilary Uguru

***Abstract*— The knowledge of mechanical properties biomaterials is essential for the proper design of harvesting and processing machineries. In this study, seven mechanical parameters (failure force, failure energy, maximum compressive force, rupture force, rupture energy, maximum strain and relative deformation at rupture) of gmelina fruit was measured at three different fruit sizes (small, medium and large) and in two different fruit orientations (axial and Longitudinal), at a loading speed of 20 mm/min. The results obtained statistically showed that fruit size significantly ($P < 0.05$) affected the failure force, maximum compressive force, rupture force, rupture energy, maximum compressive strain, and relative deformation of the gmelina fruit; while it does not significantly ($P < 0.05$) affected the failure energy. Failure force was 51.01, 67.16 and 86.28; maximum compressive force was 156.47, 204.99, 263.65; Rupture force was 146.82, 185.25 and 238.57 N; Failure energy was 0.186, 0.229 and 0 .293 Nm; Rupture Energy was 0.899, 1.149, and 1475 Nm; maximum strain was 45.25, 61.69 and 79.43%; and relative deformation at rupture was 10.16, 13.13 and 16.89 mm respectively for the small, medium and large gemila fruit. The fruit loading orientation significantly ($P < 0.05$) influenced all the seven mechanical parameters tested apart from the failure force. Also, the result show that gmelina fruit was more flexible in the Longitudinal loading orientation, in all the seven mechanical parameters studied, as the and energy required to initiate failure and rupture of the fruit under axial loading direction was lower than under Longitudinal loading. In respite to the fruit size, the all the seven parameters studied increased progressively from the small size through the medium to the large fruit.**

***Index Terms*— Gmelina fruit; mechanical properties; fruit size; loading orientation; Quasi-static loading; failure point; rupture point**

I. INTRODUCTION

Gmelina arborea (*Gmelina arboreal* Roxb) is a fast-growing tree, which grows on different localities and prefers moist fertile valleys, they attain moderate to large height up to 40 m and 140 cm in diameter [1]. It is occurring naturally throughout greater part of India at altitudes up to 1500 m. It also occurs naturally in Myanmar, Thailand, Laos, Cambodia, Vietnam, and in southern provinces of China, and has been planted extensively in Sierra Leone, Nigeria and Malaysia [2]. This tree is commonly planted as a garden and an avenue tree; growing in villages along agricultural land and on village community lands and wastelands. Flowering takes place during February to April whereas fruiting starts from May onwards up to June. The fruit is up to 2.5 cm long, smooth, dark green, turning yellow when ripe and has a fruity smell [3].

Gmelina arborea seed contains very little kernel but the kernel is quite rich in oil (53 wt.%) [3]; therefore, it is necessary to study its medicinal and industrial value. Gmelina seed oil have been found to be a sustainable material for biodiesel and alkyd resin synthesis in terms of its availability and renewability. Gmelina seed oilbased biodiesel have been produced keeping two criteria in mind; the biodiesel met all the technical and industrial standards of ASTM D6751 and EN 14214, and, met all the ecologically relevant standards [3] [4]. The roots and bark of Gmelina Arborea are majorly used as herbs and laxatives while the leaves serve as feeds for cattle and goats among other uses [5] [6].

Recently, several researchers have researched on the mechanical and physical properties of fruits and seeds, in relation to their moisture contents. According to [7], the failure stress of corn decreased, whereas the failure strain increased with an increase in the moisture content and temperature. The maximum compressive stress for wheat and canola decreased linearly with an increase in the moisture content [8]. The stress, strain, modulus of deformability, and energy to the yield point were found to be functions of the loading rate and moisture content for different varieties of wheat kernels [9]. Some engineering properties of locust bean seed were investigated by [10] and concluded that the seed orientation affected the cracking resistance of the bean. that gave the least resistance to cracking was along the thickness. In 2008, [11] studied the effects of the moisture content, seed size, loading rate, and seed orientation on the force and energy required for fracturing cumin seed under quasi-static loading. Their results showed that the force required for initiating the seed rupture decreased from 15.7 to 11.96 N and 58.2 to 28.8 N, and the energy absorbed at the seed rupture increased from 1.8 to 8.6 mJ and 7.6 to 14.6 mJ, with an increase in the moisture content from 5.7% to 15% dry basis for vertical and horizontal orientations, respectively. The fracture resistance of cumin seed for the loading rates of 2 and 5 mm/min and showed that both the rupture force and energy decreased as the loading rate increased [11].

The optimal design and development of harvesting and processing equipment requires an understanding of the dynamic behaviour of biomaterial particulates. In agricultural and food processes involving particulates, interest is not only focused on the mechanical behaviour and flow of particles within the bulk system but also on the resulting deformation of the individual particles [12]. Agricultural and food materials tend to behave as viscoelastic materials when they are subjected to various conditions of stress and strain [13]. With proper setting of the pressing force in relation to the

Eng. Oghenerukevwe P.O., Lecturer at Department of Mechanical Engineering, Delta state polytechnic, Ozoro, Nigeria.

Mr. Hilary Uguru, Lecturer, Department of Agricultural and Bio-Environmental Engineering, Delta state polytechnic, Ozoro, Nigeria

optimal moisture content, minimum energy input but high efficiency can be achieved within a technology line [14]. There are various ways of extracting oil from oilseeds but solvent extraction has been reported to be most efficient techniques [15]. There is need therefore, for process industries to optimize current methods of extraction, thereby improving the profitability of production and ensuring a sufficient supply of oil.

In our literature review, there is dearth Knowledge about the mechanical properties of gmelina seeds, necessary for the design and development of gmelina oil extraction machine. Therefore, the objective of this study was to investigate the behaviour of different sizes gmelina friut under compression loading, at different loading orientation that will be necessary in the design of handling and processing machine. Parameters including force and energy at failure and rupture point, maximum deformation, and unit size energy were also considered in the study.

II. MATERIALS AND METHODS

A Materials

The gmelina fruits were collected from Delta state polytechnic, Ozoro, Delta state, Nigeria; and were manually inspected to remove dirt, foreign materials, pest infested and broken seeds. The fruits were sorted into small, medium and large size ready to be used for the experiment.

B Fruit size determination

To determine the average size of the fruit, a sample of 40 fruits from each category was randomly selected. The three linear dimensions of the seeds, namely length (L), width (W) and thickness (T) were carefully measured using micrometer reading to 0.01 mm. The geometric mean diameter (D_g) and total surface were computed using the following equations [16].

Geometric mean (D_g)

The geometric mean was calculated by the equations (1)

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

Surface area (S)

The surface area of the fruit and nut was determined according to the following equation.

$$S = \pi D_g^2 \qquad (2)$$

C Mechanical properties determination

The mechanical test of the gmelina fruit was done at the Material Testing Laboratory of the National Center for agricultural Mechanization (NCAM), Ilorin, Kwara state, Nigeria. Each specimen was loaded in a Universal Testing Machine (Testometric model, series 500-532) equipped with a 50 N compression load cell and integrator, with measurement accuracy of 0.001 N. equipped with a 500 N compression load cell as was shown in Figure 1. Each fruit sample was placed in the machine under the flat compression tool (Figures 1 and 2), ensuring that the centre of the tool was in alignment with the cut sample, and compressed at the speed rate of 20 mm/min. As the compression progresses, a load-deformation curve was plotted automatically in relation to the response of each fruit to compression. The electronic computing unit of the machine measured the selected parameters (force, energy, deformation and strain) at failure and rupture point of the gmelina fruit automatically. The following parameters were interpreted by the testometric software of the Universal Testing Machine.

i. Failure force
ii. Maximum compressive force (F_{max})
iii. Rupture force
iv. Failure Energy
v. Rupture Energy
vi. Maximum strain
vii. Relative deformation at rupture

According to [17], bioyield point is related to a failure in the microstructure of the material associated with an initial disruption of cellular structure; and the rupture point of the material, correlates to the macroscopic failure (breaking point) in the sample, the failure strength was taken as the stress at which the sample failed in its internal cellular structure. Whole sample (fruit) was used for this experiment because whole-grain/seed data was more useful in the design of processing machinery and storage containers [18]. Each test was carried out on at 10 replications.

Figure 1: Gmelina fruit undergoing compression testing (Longitudinal loading orientation)

Figure 2: Gmelina fruit undergoing compression testing (Axial loading orientation)

C Statistical analysis

The experiments were conducted with ten replications for each loading orientation and fruit size of the gmelina fruit. The analysis of variance (ANOVA) was carried out on a completely randomized design with factorial experiment using SPSS 20.0 software. The significant differences of means were compared by using the Duncan's multiple ranges test at 5% significant level. Regression equations were computed by using Microsoft Excel software (2010).

III. RESULTS AND DISCUSSION

The analysis of variance (ANOVA) of the mechanical parameters of the gmelina fruit is presented in Table 1. The ANOVA result indicated that fruit size significantly ($P < 0.05$) affected the failure force, maximum compressive force, rupture force, rupture energy, maximum compressive strain, and relative deformation of the gmelina fruit; while it does not significantly ($P < 0.05$) affected the failure energy. The fruit loading orientation significantly ($P < 0.05$) influenced all the seven mechanical parameters tested apart from the failure force. Finally, the interaction effect of fruit × fruit testing orientation does not significantly ($P < 0.05$) affected the seven mechanical parameters investigated.

Table 1: Analysis of variance (ANOVA) of fruit size and loading orientation on the mechanical parameters of gmelina fruit

Source of variation	Dependent Variable	df	F	Sig
F	Failure force	1	3.4773	0.004914*
	F_{max}	1	12.865	0.000987*
	Rupture force	1	9.436	0.004038*
	Failure energy	1	0.92944	0.595873^{ns}
	Rupture Energy	1	13.070	9.11E-04*
	Maximum strain	1	85.027	5.18E-11*
	Deformation at Rupture	1	47.118	4.956E-08*
L	Failure force	1	6.555	0.130173^{ns}
	F_{max}	1	25.710	1.21E-05*
	Rupture force	1	13.966	0.028264*
	Failure energy	1	12.056	0.001361*
	Rupture Energy	1	50.748	2.26E-08*
	Maximum strain	1	44.503	8.9E-08*
	Deformation at Rupture	1	103.564	3.88E-12*
F x L	Failure force	1	0.0719	0.790101^{ns}
	F_{max}	1	0.3537	0.555769^{ns}
	Rupture force	1	0.0781	0.781510^{ns}
	Failure energy	1	1.2869	0.264114^{ns}
	Rupture Energy	1	0.3043	0.584618^{ns}
	Maximum strain	1	0.6117	0.439273^{ns}
	Deformation at Rupture	1	2.1976	0.146925^{ns}

* =Significant at ($P<0.05$), ns= non-significant, L = loading orientation, F = Fruit size.

In the following sections, the effects of each factor on the six mechanical parameters are comprehensively discussed.

A Fruit size

There was significant difference between small, medium and large seed size ($P < 0.05$) as shown in Table 1. The force and energy required to initiate the fruit failure and rupture increased as the fruit increased from small to large size. From the research the fruit size has no effect on failure energy of the gmelina fruit at but fruit loading orientation. This may be attributed to the fact that increase in size of the fruit, leads to more resistance of the fruit to rupture, and larger seeds possess large modulus of elasticity and capable of being more deformable under compressive loading and subsequently fruit failure and an increase in rupture point. A similar trend was reported [11] on cumin seed. The force and energy required to initiate the fruit failure and rupture increased as fruit size increased from small (16.5mm to 35.2 mm) as shown Table 2.

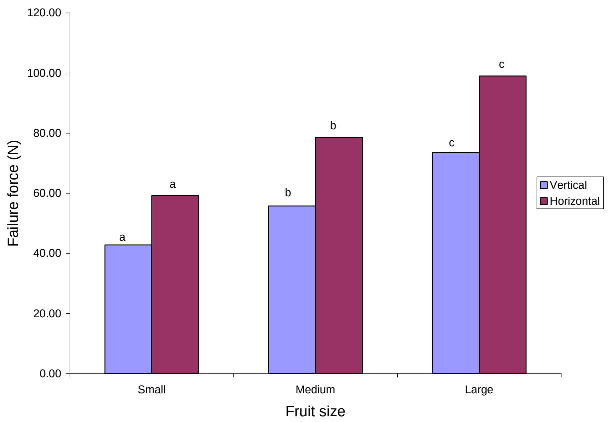
Table 2: Mean comparison of the seven mechanical parameters of gmelina fruit in different fruit size categories.

Parameters	**Fruit size (mm)**		
	Small (15–19 mm)	Medium (20-24 mm)	Large (25-29 mm)
Failure force (N)	51.01^{a}	67.16^{a,b}	86.28^{b}
F_{max} (N)	156.47^{a}	204.99^{b}	263.65^{c}
Rupture force (N)	146.82^{a}	185.25^{b}	238.57^{c}
Failure Energy (Nm)	0.186^{a}	0.229^{a}	0 .293^{a}
Rupture energy (Nm)	0.899^{a}	1.149^{b}	1.475^{c}
Maximum strain (%)	45.25^{b}	61.69^{b}	79.43^{c}
Relative deformation at rupture (mm)	10.16^{a}	13.13^{b}	16.89^{c}

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

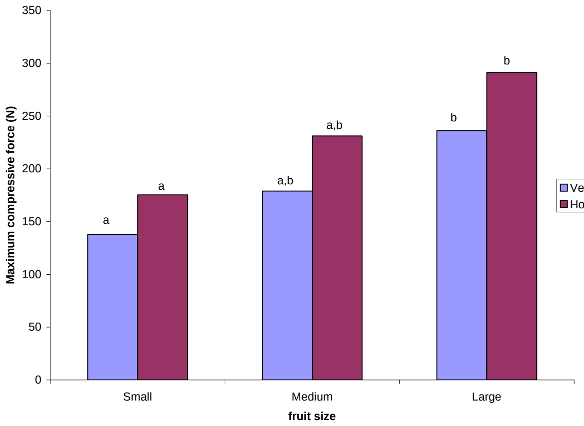
B Fruit loading orientation

From the results, the gmelina fruit was more flexible in the Longitudinal (horizontal) loading direction, in all the seven mechanical parameters studied. The force and energy required to initiate failure and rupture of the fruit under axial (vertical) loading direction was lesser than under horizontal loading. As presented in Figures 3,4,5,6,7,8,9 and 10, the values of the force and energy at failure and rupture in the horizontal orientation was statistically more than those of the vertical orientation. This can be attributed to the fact that the gemilna fruit is subjected to smaller contact area between the compressing plates of universal testing machine during vertical loading orientation. A similar trend was reported by [19] for cumin grain where the maximum energy absorbed for the cumin grain was found to be 14.8 and 20.4 mJ at the moisture content of 7% (d.b), in the horizontal and vertical orientations, respectively. Similarly, [10] [20] reported similar trend for paddy grains and locust bean respectively. In contrast to our result, [21] reported that no important difference in rupture force between both seed orientations was measured.



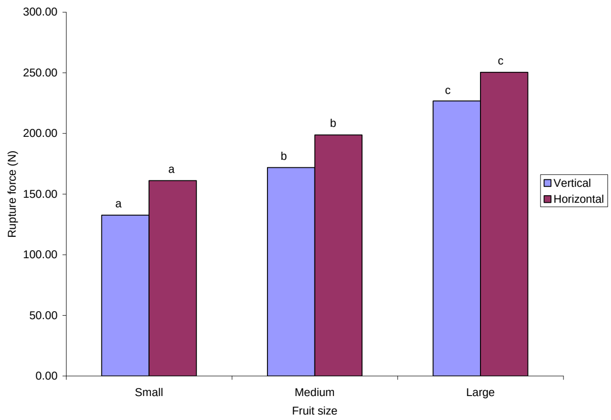
The same common letter in the same column are not significantly different ($P < 0.05$) according to Duncan's multiple ranges test

Figure 3: Correlation between failure force and loading orientation of gmelina fruit



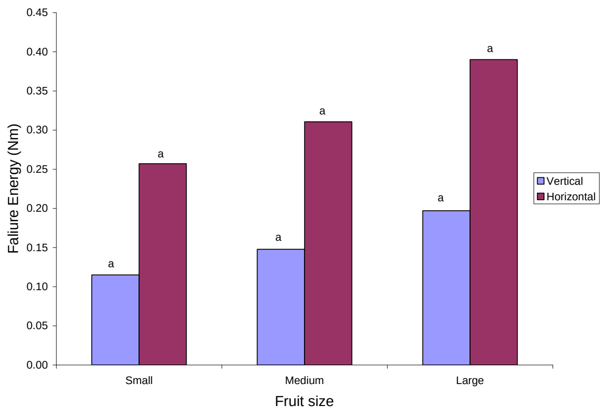
The same common letter in the same column are not significantly different ($P < 0.05$) according to Duncan's multiple ranges test

Figure 4: Correlation between Maximum compressive force (F_{max}) and loading orientation of gmelina fruit.



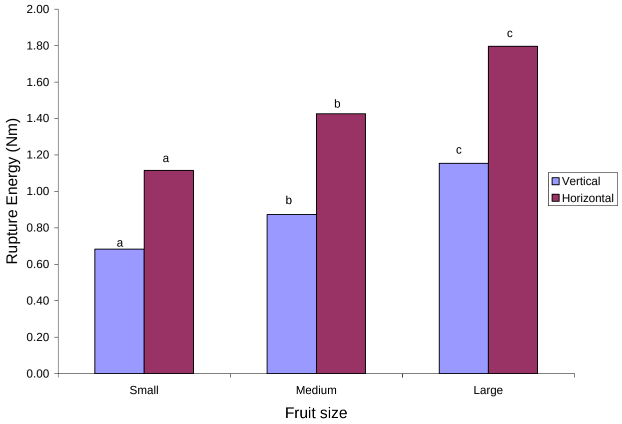
The same common letter in the same column are not significantly different ($P < 0.05$) according to Duncan's multiple ranges test

Figure 5: Correlation between rupture force and loading orientation of gmelina fruit



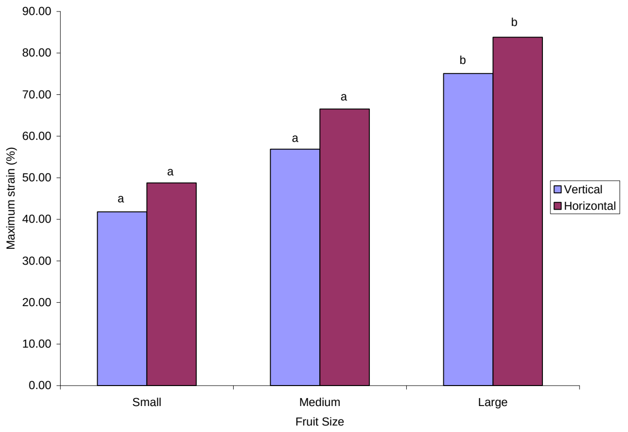
The same common letter in the same column are not significantly different ($P < 0.05$) according to Duncan's multiple ranges test

Figure 6: Correlation between failure energy and loading orientation of gmelina fruit



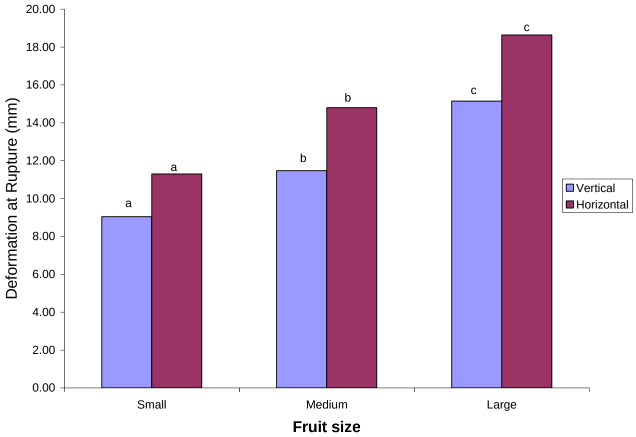
The same common letter in the same column are not significantly different ($P < 0.05$) according to Duncan's multiple ranges test

Figure 7: Correlation between rupture energy and loading orientation of gmelina fruit



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

Figure 8: Correlation between maximim strain and loading orientation of gmelina fruit



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

Figure 9: Correlation between relative deformation at rupture and loading orientation of gmelina fruit

IV CONCLUSION

From the results of the research, it can be concluded that the gmelina fruit was more flexible in the Longitudinal (horizontal) loading direction, in all the seven mechanical parameters studied. The force and energy required to initiate failure and rupture of the fruit under axial (vertical) loading direction was lesser than under horizontal loading. Also, the mechanical parameters of the gmelina fruit is highly dependent the fruit size. As the size of the fruit increases from Small (15 – 19mm), to Medium (20-24mm), and Large (25-29mm), the fruit failure

force was 51.01, 67.16 and 86.28; maximum compressive force was 156.47, 204.99, 263.65; Rupture force was 146.82, 185.25 and 238.57 N; Failure energy was 0.186, 0.229 and 0 .293 Nm; Rupture Energy was 0.899, 1.149, and 1475 Nm; maximum strain was 45.25, 61.69 and 79.43%; and relative deformation at rupture was 10.16, 13.13 and 16.89 mm respectively. The results gotten from this research will provide useful data for mechanical engineers in the design and development of suitable gemilna fruits handling, storage and processing equipment.

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