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Mechanical properties of the macaw palm fruit-rachilla system[1]

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ABSTRACT

The fruit of the native macaw palm [*Acrocomia aculeata* (lacq) Lood. ex Mart] is an alternative for biodiesel production because of the plant characteristics, as well as its adaptability, hardiness and high vegetable oil yield. However, its exploitation remains extractive and there are significant difficulties in its harvest. This study aimed to determine the mechanical properties of the macaw palm fruit-rachilla system that will support the design of harvest machines based on mechanical vibration. Ten samples of four accessions in the immature and mature stages of maturity were used. Traction and vibration tests were conducted to determine the mechanical properties of the macaw palm fruit-rachilla system. The elastic modulus of the rachilla was 188.39-385.09 MPa for the immature stage and 109.02-320.54 MPa for the mature stage. The Poisson's ratio for the rachilla varied between 0.20 and 0.52 for the immature stage and between 0.16 and 0.52 for the mature stage. The damping ratio varied between 0.02 and 0.12 for the immature stage and between 0.06 and 0.12 for the mature stage. The fruit-rachilla system was characterized as underdamped.

KEYWORDS: *Acrocomia aculeata*; biodiesel; damping ratio; Poisson's ratio.

RESUMO

Propriedades mecânicas do sistema fruto-ráquila de macaúba

O fruto da palmeira nativa macaúba [*Acrocomia aculeata* (lacq) Lood. ex Mart] é uma alternativa para a produção de biodiesel devido às características da planta, como sua adaptabilidade, rusticidade e alta produção de óleo vegetal. Contudo, sua exploração ainda é extrativista e há grandes dificuldades em sua colheita. Objetivou-se determinar as propriedades mecânicas do sistema fruto-ráquila de macaúba que servirão de suporte aos projetos de máquinas para colheita por vibração mecânica. Foram utilizadas dez amostras de quatro acessos, nos estádios de maturação imaturo e maduro. Ensaios de tração e vibração foram realizados para determinar as propriedades mecânicas do sistema fruto-ráquila. O módulo de elasticidade obtido para a ráquila foi de 188,39-385,09 MPa para o estádio imaturo e 109,02-320,54 MPa para o maduro. A razão de Poisson para a ráquila ficou entre 0,20 e 0,52 para o estádio imaturo e entre 0,16 e 0,52 para o maduro. A razão de amortecimento encontrada variou entre 0,02 e 0,12 para o estádio imaturo e entre 0,06 e 0,12 para o maduro. O sistema fruto-ráquila foi caracterizado como subamortecido.

PALAVRAS-CHAVE: *Acrocomia aculeata*; biodiesel; razão de amortecimento; razão de Poisson.

INTRODUCTION

The current biodiesel production in Brazil is estimated around four billion liters per year (Brasil 2015). Brazil, a country with edaphoclimatic characteristics favorable to silviculture and plant production, has a large amount of raw material for biodiesel production. A native species that has recently gained prominence as a promising raw material for biodiesel production is the macaw palm [*Acrocomia aculeata* (lacq) Lood. ex Mart] (Ciconini et al. 2013).

The macaw palm exhibits hardiness, significant adaptability in different regions and high oil yield (around 5,000 kg ha^{-1}) (Tickell 2000, Ferrari & Azevedo Filho 2012). In addition to its use for biodiesel production, the constituent parts of the fruit can be used in the cosmetic, food and pharmaceutical industries (Ciconini et al. 2013, Brandão et al. 2014).

Exploitation of the macaw palm is currently based on extractivism. The fruits can be harvested with a scythe to cut the bunches or collected on the ground after they fall (Ferrari & Azevedo Filho 2012). To improve fruit quality and harvest efficiency, it is

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necessary to study different harvest methods. One of the alternatives is the use of machines that apply mechanical vibration for fruit detachment.

The mechanical vibration principle has been used for different crops, including coffee (Santos et al. 2015), Barbados nut (Veronesi et al. 2012), pistachio (Polat et al. 2007) and olive (Dias et al. 2004). Several factors influence vibration harvest, such as the shape, size, structure and maturity stage of fruits, as well as frequency and amplitude of vibration (Ferraz et al. 2012, Coelho et al. 2015, Santos et al. 2015, Ferreira Junior et al. 2016).

Although the macaw palm exhibits considerable potential, consolidating it as a raw material for biodiesel production requires information such as physical, mechanical and modal characterization (natural frequencies and mode shapes), propagation and domestication techniques, harvest and extraction methodologies and oil composition.

The knowledge of physical and mechanical properties of agricultural products is essential for the development of harvest and post-harvest mechanisms. These properties are specific for each species and product and can be influenced by the environment, during its formation and development (Costa et al. 2014, Coelho et al. 2015 and 2016, Villar et al. 2017).

Little is known about the physical and mechanical properties of macaw palm at different stages of maturity, and the knowledge of these properties may be used as the basis for machines developed to detach macaw palm fruits by mechanical vibration and to develop selective harvest processes (Villar et al. 2017).

As such, this study aimed to determine the mechanical properties of the macaw palm fruit-rachilla system, for different accessions, in the immature and mature stages.

MATERIAL AND METHODS

The study was conducted using bunches of macaw palm collected in September 2015 in the immature stage and in December 2015 in the mature stage. The palm trees originated from the following accessions: Abaeté, Minas Gerais (MG) state (BD27); Pitangui/Martinho Campos, MG (BD40); Prudente de Moraes/Matozinhos, MG (BGP29); and Mirandópolis, São Paulo (SP) state (BGP35). However, to carry out the traction tests to determine the Poisson's ratio in the immature stage, samples of the following accessions were used: São João Del Rey/Lavras, MG (BGP53); Três Marias, MG (BGP31); Ibiá/Araxá, MG (BGP12); and Belo Horizonte, MG (BGP13), depending on the availability in the collection area.

Bunches were always collected in the morning and the tests conducted up to 24 h after collections. They were randomly selected in palm trees, which were also randomly chosen from the germplasm bank of the Universidade Federal de Viçosa (MG). The samples used for traction tests consisted only of rachillas cut directly from the bunches (Figure 1), while those used for vibration tests were composed of a rachilla with one fruit, also cut directly from the bunches (Figure 2). The samples used for the traction and vibration tests were analyzed individually, constituting the experimental units used in this study.

In the traction tests, the rachillas were standardized at a length of 12 cm. The samples were crimped at both ends, leaving 5 cm free in the middle third (Figure 3).

Photo: Nara Silveira Velloso

Figure 1. Samples of rachillas cut from macaw palm bunches and used in the traction tests.

Photo: Nara Silveira Velloso

Figure 2. Samples of rachillas with one fruit cut directly from macaw palm bunches and used in vibration tests.

Vibration tests for bunches of immature fruits were performed with 15 cm-long samples for the BD27 and BGP35 accessions and 13 cm for BD40 and BGP29. For vibration tests of bunches with mature fruit, the lengths were 12 cm for BD40; 13 cm for BD27 and BGP29; and 15 cm for BGP35. This difference in length is due to the heterogeneous development of the bunches. The samples were crimped by 2 cm at the opposite end to the fruit (Figure 4).

Photo: Nara Silveira Velloso

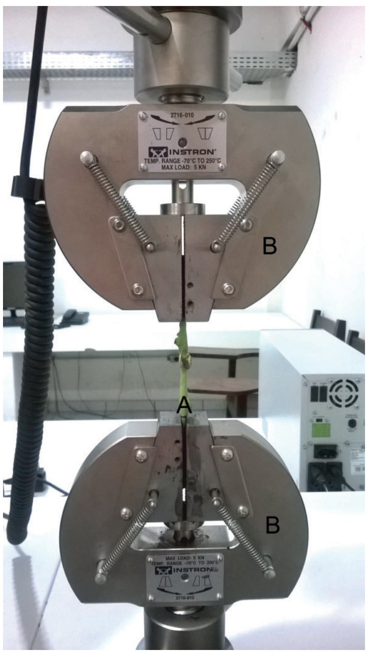

Figure 3. Crimping of a rachilla sample (A) between the two grips (B) of the Instron 3365 universal testing machine used for the traction test, with 5 cm between grips.

Photo: Nara Silveira Velloso

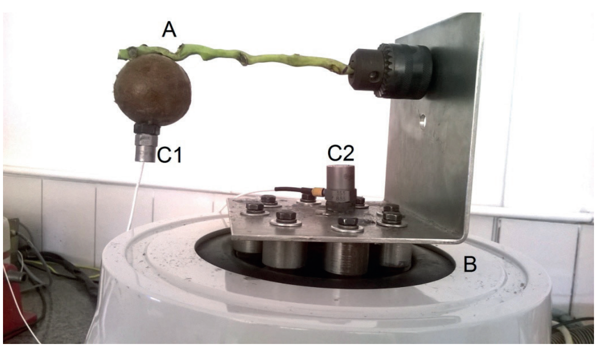

Figure 4. Rachilla sample with one fruit (A) crimped at one of the ends, in a vibration test using a LDS M6-CE V555 electromagnetic vibrator (B) and a PCB Piezotronics 352C33 high-sensitivity accelerometer to measure the sample (C1) and control the test (C2).

To analyze the influence of the maturity stage, the data were submitted to the Wilcoxon test at 5 %. The two treatments were tested with 40 repetitions and one sample per repetition.

To assess the influence of accessions, the data were submitted to the Kruskal-Wallis test at 5 %. The four accessions were tested with 10 repetitions and one sample per repetition.

All the statistical analyses were conducted using the R programming (version 3.4.0) and Assistat (version 6.2) softwares (Silva & Azevedo 2002, R Core Team 2015).

To determine the physical properties (elasticity modulus and Poisson's ratio) of the rachillas, a universal testing machine (Instron 3365), with a load capacity of 5 kN, was used. Rachilla samples were submitted to a pre-load of 2 N, followed by a constant strain rate of 3 mm min^{-1}. A routine was created in the Bluehill3 software to control the tests. The geometries of the samples were considered cylindrical, with constant cross-sectional areas.

During the elasticity modulus tests, the samples were submitted to tensile stress until rupture. Specific stress and strain values were measured. Based on these data, stress-strain graphs were created and the elasticity modulus was calculated in the elastic zone for each sample, using the tangent method (Garcia et al. 2012).

To determine the Poisson's ratio, samples were longitudinally strained (deformed) by 2 mm. After the pre-established longitudinal strain of the samples, longitudinal and cross-sectional strains were measured.

Longitudinal strains were measured directly, using a Mitutoyo 500-784 digital caliper with accuracy of ± 0.02 mm. Cross-sectional strains were also measured directly, using a Mitutoyo outside micrometer with a 0-25 mm measuring range, 0.01 mm graduation and ± 0.002 mm accuracy. The cross-sectional strains were measured at three points on each sample and longitudinal strain at the midpoint between the grips of the universal test machine.

The longitudinal and cross-sectional geometric variations to the tensile stress applied made it possible to determine the Poisson's ratio, considering the material used (rachilla) as isotropic, according to the following equation:

$$v = - \frac{(\mathcal{E}_T)}{(\mathcal{E}_L)}$$

where v is the Poisson's ratio, ε_T the cross-sectional strain (mm) and ε_L the longitudinal strain (mm).

To determine the damping ratio and damping coefficient of the fruit-rachilla system, the logarithmic decrement method (Rao 2008) was used. This method depends on determining the natural logarithm of the relation between two successive amplitudes of any measures in a same direction, as it follows:

$$\zeta = \frac{\ln\left(\frac{x_{i+1}}{x_i}\right)}{\sqrt{(2\pi)^2 + \ln\left(\frac{x_{i+1}}{x_i}\right)^2}}$$

where ζ is the damping ratio of the system, x_i the amplitude of acceleration in time i (mm s^{-2}) and x_{i+1} the amplitude of successive acceleration to x_i (mm s^{-2}), and

$$C = \frac{\ln\left(\frac{x_{i+1}}{x_i}\right)}{2\pi} \cdot 2 \cdot \omega_n \cdot m$$

where C is the damping coefficient of the system (Ns m^{-1}), x_i the amplitude of acceleration in time i (mm s^{-2}), x_{i+1} the amplitude of successive acceleration to x_i (mm s^{-2}), ω_n the undamped natural frequency of the system (Hz) and m the total mass of the system (g).

Amplitudes were measured using PCB Piezotronics 352C33 high-sensitivity accelerometers [100.7 mv/g(Eu)]. A routine was created to acquire acceleration data in the LabView software (NIC 1998). This routine managed a National Instruments NI cDAQ-9174 data acquisition system with four channels, which was used to read the accelerometer measurements with a sampling rate of 400 Hz.

To promote sample vibration, a Ling Dynamic Systems COMET$_{USB}$ vibration control system, a PA 1000 L amplifier connected to a FPS 10 L field power supply and a M6-CE V555 electromagnetic vibrator were used. The initial displacement of the fruit-rachilla system was conducted from a half-sine wave impulse generated at 100 % of the acceleration amplitude, which was configured for 5 times the gravitational acceleration (g).

The samples were attached to the electromagnetic vibrator by an apparatus created specifically for these tests. The accelerometers were attached to the vertical plane, directly onto the fruits (Figure 4). The mass of the accelerometers was less than 10 % of the total mass of the system to be analyzed, in order to minimize interferences in their dynamic response (Baharin & Rahman 2009).

RESULTS AND DISCUSSION

The elasticity modulus was determined using the tangent method in the fraction of the stress-strain curve on which the elastic zone is found (Figure 5).

The values determined for the elasticity modulus decreased as the maturity stage of the bunch evolved (Table 1). The results are similar to those found by Tinoco et al. (2014) and Coelho et al. (2015), who studied the fruit-peduncle system of coffee plants.

Brandão et al. (2014) also reported that the biometric characteristics of the macaw palm fruit, such as external longitudinal and latitudinal diameters, also display a decline in values with the evolution of the maturity stage of the fruits. The authors also observed significant differences in

Table 1. Mean elasticity modulus and Poisson's ratio values for macaw palm rachillas, in the immature and mature stages of maturity, and Wilcoxon test results.

Stage	Elasticity modulus (MPa)	Poisson's ratio
Immature	286.74	0.36
Mature	214.78	0.34
p-value	0.001386*	0.3836

* Averages differ statistically, according to the Wilcoxon test at 5 %.

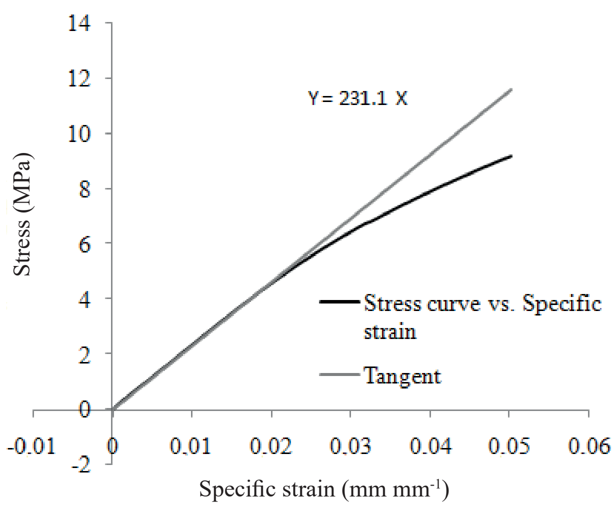

Figure 5. Stress curve and specific strain and its tangent, obtained experimentally for macaw palm rachilla in the mature stage.

phenotypic traits between the locations of the plants under study.

This reduction is considered a consequence of fruit maturity, and the junction between the fruit and rachilla weakens for detachment to occur (Laviola et al. 2007 and 2009).

No significant differences were found for the Poisson's ratio between the two maturity stages studied (Table 1). The results were obtained considering only valid tests. Thus, 30 samples were considered for the immature stage and 24 for the mature stage.

The elasticity modulus and Poisson's ratio showed standard deviations of 98.35 MPa and 105.76 MPa and 0.16 MPa and 0.18 MPa, respectively for immature and mature stages. Among accessions, the elasticity modulus varied 188.39-385.09 MPa for the immature stage and 109.02-320.54 MPa for the mature stage. The Poisson's ratio ranged 0.20-0.52 for the immature stage and 0.16-0.52 for the mature stage.

The values obtained for the elasticity modulus are below those reported for natural fibers such as piassava (6.2 GPa), coconut (3-6 GPa) and sisal (9.4-22 GPa) (D'Almeida et al. 2006). However, they are closer to the reference values for wood, which ranged between 0.9 GPa and 1.6 GPa, in the study by Garcia et al. (2012). The different values obtained may be due to the different physical characteristics of fibers, in addition to variations in test parameters, such as the speed and specific strain used.

The values found for the Poisson's ratio are within the reference values for solid materials, which are between 0.25 and 0.33 for wood (Garcia et al. 2012), and for isotropic materials, which ranged between zero and 0.50 (Callister Júnior 2007), corroborating the value of 0.35 reported by Coelho et al. (2015), for the peduncle of the coffee plant.

The elasticity modulus showed a high heterogeneity between the accessions under study (Table 2). Similarly, Ciconini et al. (2013) observed a wide variation in macaw palm fruits characteristics from different regions. Regional variations were also reported by Sanjinez-Argandoña & Chuba (2011), who studied different macaw palm fruit traits.

According to Botezelli et al. (2000), this may be due to the different localities, whose environmental variability may result in different plant phenotypes. Also, variation among regions may also be explained by the genetic structure between isolated populations. Fruit maturity is also not uniform, what attenuates these differences and compromises the harvest process (Clement et al. 2005). Also, the rachillas lengths used were not equal among accessions, what may confer differences in the stiffness of the systems. These variations interfere directly in the dynamic response of the bunches and, consequently, in the mechanical vibration harvest.

The elasticity modulus and Poisson's ratio are associated with the rigidity of the material, and their variations interfere directly in the natural frequencies of the system, which serve as the basis for projects to develop machines that use mechanical vibration harvest (Garcia et al. 2012).

The damping ratio and damping coefficient were calculated using the relation between any two successive amplitudes obtained from logarithmic decrement curves (Figure 6).

The damping ratio and damping coefficient show no significant differences for the influence of maturity stage (Table 3). However, the fruit-rachilla system showed a tendency to increase the damping ratio as the maturity of bunches evolve, which indicates that, in the mature stage, the system displays greater damping capacity and lower vibration amplitude when submitted to excitation.

The standard deviations found for the damping coefficient were 0.57 Ns m^{-1} and 0.58 Ns m^{-1} for the

Table 2. Average elasticity modulus and Poisson's ratio for macaw palm rachillas, in the immature and mature stages, from all the sampled accessions, and Kruskal-Wallis test results.

Accession	Elasticity modulus (MPa)		Poisson's ratio			
	Immature	Mature	Accession	Immature	Accession	Mature
BD27	307.84 ab	184.12 ab	BGP53	0.39 a	BD27	0.45 a
BD40	304.61 ab	305.59 b	BGP31	0.41 a	BD40	0.37 a
BGP29	337.56 b	247.54 b	BGP13	0.32 a	BGP29	0.31 a
BGP35	196.93 a	121.88 a	BGP12	0.32 a	BGP35	0.26 a
H	11.3208	20.6971		1.8909		5.0667

H: critical limit from the Kruskal-Wallis test; BD27 - Abaeté, MG; BD40 - Pitangui/Martinho Campos, MG; BGP29 - Prudente de Moraes/Matozinhos, MG; BGP35 - Mirandópolis, SP; BGP53 - São João Del Rey/Lavras, MG; BGP31 - Três Marias, MG; BGP12 - Ibiá/Araxá, MG; BGP 13 - Belo Horizonte, MG. Means followed by the same letter in the column do not differ statistically, according to the Kruskal-Wallis test at 5 %.

immature and mature stages, respectively, and, for the damping ratio, the immature and mature stage values were 0.05 and 0.03, respectively. Among all the accessions, the damping ratio range was 0.02-0.12 in the immature stage and 0.06-0.12 in the mature stage. The range for the damping coefficient with the immature stage was 0.24-1.38 Ns m^{-1} and with the mature stage 0.34-1.50 Ns m^{-1}.

No significant differences were found for damping coefficient or damping ratio values between the accessions studied (Table 4).

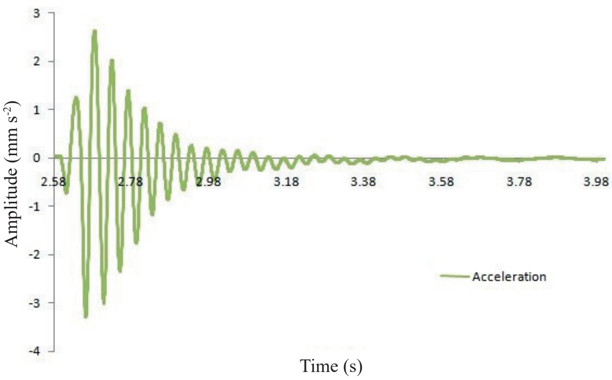

Figure 6. Amplitude of acceleration, as a function of time, for the fruit-rachilla system of the macaw palm in the mature stage.

Table 3. Average damping coefficient and damping ratio values for the fruit-rachilla system of the macaw palm, in the immature and mature stages, and Wilcoxon test results.

Maturity stage	Damping coefficient (Ns m^{-1})	Damping ratio
Immature	0.81	0.07
Mature	0.92	0.09
p-value	0.4669	0.3015

* Means differ statistically, according to the Wilcoxon test at 5 %.

For very low damping values, the damped vibration frequency tends to undamped natural frequency (Rao 2008). This behavior is observed for the systems studied here.

Coelho et al. (2015) studied the fruit-peduncle system of coffee plants and found damping ratio values of 0.15 and 0.09 for the immature and cherry stages, respectively, while Villibor et al. (2016) reported 0.149 and 0.126 for the immature and cherry stages, respectively. These values are close to those obtained in the present study for the fruit-rachilla system of the macaw palm. However, the values observed for the damping ratio were lower than the one characterizing the fruit-rachilla system as underdamped (Rao 2008).

Our results provide a better understanding of the mechanics of the macaw fruit-rachilla system. The determination of its mechanical properties assists on predicting the behavior of the system under different forces and vibration frequencies. This knowledge may facilitate the decision making in the design phase of a mechanical harvest system.

CONCLUSIONS

1. The macaw palm fruit-rachilla system is characterized as underdamped;
2. The methodology used allows the evaluation of mechanical properties of the macaw palm fruit-rachilla system, which may serve as a basis to predict the dynamic behavior of the plant under the use of different harvest machines.

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Table 4. Average damping coefficient and ratio values for the fruit-rachilla system of the macaw palm, in the immature and mature stages, considering all the accessions, and Kruskal-Wallis test results.

Accession	Damping coefficient (Ns m^{-1})		Damping ratio	
	Immature	Mature	Immature	Mature
BD27	0.61 a	0.93 a	0.07 a	0.08 a
BD40	0.66 a	0.89 a	0.07 a	0.12 a
BGP29	0.87 a	1.34 a	0.07 a	0.13 a
BGP35	1.12 a	0.58 a	0.08 a	0.05 a
H	1.6796	2.1534	0.5455	4.1322

H: critical limit from the Kruskal-Wallis test. BD27 - Abaeté, MG; BD40 - Pitangui/Martinho Campos, MG; BGP29 - Prudente de Moraes/Matozinhos, MG; BGP35 - Mirandópolis, SP. Averages followed by the same letter in the column do not differ statistically, according to the Kruskal-Wallis test at 5 %.

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