Original Research Article

Effect of Hand Size and Variety on Mechanical Properties of Intact Plantain (*Musa paradisiaca*) Hands under quasi-static loading

ABSTRACT

The mechanical properties of two varieties of unripe plantain fruits (hands), namely, Dwarf hybrid and local, were evaluated in this study. Six mechanical parameters (bio-yield force, bio-yield energy, maximum compressive force, rupture force, rupture energy and relative deformation at rupture) of the plantain hands were evaluated at two different fruit sizes (small and large), under a compressive loading speed of 20 mm/min, using the Universal Testing Machine. The results obtained statistically showed that plantain variety significantly ($P < 0.05$) affected only the rupture energy and the relative deformation at rupture; whereas, plantain cultivar had no significantly influence on the remaining four parameters. In respite to the fruit size, the all the six mechanical parameters studied increased from the small size to the large size. The results also show that for both varieties, the local plantain variety had higher values than in the improved variety. For the local variety, the bio-yield force and bio-yield energy increased from 1995.76 to 2315.3 N, and 6.05 to 9.69 Nm; 1659.41 to 1975.43 N, and 5.12 to 7.23 Nm for the improved variety. Similarly, all the rupture parameters (rupture force, rupture energy, relative deformation at rupture) values increased from 2653.13 to 3011.64 N, 21.69 to 24.41 Nm, and 18.28 to 21.63 mm for the local variety; and 2313.80 to 2688.71 N, 15.31 to 17.36 Nm and 14.15 to 16.09 mm in the improved variety.

Keywords: Plantain hand, mechanical properties, Quasi-static loading; failure point; rupture point,

1.0 INTRODUCTION

Plantain (*Musa paradisiaca*) is a large perennial herbaceous plant that originated in Southeast Asia [1], existing in the world are 68 species and two primary hybrids of plantain [2]. In the family of plantain *Musaseae* includes bananas (*Musa sapientum* and *Musa cavendishii*) which has the same growth pattern as plantain but are differentiated from one another by stem and leaf colour, fruit shape and storage of nutritional element of which in the fruit (hand) of plantain it is carbohydrate while in banana it is sugar [3]. Plantain (*Musa Paradisiaca* L.) is a crop which is generally grown in the tropical and temperate region of the world, and is a good source of vitamins and dietary fibre. The mature fruit, i.e. the plantain bunch, has valuable economic and nutritional importance, and is the main part of the fruit. A bunch consists of several ‘hands’ (several plantains that are attached in a single bunch), each having a length in the range of 2.5–12 inches, and width of between 0.75 to 2 inches [4]. Plantain production hits over thirty-five million tons in year 2016 [5]. Presently, it is grown in over 130 countries of the world, with Cameroon as the world leading producer (about 4.5 million tons). In Nigeria, for agro-climate reasons, plantain cultivation is concentrated in the southern region of the country. This crop also serves as source of income for rural farmers and substantial foreign exchange can be earned from export [6].

The mature plantain hands (ripe or unripe) are consumed boiled, steamed, baked, pounded, roasted, or sliced and fried into chips. Overripe plantains are processed into beer or spiced with chili pepper, fried with palm oil and served as snacks (*dodo-ikire*). Industrially, plantain fruits serve as composite in the making of baby food (*Babena* and *Soyamusa*), bread, biscuit and others [7-8]. According to Treche [9], 69.4 percentage of plantains and other cooking bananas are used for human consumption while 8.0 percentage are used for animal feed. Post-harvest losses and transformed quantities in the world are 11.5 percentage and 11 percentage, respectively. Plantain contains significant amount of calcium when compared to cocoyam, sweet potato, maize and sorghum which, contain 0.37 mg; 0.13 mg; 0.08 mg and 0.15 mg respectively [10]. Plantain is considered to which help in the management of high blood pressure and heart diseases. Additional information emphasizes on the low level of toxic and anti-nutrient substance namely cyanogenic glucosides and gluco alkaloides that plays safe for human consumption [1].

Knowledge of the Engineering properties of fruits is an important attribute in the design of their, harvesting, processing, handling and packaging systems. Many studies have been reported on the physical and mechanical properties of fruits, such as date fruit [11], melon [12], and citrus fruits [13]. In addition, [25] conciliated the temperature effect of ripening treatment on properties of banana fruit. Also, Salvador [14] studied the changes in color and texture of banana during storage at 10 ºC and 20 ºC. They found that during storage, the change in peel color from green to yellow was gradual in the M. *Cavendish* samples, whereas the M. *Paradisiacal* variety presented a different pattern, remaining green for the first 8 days and then changing rapidly to a yellow tone from day 12 onwards. The mechanical properties of intact plantain fruit are vital attributes in the design of its harvesting, handling and packaging system. According to Asoegwu [15], reduction in losses of plantain fruit during harvesting, transportation, packaging and storage, requires the understanding of its physical and mechanical properties. Johnson and Dover [16] studied some factors influencing the bruising susceptibility of a variety of apples (Bramley's Seedling). In the study of Johnson and Dover, fruits from 24 commercial orchards were tested during six seasons. It was observed that bruising susceptibility (measured by means of an instrumented pendulum, applying 0.19 J of impact input energy) varies in a greater measure within a season (between orchards) than between seasons.

Some researches have been done on the mechanical properties of cut plantain hands [15], but there is dearth information on the mechanical properties of intact plantain fruits, necessary for the design and development packaging and storage system. Hence, the main aim of this study is to determine the mechanical properties namely, bio-yield force, maximum compressive force, rupture force, bio-yield energy, rupture energy and relative deformation at rupture, of intact plantain fruit with respect to its different fruit (hand) sizes; which will provide relevant data for the design and development of packaging and storage systems.

2.0 MATERIALS AND METHODS

2.1 Samples Collection

The matured plantain bunches, improved (*Dwarf* hybrid) and local varieties, were harvested from a research farm located in Ozoro, Delta state, Nigeria. They were all harvested at a stage of maximal maturity when at least one ripe fruit appears on the bunch [17]. The plantain hands from the upper region of the bunches were cleaned and selected based on uniformity in size, cylindrical shape and freedom from mechanical damage.

2.2 Plantain Hand Size Determination

To determine the average size of the fruit, samples (plantain hands) from each variety were randomly selected. The three linear dimensions of the seeds, namely length (L) and diameter (W) were carefully measured using digital vernier caliper reading to 0.01 mm. The geometric mean diameter (D_g) and total surface (S) were computed using the following equations [18].

Geometric mean diameter

$$D_g = \sqrt[3]{L \times W}$$

Surface area

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

$$S = \pi D_g^2$$

2.3 Mechanical Properties Determination

The mechanical test of the intact plantain hand was done at the Material Testing Laboratory of the National Center for agricultural Mechanization (NCAM), Ilorin, Kwara state, Nigeria, using 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. Each hand sample was placed in the machine under the flat compression tool (Figures 1), ensuring that the centre of the tool was in alignment with the 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 plantain hand automatically, and the following parameters were interpreted by the testometric software of the Universal Testing Machine.

i. Bio-yield force
ii. Maximum compressive force (F_{max})

iii. Rupture force
iv. Bio-yield energy
v. Rupture energy
vi. Relative deformation at rupture

The surface of contact between seed and the compression plate changes during compression, making compression stress, the most popular and univocal physical parameter, difficult to use [19]. The number of plantain hands were limited; therefore, the determinations were made in 15 repetitions.

Figure 1: Plantain hand undergoing quasi compression testing

Plantain hands like other biological materials has complex biomechanical systems of very complex behaviour and cannot be characterized by simple constants [18], it is therefore necessary to introduced some concepts such as bio-yield and rupture points. The bio-yield point indicates the initial cell rupture in the whole fruit and is used as a criterion for maximum allowable load that the plantain hand can sustains without showing any visible damage [20]. The rupture point dictates failure over a significant volume of material causing fracture planes or cracks in the macrostructure of the plantain hands. The rupture energy (Toughness) is the work required to initiate rupture of the plantain fruit, which is the area under the force-deformation curve up to the rupture point [15]. The bio-yield energy (firmness)of the plantain hand is the ability of the hand to store energy in the hand's elasticity range.

C Statistical analysis
The experiments were conducted with ten replications for each plantain hand size. The analysis of variance (ANOVA) was carried out using SPSS 20.0 software. The significant differences of means were compared by using the Duncan’s multiple ranges test at 5% significant level.

3.0 RESULTS AND DISCUSSION
The Analysis of Variance (ANOVA) of the mechanical parameters of the plantain hand are presented in Table 1. The ANOVA results indicated that plantain hand size did not significantly affects the bio-yield force, bio-yield energy, maximum compressive force, rupture force, rupture energy; while the plantain variety significantly ($P < .05$) influenced only the rupture energy and relative deformation at rupture of the plantain hands. Finally, the interaction effect of plantain variety and plantain hand size does not significantly ($P < .05$) affected the six mechanical parameters investigated.

Table 1: Analysis of variance (ANOVA) of size and variety on the mechanical parameters of plantain hands

Source of variation	df	Bio-yield force	F_{Max}	Rupture Force	Bio-yield energy	Rupture energy	Relative deformation at rupture
C	1	0.2414^{ns}	0.0896^{ns}	0.0979^{ns}	0.0933^{ns}	0.0021*	0.0019*
S	1	0.2685^{ns}	0.8497^{ns}	0.0717^{ns}	0.2941^{ns}	0.1533^{ns}	0.0383*
C x S	1	0.9949	0.3162	0.9641	0.6245	0.8283	0.5271

* =Significant at (P<0.05), ns= non-significant, C = plantain variety, S = plantain hand size.

Table 2: Mean comparison of the six mechanical parameters of plantain hand at different hand size categories and plantain variety

Parameters	Plantain Hand Size			
	Small (1521 mm^2)		Large (2124 mm^2)	
	Improved variety	Local variety	Improved variety	Local variety
Bio-yield Force (N)	1659.14^a	1995.36^a	1975.43^a	2315.3^a
F_{Max} (N)	2313.80^a	1792.04^a	2669.23^a	3029.51^a
Rupture Force (N)	2313.80^a	2688.71^a	2653.13^a	3011.64^a
Bio-yield Energy (Nm)	5.12^a	6.05^a	7.23^a	9.69^a
Rupture Energy (Nm)	15.31^a	17.36^b	21.69^a	24.41^b
Relative Deformation at Rupture (mm)	14.15^a	16.09^b	18.28^a	21.63^b

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

In reference to the mean separation table (Table 2), the local plantain variety shows higher values of failure force, rupture force, maximum compressive force, failure energy rupture energy and relative deformation at rupture than the improved variety sample, which could be attributed to the differences in the microstructure of the two plantain varieties. The force and energy required to initiate the plantain hand failure increased as the hand size increased from small to large size (Table 2), in the two plantain varieties. This may be attributed to the fact that increment in plantain hand size leads to its more resistance to failure, and larger hand possess large modulus of elasticity and capable of being more deformable under compressive loading [21]. A similar trend was reported for cut plantain hands, where the energy required to rupture a cut out section of plantain hand increased from 0.259 J to 0.410 J as the cut size section increased from 5.45 cm^3 to 9.45 cm^3 [15]. According to Sadowska [19], despite variability of the size and the fracture force of seeds representing different accessions and varieties, there was a clear tendency towards an increase in fracture force along with an increase in seed size.

Like the bio-yield parameters, the rupture parameters (force, energy and relative deformation), all increased with the plantain hand size, higher in the local variety than in the improved variety. This behavioral trend agrees with the theory of normal behavior of viscoelastic materials like processed apple [22]. Similar trend was reported on cumin seed, where 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) [23]. For cut out section of plantain hands, all bio-yield and rupture parameters (strength, strain, and energy) increased with increased in loading cross-sectional area [15]. Rupture energy is a popular measure of mechanical resistance, and from the rupture energy values, the most mechanically resistant plantain hands were the local variety which required the highest rupture energy, whereas, the hands of the improved variety required the lower rupture energy (Table 2). The result of this research confirms the sensitivity of many agricultural products to mechanical damage due to variation in their sizes and varieties. The hand size, therefore plays an important role in the mechanical behaviour of the intact plantain hand. Variability of the size and the fracture force of seeds representing different accessions and varieties, there was a clear tendency towards an increase in fracture force along with an increase in seed size [19]. On a research on seeds of the Boomer variety, it was found that the largest in size required a higher fracture force than smaller seeds [24]. Plantain hands firmness and toughness which is affected by hand size and microstructure, is also an important factor that influences plantain hand damage during transportation storage.

4.0 CONCLUSION

From the results of the research, it can be concluded that the variety of plantain markedly influences its properties. Rupture point, an important parameter of the mechanical resistance of fruits and seeds, is significantly affected by plantain hand size in the two plantain varieties. Like the rupture parameters, the bio-yield parameters (force, and energy) all increased with the hand size, higher in the local variety than in the improved variety. As the size of the fruit increases from Small (1521 mm^2), to Large (2124 mm^2), the bio-yield force and bio-yield energy increased from 1995.76 to 2315.3 N, and 6.05 to 9.69 Nm for the local variety; and 1659.41 to 1975.43 N, and 5.12 to 7.23 Nm for the improved variety. Similarly, all the rupture parameters (rupture force, rupture energy, relative deformation at rupture) values increased from 2653.13 to 3011.64 N, 21.69 to 24.41 Nm, and 18.28 to 21.63 mm for the local variety; and 2313.80 to 2688.71 N, 15.31 to 17.36 Nm and 14.15 to 16.09 mm in the improved variety. The results gotten from this research will provide useful data for mechanical engineers in the design and development of suitable plantain hands handling, storage and processing systems.

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