Journal of Applied Sciences

ISSN 1812-5654

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Journal of Applied Sciences 13 (7): 1004-1012, 2013
ISSN 1812-5654 / DOI: 10.3923/jas.2013.1004.1012

Physical and Mechanical Properties of *Jatropha curcas* L. Fruits from Different Planting Densities

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Abstract: *Jatropha curcas* L. is a versatile and rugged crop with enormous unexploited potentials. In order to efficiently take advantage of its full potentials, its physical and mechanical properties need to be well understood. Laboratory tests were conducted to investigate the properties of *Jatropha curcas* L. fruits obtained from trees of three planting densities namely 10880, 5446 and 3630 plants acre^{-1}. The properties included detachment force, rupture force, deformation at rupture point, deformation ratio at rupture point, hardness, energy used for rupture at both vertical and horizontal loading positions. Other properties studied were 1000 unit mass, dimensions, sphericity, bulk density, solid density, porosity, coefficient of static friction on plywood, steel and stainless steel. The solid density value of 0.97 g cm^{-3} was obtained which implies that the fruit could float in water for easy cleaning and separation from foreign materials. It was observed that the fruit had the least coefficient of static friction on stainless steel (0.44). The average values obtained for the detachment force and rupture force at vertical orientation were 16.62 N and 57.17 N, respectively. No clear cut trend was observed in the physical and mechanical properties with respect to planting density. However, the mechanical properties were significantly different with respect to the orientation of the fruits. Both the physical and mechanical properties are essential for the design and development of harvesting and processing machines for *Jatropha curcas* L. fruit.

Key words: *Jatropha curcas* L., detachment force, harvesting machine

INTRODUCTION

Jatropha curcas L. also known as physic nut is a self propagating drought resistant small tree that belongs to the family Euphorbiaceae. It grows well in arid, semi-arid and tropical humid areas. It has the potential of reclaiming marginal soils and to lessen the risk of erosion and desertification (Openshaw, 2000; Jongschaap *et al*., 2007). The whole of *Jatropha curcas* L. tree is of high economic importance because all its parts are useful for various purposes (Openshaw, 2000; Augustus *et al*., 2002; Wood, 2005; Achten *et al*, 2008; Amirah and Khan, 2012). The trees are not browsed by animals, hence could be used as hedges to fence farms or garden. The bark contains tannin and it produces dark blue dye. The leaves could be fed to silk worms and it yields dye and latex that have medicinal values. Among others, the oil obtained from *Jatropha curcas* L. seed could be used to make fungicide, biodiesel, insecticide, lubricant, soap, nematicide and molluscicide, (Ong *et al*., 2012; Labis *et al*., 2011; Lubis *et al*., 2012; Syam *et al*., 2009). The pressed seed cake is a good source of biogas and fertilizer production. The root yields yellow oils with strong antihelminthic characteristics (Sayyar *et al*., 2011).

Although, *Jatropha curcas* L. does not possess much nutritional value, it is an excellent raw material for biodiesel production. The oil extract has good physicochemical characteristics which make it useful as non-edible vegetable oil feedstock in the oleochemical industries (Akbar *et al*., 2009). Also, high level of oil, polyphenol and hydrocarbon were discovered in the seed of *Jatropha curcas* L. by (Augustus *et al*., 2002). It was found that the gross heat value of the oil fraction was 37.83 MJ kg^{-1} which is greater than that of anthracite coal. Likewise, gross heat value of the hydrocarbon fraction was 40.63 MJ kg^{-1} which again is greater than that of crude oil. With these results, it was claimed that *Jatropha curcas* L. may serve as an intermediate source of energy with lower negative impact on the environment.

With the current awareness about the great potentials of *Jatropha curcas* L. and the possibilities of designing machines for its exploitation, some studies have

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been done on its engineering properties. Sirisomboon *et al.* (2007), carried out a study on the fruits, kernels and nuts of the *Jatropha curcas* L. from Thailand as it regards their mechanical and physical properties after harvesting. However, only horizontal loading position was used for the determination of the mechanical properties. Likewise, Pradhan *et al.* (2009) studied some physical properties of *Jatropha curcas* L. fruits at moisture contents ranging from 7.97-23.33% dry basis. Except for the bulk density, true density, porosity and crushing strength of *Jatropha curcas* L. fruits that decreased with increase in moisture content, all other physical properties increased with increasing moisture content in the specified range.

Being a wild plant, not much investigation has been carried with respect to the good agriculture practice in the cultivation of *Jatropha curcas* L. as a source of energy. Due to competition for resources from the environment, increase in plant density results in increase in the amount of dominated plants which exhibit retarded development, small stem and reduction in yield (Hussein, 2009; Feng *et al*., 2011). Chikara *et al.* (2007) claimed that competition among planted crops which is a reflection of planting density has a direct impact on the growth and size distribution of the individual plant. Significant differences were observed in the growth and yield of *Jatropha curcas* L. due to tree spacings. Also, fruit yield on area basis was found to be positively correlated with plant density. Therefore, it was claimed that actual spacing of *Jatropha curcas* L. should be determined based on end use, soil quality/condition, humidity, rainfall, intercropping etc. In view of this, Jongschaap *et al.* (2007) asserted that an analytical framework that could be applied to *Jatropha curcas* L. tillage system was necessary. The framework should provide clear scope of *Jatropha curcas* L. in different environment and social setting.

The essence of determining the physical and mechanical properties of *Jatropha curcas* L. fruits is to assist in the design of the equipment and structures for harvesting, handling, transportation, processing, storage, drying, oil extraction and quality assessment (Sirisomboon *et al*., 2007; Dash *et al*., 2008; Pradhan *et al*., 2009; Nazerian *et al*., 2011). Although, some of the physical and mechanical properties of *Jatropha curcas* L. fruits have been reported, information on the detachment force needed to harvest the fruit and the mechanical properties in vertical loading position are still lacking. Therefore, the objective of this study was to investigate the effects of planting density on the physical and mechanical characteristics of the *Jatropha curcas* L. fruits and also the effect of different loading positions on its mechanical properties. Accurate determination of these parameters will assist in the design and fabrication of an appropriate harvesting machine for *Jatropha curcas* L. fruits.

MATERIALS AND METHODS

Experimental sample: The *Jatropha curcas* L. fruits used for this study were obtained from Kluang Johor in Peninsular Malaysia. The plantation covers a total area of 10 acres with plants of about 2 years old. After planting, the plants were left to grow wild with little crop care operations as regards watering, fertilizer and herbicide applications by the plantation management. However, grass cutting operations were conducted once in a while along the planting row by contract workers. The 6-acre study plot used for the experiment was planted with the plants having three different planting densities in the respective individual sub-plots with almost equal area size. The remaining plantation area had *Jatropha curcas* L. trees with dragon fruit trees planted in-between. The three planting densities studied were 2 ft row distance by 2 ft planting distance (i.e., T22) with 10880 plants acre^{-1}, 4 ft row distance by 2 ft planting distance (i.e., T42) with 5446 plants acre^{-1} and 6 ft row distance by 2 ft planting distance (i.e., T62) with 3630 plants acre^{-1}. A total of 100 matured *Jatropha curcas* L. fruits at yellow fruit stage were selectively harvested from each planting sub-plot and the fruits collected were used as the test samples for the study. The physical property tests were done at the plantation field on the same day of harvesting while the mechanical property test was done in the laboratory within less than 24 h after harvesting. As for the latter test, the harvested fruits were immediately placed in a sealed polystyrene box and transported back to the laboratory for the determination test.

Physical properties

Sizes, geometric mean diameter, sphericity and surface area: Each of the 50 sampled fruits was measured for the longest intercept (a), longest intercept normal to a (b) and longest intercept normal to a and b (c), using a digital Vernier caliper (Mitutoyo Digimatic model with 0.01 mm accuracy) (Fig. 1). According to Mohsenin (1980), the geometric mean diameter d_g in mm is given by:

$$d_g = (abc)^{1/3} \tag{1}$$

The sphericity, φ is given by:

$$\phi = \frac{(abc)^{1/3}}{a} = \frac{d_g}{a} \tag{2}$$

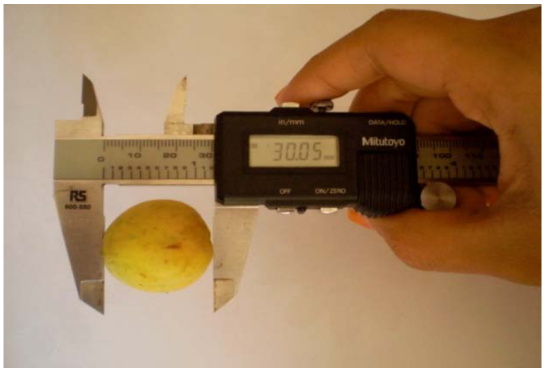

Fig. 1: Determination for dimensions a, b and c

and surface area of fruit, S_F in mm^2 is given by:

$$S_F = \pi d_g^2 \tag{3}$$

where, a is the longest intercept, b is the longest intercept normal to a and c is the longest intercept normal to a and b, in mm.

Solid density, bulk density and porosity: Each of the 20 sampled fruits was weighed for its mass using a Sartorios B3100S digital electronic balance with reading accuracy to 0.01 g. The volume of the individual fruit was determined by suspending it with a thread and weighing the fruit in toluene (Mohsenin, 1980). The volume V in cm^3 was determined using the principle of buoyancy:

$$V = \frac{m_t}{\rho_t} \tag{4}$$

where, m_t is the mass of fruit weighed in toluene in g and ρ_t is the density of toluene (0.87 g cm^{-3}).

The density of fruit, ρ was calculated using the equation:

$$\rho = \frac{m_{fa}}{V} \tag{5}$$

where, m_{fa} is the mass of fruit in air (g) and V is the volume of fruit (cm^3).

Bulk density of fruits was determined by putting the bulk fruits into a container of known weight and volume and then weighed. Bulk density, ρ_b in g cm^{-3} was calculated using the following equation:

$$\rho_b = \frac{m_{bf}}{V_c} \tag{6}$$

where, m_{bf} is the mass of bulk fruits (g) and V_c is the volume containing the mass.

Porosity ε in % was calculated from the following equation:

$$\varepsilon = \left[1 - \frac{\rho_b}{\rho_s}\right]100 \tag{7}$$

where, ρ_b is the bulk density and ρ_s is the solid density 1000 unit mass and specific surface area.

The whole 100 fruits were used in the determination of 1000 unit mass. The fruits were put into a container and weighed using the Sartorios B3100S digital electronic balance. The 1000 unit mass was calculated using:

$$1000\text{-unit mass} = 100 \text{ unit mass} \times 10 \tag{8}$$

The specific surface area of fruit S_s in mm^2 cm^{-3} was obtained from:

$$S_s = \frac{S_F \rho_b}{m_u} \tag{9}$$

where, S_F is the surface area of fruit in mm^2, ρ_b, is the bulk density of fruits, in g cm^{-3}, m_u, is the mass of one unit of fruit, in g.

Moisture content: Moisture measurement method for peanuts in ASAE S410.1 DEC1982 (R2008) (ASABE, 2008) was adapted for the determination of moisture content of *Jatropha curcas* L. fruits. Each of the 5 sampled fruits was manually separated for the hulls, nut shells and kernels. The hulls, nut shells and kernels were weighed separately using a Sartorios B1205 digital electronic balance with reading accuracy of 0.0001 g. They were then dried in a hot-air oven (Memerth, model 500, W.Germany) at 130°C for 6 h. Then, they were left in the desiccators for 1 h to cool down, after which they were weighed. This process was repeated until the weight remained constant. The moisture content of the whole fruit or M_F in % was computed from the following equation:

$$M_F = \frac{100\left[(m_{Hi} - m_{Hf}) + (m_{si} - m_{sf}) + (m_{Ki} - m_{Kf})\right]}{m_{Fi}} \tag{10}$$

where, m is mass in g and the subscripts F, H, S, K, i and f stand for fruit, hull, shell, kernel, initial and final, respectively.

Coefficients of static friction: The coefficients of static friction of *Jatropha curcas* L. fruits against surfaces of plywood, mild steel and stainless steel were determined. A transparent box of 100 mm length, 100 mm width and

63 mm height without base and lid was placed on an adjustable tilting plate. The box was filled with 20 sampled fruits and a 1 kg steel weight was placed on the top to press the fruits for a few seconds. The box was then lifted up 1 cm so that only the fruits touched the plate. Manually, the inclination of the plate was increased gradually until the box started to slide down and at that point, the angle of tilt θ in degree was read with a protractor. The determination was repeated three times for each surface. The coefficient of static friction μ was calculated from the formula:

$$\mu = \tan\theta \tag{11}$$

Angle of repose: The angle of repose of fruits was measured by filling method (Amin *et al.,* 2004) and emptying method (Bart-Plange and Baryeh, 2003). In the filling method, a hollow PVC cylinder of 160 mm in diameter and 160 mm in height and a wooden table were used for the determination. The cylinder was placed in a container containing one layer of fruits. Then, it was filled with *Jatropha curcas* fruits and raised slowly until it formed a cone of fruits. The diameter and height of the cone were measured and recorded. The angle of repose was calculated by using the equation:

$$\phi = \tan^{-1}\left(\frac{2H}{D}\right) \tag{12}$$

where, H and D are the height and diameter of the cone in cm, respectively.

In the emptying method, transparent acrylic box with dimensions of 200 by 200 mm by 400 mm which had a front sliding panel was used. The box was filled with fruits, and the front sliding panel was quickly slid upwards allowing the fruits to flow out and form a natural heap. The height of fruits at two points in the sloping fruit heap and the horizontal distance between the two points were measured (Bart-Plange and Baryeh, 2003). This was done in three replicates. The angle of repose was determined using the following relationship:

$$\theta_e = \tan^{-1}\frac{(h_2 - h_1)}{(x_2 - x_1)} \tag{13}$$

where, h_1 and h_2 are the heights of fruits at two points in cm while x_1 and x_2 are the horizontal distances between the two points in cm, respectively.

Mechanical properties

Detachment force: The 50 units fruits sample were randomly harvested from the available trees within the sub-plot for this determination. A digital force gauge (Model Aikoh) with reading accuracy of 0.01 N was used to measure the detachment force of the fruits from it stalks (Fig. 2). The digital force gauge was attached to the stalk just near to the fruit and was pulled horizontally until the fruit detached (Fig. 3). The measurement was read from the digital force gauge and recorded.

Fig. 2: Digital force gauge

Fig. 3: Measurement of detachment force

Rupture force, deformation at rupture point, deformation ratio at rupture point, hardness and energy used for rupture.

The 20 units of fruits sample were used for vertical loading position (Fig. 4a) and 20 units fruits sample were used for horizontal loading position (Fig. 4b). The tests were carried out using a Universal Testing Machine (Instron, model 5565, England) where each fruit was placed on the platform of the machine in either vertical or horizontal loading positions. A compression tool with circular end was used to compress the sample at the deformation speed of 30 mm min^{-1} until the fruit was broken. The rupture force, deformation at rupture point,

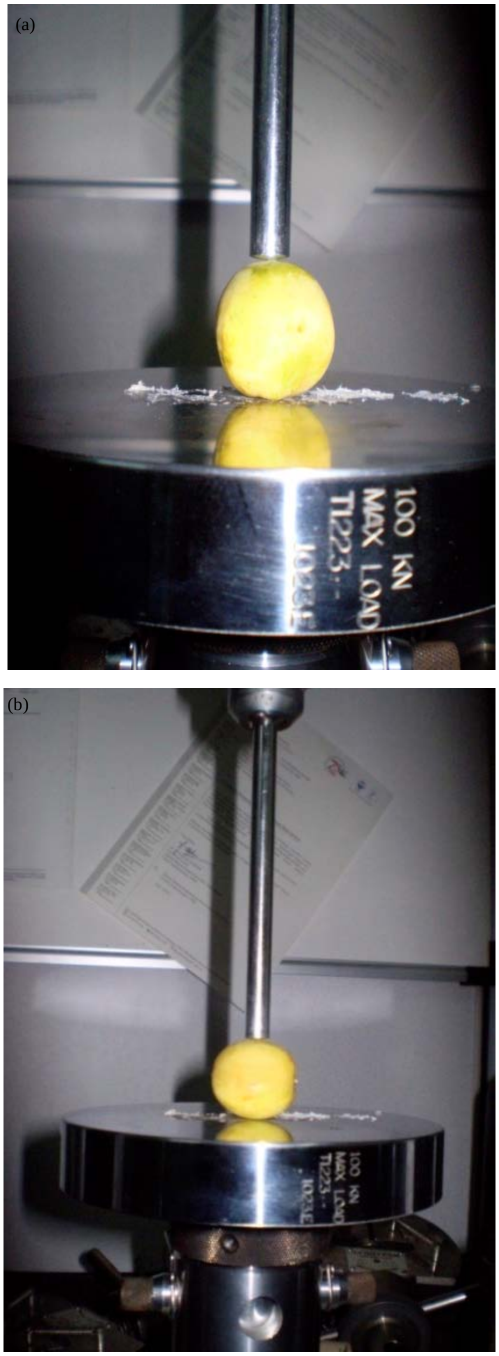

Fig. 4(a-b) : Two different loading positions of *Jatropha curcas* L. fruits

deformation ratio at rupture point, hardness and energy used for rupture were estimated for both the vertical and horizontal loading positions. The values were computed by the Merlin Software in the computer system that controls and run the Universal Testing Machine.

RESULTS AND DISCUSSION

Physical properties: Table 1 shows the descriptive statistics of the physical properties of *Jatropha curcas* L. fruits irrespective of planting density. Any distribution is said to have a statistically normal distribution or show a bell-shape frequency distribution if its mean, median and mode are equal, kurtosis value is zero and skewness value is zero. All of the measured physical properties in Table 1 display the qualities of an almost normal distribution. However, there are some properties having distribution with slightly thicker tail as denoted by positive number slightly greater than 0 and slightly thinner tail as denoted by negative number slightly greater than 0. Hence, these properties are slightly skewed distribution, being slightly right skewed distribution as denoted by positive number slightly greater than 0 and being slightly left skewed distribution as denoted by a negative number slightly greater than 0.

Jatropha curcas L. fruit could be considered as having a spherical shape since its mean sphericity value is 0.97. Hence, an inclined smooth surface will be suitable for the purpose of transferring the fruits from one part of a machine to the other. Also, the mean solid density of the fruit is 0.9735 gm cm^{-3} which is slightly less than the density of water due to the presence of air pores between the hull and the nut. This implies that the fruit can float on water. Hence, the fruit can be easily cleaned in water and scooped out afterwards. The fruit had the lowest coefficient of static friction on stainless steel. This indicates that stainless metals could be the best material for the construction of any processing machines for the fruit especially where free movement of the fruits is required.

In comparison, the values for 1000-unit mass, porosity, surface area, angle repose by filling method and by emptying method for the fruits obtained by Sirisomboon *et al.* (2007) were higher than those obtained in this study by 13.43, 5.12, 11.98, 34.66 and 20.81%, respectively. The same trend were observed for coefficient of static friction on plywood, steel and stainless steel which were 4.88, 9.72 and 5.07%, respectively more than the values obtained in this research. However, the values of sphericity, bulk density, solid density and specific surface area obtained in this study were 1.57, 7.24, 2.41 and 18.96%, respectively greater than those observed by Sirisomboon *et al.* (2007). The disparity in values could be understood from the fact that the fruits used for this study were obtained from *Jatropha curcas* L. trees with three different planting

Table 1: Descriptive statistics of the physical properties of *Jatropha curcas* L. fruits irrespective of planting density

	Descriptive statistics							
Parameters	N	Mean	Mode	Median	Kurtosis	Skewness	t-value	95% CI
1000- unit mass (g)	3	12605.2110	-	1261.3500	-1.7043	-0.2806	4.3030	1260.5211±99.271
Longest intercept (mm)	50	30.6925	29.1700	30.6800	-0.2370	-0.0569	2.0116	30.6925±0.1860
Longest intercept normal to a (mm)	50	29.6953	29.2300	29.6650	0.1223	-0.0857	2.0116	29.6953±0.1849
Longest intercept normal to a and b (mm)	50	28.5716	27.3700	28.6800	1.4128	-0.5860	2.0116	28.5716±0.2185
Geometric mean diameter (mm)	50	29.6361	28.4600	29.6500	0.3602	-0.1557	2.0116	29.6361±0.1804
Sphericity	50	0.9652	0.9700	0.9700	0.9157	-0.6948	2.0116	0.9652±0.0030
Bulk density (g cm^{-3})	3	0.5067	0.4900	0.5100	-1.7143	-0.4628	4.3030	0.5067±0.01897
Solid density (g cm^{-3})	20	0.9735	0.9800	0.9800	2.0112	-0.9922	2.0930	0.9735±0.0045
Porosity (%)	20	47.9407	47.9600	47.9600	0.0194	-0.1596	2.0930	47.94067±0.4028
Surface area (mm^2)	50	2763.0700	-	2762.3250	0.3078	-0.0273	2.0116	2763.07±33.5069
Specific surface area (mm^2 cm^{-3})	50	111.0553	101.0600	111.3200	0.0218	-0.1295	2.0116	111.0553±1.4294
Coefficient of static friction on surfaces								
Plywood	3	0.4756	0.4700	0.4700	2.2921	-0.7045	4.3030	0.4756±0.0662
Steel	3	0.5778	0.5500	0.5800	-1.7408	-0.0036	4.3030	0.5778±0.0485
Stainless steel	3	0.4367	0.4200	0.4200	-0.7125	0.6838	4.3030	0.4367±0.0875
Angle of repose								
Filling method	3	34.9767	34.5900	34.5900	-0.5393	0.2385	4.3030	34.9767±2.8412
Emptying method	3	33.9822	-	32.2000	4.0528	1.8651	4.3030	33.9822±5.9597
Moisture content (%)	5	73.3884	-	73.3646	0.4447	0.2317	2.7760	73.3884±1.7925

Table 2: Comparison of Physical properties of *Jatropha curcas* L. fruits based on three types of planting densities

	95%CI*				
Parameters	N	Pr>F**	T22	T42	T62
1000-unit mass	3	<0.0001	12679.267±11.939^a	12520.767±9.317^c	12615.600±15.457^b
Longest intercept (mm)	50	0.1246	30.5688±0.3446	30.5496±0.3396	30.9590±0.2695
Longest intercept normal to a (mm)	50	0.3379	29.5040±0.3885	29.8056±0.3186	29.7764±0.2343
Longest intercept normal to a and b (mm)	50	0.2902	28.4984±0.4618	28.4082±0.3979	28.8082±0.2383
Geometric mean diameter (mm)	50	0.2925	29.5068±0.3747	29.5692±0.3204	29.8322±0.2213
Sphericity	50	0.3792	0.9686±0.0060	0.9680±0.0050	0.9630±0.0045
Bulk density (g cm^{-3})	3	<0.0001	0.5100±0.0000^b	0.4900±0.0000^c	0.5200±0.0000^a
Solid density (g cm^{-3})	20	0.5211	0.9720±0.0089	0.9715±0.0066	0.9770±0.0076
Porosity (%)	20	<0.0001	47.5105±0.4961^b	49.5510±0.3545^a	46.7605±0.4221^c
Surface area (mm^2)	50	0.3283	2740.5500±69.3292	2750.7310±59.5936	2797.8000±41.5921
Specific surface area (mm^2 cm^{-3})	50	<0.0001	110.2276±2.7884^b	107.6564±2.3326^b	115.2820±1.7136^a
Coefficient of static friction surfaces					
Plywood	3	0.5805	0.4767±0.0574	0.4967±0.1147	0.4533±0.1654
Steel	3	0.7541	0.5767±0.0625	0.5667±0.1174	0.5900±0.0090
Stainless steel	3	0.2107	0.4733±0.1368	0.3867±0.0759	0.4500±0.1739
Angle of repose					
Filling method (deg)	3	0.4036	34.7267±5.4213	33.9533±2.7396	36.2500±5.8900
Emptying method (deg)	3	0.2658	33.5433±6.7769	31.3600±2.1430	37.0433±14.9500
Moisture content (%)	5	0.6818	72.5466±1.5390	73.7095±5.1826	73.9091±1.5568

*Means having different letter subscript are considered to be significantly different at 5% level of significance, T22: 2 ft row distance by 2 ft planting distance; T42: 4 ft row distance by 2 ft planting distance; T62: 6 ft row distance by 2 ft planting distance

densities. Again, the measurements taken by Sirisomboon *et al.* (2007) were done after 24 h of harvest whereas in this study, all measurements were done within 24 h of harvest. Moisture loss could have caused the differences in value as observed by Pradhan *et al.* (2009).

The results of the Duncan's multiple range test used for the comparison of physical properties of *Jatropha curcas* L. fruits based on three types of planting densities are shown on Table 2. This table indicates that the 1000 unit mass, bulk density, porosity and specific surface area for the fruit are significantly different at 5% level of significance. These four physical properties are crucial in the design consideration of machines for harvesting, dehulling, drying and storage.

It was discovered that the planting density T42 had the lowest mean values for 1000 unit mass, bulk density and specific surface area (12520.77, 0.49 g cm^{-3} and 107.66 mm^2 cm^{-3}, respectively). However, T42 had the highest mean value of 49.55 % for porosity. On the other hand, the planting density T62 was observed to have the highest mean values for bulk density (0.52 g cm^{-3}) and specific surface area (115.28 mm^2 cm^{-3}). It had the lowest value of 46.76% for porosity. Hence, planting density should be taken into consideration when designing machines and structures for harvesting and processing *Jatropha curcas* L. fruits.

Mechanical properties: The descriptive statistics of mechanical properties of *Jatropha curcas* L. fruits

Table 3: Descriptive statistics of mechanical properties of *Jatropha curcas* L. fruits irrespective of planting densities

	Descriptive statistics							
Parameters	N	Mean	Mode	Median	Kurtosis	Skewness	t value	95% CI
Detachment force (N)	50	16.6181	16.1600	17.5000	-0.1577	-0.6108	2.0116	16.6181±0.5525
Vertical alignment								
Rupture force (N)	20	57.1680	54.8600	57.3050	0.4544	-0.2598	2.0930	57.168±2.5532
Deformation at rupture point (mm)	20	5.0425	5.6100	5.1000	-0.6987	0.2688	2.0930	5.0425±0.3485
Deformation ratio at rupture poin (mm)	20	0.1643	0.1900	0.1700	-0.4839	0.2570	2.0930	0.1643±0.0116
Hardness (N mm^{-1})	20	11.9563	12.2700	11.6700	2.3972	1.2916	2.0930	11.9563±0.8503
Energy used for rupture (N mm)	20	0.1757	0.1700	0.1800	-0.5638	-0.2448	2.0930	0.1757±0.0192
Horizontal alignment								
Rupture force (N)	20	127.3970	-	126.4450	1.8844	-0.2067	2.0930	127.397±8.7691
Deformation at rupture point (mm)	20	5.4652	6.6000	5.4650	0.1729	-0.0377	2.0930	5.4652±0.2528
Deformation ratio at rupture point (mm)	20	0.1918	0.1800	0.1800	4.1725	0.7346	2.0930	0.1918±0.0125
Hardness (N mm^{-1})	20	23.4848	-	23.6450	1.4857	-0.6967	2.0930	23.4848±1.3529
Energy used for rupture (N mm)	20	380.3000	430.0000	380.0000	0.4877	0.0090	2.0930	380.3000±33.0000

Table 4: Comparison of mechanical properties of *Jatropha curcas* L. fruits based on three types of planting densities

	95%CI*				
Parameter	N	Pr>F**	T22	T42	T62
Detachment force (N)	50	0.2122	17.2770±0.9446	16.4510±0.9910	16.1264±0.9232
Vertical alignment					
Rupture force (N)	20	0.4943	57.6120±5.3702	55.1945±4.1804	58.6975±3.5959
Deformation at rupture point (mm)	20	0.5602	4.7885±0.6451	5.1380±0.5343	5.2010±0.6379
Deformation ratio at rupture point (mm)	20	0.8045	0.1595±0.0225	0.1685±0.0173	0.1650±0.0208
Hardness (N mm^{-1})	20	0.218	12.7610±1.7144	11.0300±0.8813	12.0780±1.6337
Energy used for rupture (N mm)	20	0.5514	0.1625±0.0395	0.1775±0.0272	0.1870±0.0321
Horizontal alignment					
Rupture force (N)	20	0.0013	133.5240±15.2359^{b}	107.2020±16.9126^{a}	141.4660±7.0614^{b}
Deformation at rupture point (mm)	20	0.6724	5.5610±0.4890	5.3125±0.5588	5.5220±0.1892
Deformation ratio at rupture poin (mm)	20	0.1339	0.1960±0.0197	0.2040±0.0233	0.1755±0.0207
Hardness (N mm^{-1})	20	0.0027	24.1145±1.8636^{a}	20.5925±2.8347^{b}	25.7475±1.5299^{a}
Energy used for rupture (N mm)	20	0.0005	416.5000^{a}±61.4000	298.0000±56.7000^{b}	426.5±28.9000^{a}

*Means having different letter subscript are considered to be significantly different at 5% level of significance, T22: 2 ft row distance by 2 ft planting distance; T42: 4 ft row distance by 2 ft planting distance; T62: 6 ft row distance by 2 ft planting distance, **Means of treatment are significant at 1% probability level if Pr>F is less than 0.01; they are significant at 5% probability level if Pr>F is less than 0.05 and they are significant at 10% probability level if Pr>F is less than 0.10

irrespective of planting densities are displayed on Table 3. Detachment force is very essential to the development of a mechanism for harvesting of fruits because it is the threshold force needed to remove the fruit from the tree stem. A mean detachment force of 16.62 N and a vertical orientation rupture force of 57.17 N were obtained for the *Jatropha curcas* L. fruits. This implies that a mechanical harvester for the fruit should be able to exert a minimum force of 16.62 N and a maximum force that is less than 57.17 N in order to harvest it without damaging it.

It could be seen in this table that there is clear differences in the mean mechanical properties values obtained for the *Jatropha curcas* L. fruits at the two different loading conditions. At the horizontal orientation of *Jatropha curcas* L. fruits, the mean values obtained for the rupture force, deformation at rupture point, deformation ratio at rupture point, hardness and energy used for rupture were larger than those obtained at vertical orientation by 55.13, 7.73, 14.43, 49.09 and 99.95%, respectively. This confirms that the orientation of the fruit must be considered in the design of processing machines for *Jatropha curcas* L. fruits because it plays significant roles on its mechanical properties. In addition, the mean values for deformation at rupture point, deformation ratio at rupture point and energy used for rupture at horizontal orientation obtained in this study were greater than those obtained by Sirisomboon *et al.* (2007) by 20.22, 21.88 and 20.88%, respectively without regard to the planting density of *Jatropha curcas* L. fruits.

Furthermore, a comparison of mechanical properties of *Jatropha curcas* L. fruits based on the three types of planting densities was carried out and the results are shown on Table 4. It could be deduced from this table that the rupture force, hardness and energy used for rupture are significantly different at 5% level of significance from one planting density to the other. The planting density T62 had the highest mean values for rupture force (141.46 N) and hardness (25.75 N mm^{-1}). Conversely, the planting density T42 had the lowest mean values for rupture force (107.20 N) and hardness (20.59 N mm^{-1}).

Finally, it has been discovered that the values obtained for similar mechanical properties of *Jatropha curcas* L. fruits differ due to loading position and planting density. Hence, planting density and loading position are factors to be considered carefully in the design of harvester, handling, transportation, processing machine for *Jatropha curcas* L. fruits.

CONCLUSION

A well calculated approach in the exploitation of *Jatropha curcas* L. through the use of appropriate machineries is imperative due to its great potential. The physical and mechanical properties that could facilitate this were studied. They included 1000 unit mass, dimensions, geometric mean diameter, sphericity, bulk density, solid density, porosity, surface area, specific surface area, coefficient of static friction on plywood, steel and stainless steel. Others were detachment force, rupture force, deformation at rupture point, deformation ratio at rupture point, hardness, energy used for rupture. A mechanical harvester for the fruit should be able to exert a minimum force of 16.62 N and a maximum force that is less than 57.17 N in order to harvest it successfully. It was observed that loading positions have considerable impact on the mechanical properties of *Jatropha curcas* L. fruits. However, there was no clear cut trend on both the physical and mechanical properties of the *Jatropha curcas* L. fruits with respect to the planting densities considered in this study.

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