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Mechanical properties of the rachis from macaw palm bunches

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ABSTRACT. Numerical implementation methods such as the finite element method can be used in machine design to study the dynamic behavior of the plant. Input parameters for using the finite element method should be set based on the geometrical, physical and mechanical system under study. Thus, the aim of this study was to determine the mechanical properties of the rachis of macaw palm in the green maturation stage at an age of 180 days and at fruit maturation. The water content was calculated using the oven method of 105 ± 3°C for 24 hours. The modulus of elasticity for the rachis was determined by means of mechanical compression testing. The Poisson's ratios were determined from the results of the longitudinal and transverse deformation of rachis test bodies. The shear tests were performed in two scenarios. In the first one, a blade was used without a tensioner, and in the second scenario, a blade was fixed with a tensioner, characterized by a chamfer at 45°. It was concluded that the modulus of elasticity of macaw palm rachis in the green maturity stage was higher than the values for the mature stage of ripeness.

Keywords: *Acrocomia aculeate*; modulus of elasticity; Poisson's ratio; shear test.

Propriedades mecânicas da ráquis do cacho de macaúba

RESUMO. Métodos de implementação numérica, como o método de elementos finitos, podem ser empregados em projetos de máquinas a fim de estudar o comportamento dinâmico da planta. Como parâmetros de entrada para utilização do método de elementos finitos, devem ser informadas as propriedades geométricas, físicas e mecânicas do sistema em estudo. Objetivou-se neste trabalho determinar as propriedades geométricas, físicas e mecânicas da ráquis de macaúba, nos estádios de maturação de frutos verdes com idade de 180 dias e maduros. O teor de água foi calculado através do método de estufa de 105 ± 3°C por 24h, as dimensões foram determinadas com o auxilio de trena e paquímetro, as massas e os volumes mensurados, empregando-se balança digital e proveta, respectivamente. O módulo de elasticidade da ráquis foi determinado por meio de ensaios mecânicos de compressão. Os coeficientes de Poisson foram determinados pelas deformações longitudinais e transversais de corpos de provas oriundos da ráquis. Concluiu-se que os módulos de elasticidade das ráquis no estádio de maturação verde foram superiores aos valores para o estádio maduro de maturação.

Palavras-chave: *Acrocomia aculeata*; módulo de elasticidade; coeficiente de Poisson; tensão de cisalhamento.

Introduction

The macaw palm (*Acrocomia aculeata*) is a native palm of tropical America, occurring from Central America to the extreme south of the American continent (Motoike et al., 2013). In Brazil, it is considered one of the most dispersed palm trees; tolerant of drought and low temperatures, this palm is found along in practically all regions of the country. The adult palm is arboreal, between 10 and 15 m in height, with a high number of spines in its trunk (Montoya, Motoike, Kuki, Oliveira, & Honório, 2015).

Mature macaw palm fruits are slightly flattened globes of yellowish-brown coloring, with a diameter varying from 3 to 6 cm. The composition of fruit by weight is approximately 20% bark, 40% pulp, 33% endocarp and 7% almond. The oils are extracted from two parts of the fruit, the almond and the pulp. Oil withdrawn from the former represents approximately 15% of total oil withdrawn from the plant and has notable uses in the pharmaceutical, food and cosmetic industries. Meanwhile, oil withdrawn from the latter has greater potential for biodiesel production (Nobre, Trogello, Borghetti, & David, 2014).

In relation to productivity, the macaw palm is a promising source of vegetable oil for industries producing fuel (Navarro-Días et al., 2014) and cosmetics (Silva, Silva, & Parente, 2009). In addition to the oil, the processing of macaw palm fruits generates co-products with high added value. There is also the possibility of the endocarp being used in the production of charcoal (Motoike et al., 2013; Nobre et al., 2014).

Different principles can be employed for the mechanized harvesting of agricultural products. In relation to macaw palm cultivation, it is believed that cutting and mechanical vibration of the palm bunches are promising working principles for harvesting machines. Cutting refers to a shear across the cross section of the rachis, promoting the separation of bunch from the plant and, afterwards, contributing to the detachment of the fruits. Generally, a Malaysian knife is used to make this operation achievable for manual harvesting (Motoike et al., 2013). Techniques based on the principle of mechanical vibration depend on knowledge of parameters such as frequency, amplitude and time of vibration. They are used in the mechanized harvesting of different crops such as coffee (Coelho, Santos, Pinto, & Queiroz, 2015) and orange (Castro-Garcia, Blanco-Roldán, Ferguson, González-Sánchez, & Gil-Ribes, 2017). This type of harvesting provides a better selection of fruits when one has knowledge about the dynamic behavior of the plant to be harvested, such as natural frequencies and vibration modes (Santos, Queiroz, Pinto, & Santos, 2010).

Currently, the operation of macaw palm harvesting is carried out using extractive methods, such as collecting fruits that fall on the ground or cutting mature bunches by means of scythes adapted to the height of the plant. In both forms of harvesting, the fruits come into contact with the soil, leaving them susceptible to both the mechanical damages of the fall and the action of microorganisms. This leads to degradation of the pulp, resulting in an oil product with low quality (Ciconini et al., 2013).

As the macaw palm's potential as a source of energy increases (Gonçalves, Batista, Rodrigues, Nogueira, & Santos, 2013), the demand for scientific data that provide knowledge about the plant and its fruits, oil composition, and physical and mechanical properties increases as well. Using this data, it would be possible to expand extractive exploitation to an industrial scale with rational and sustainable management.

In addition, it will be possible to improve industrial processes and design machines and equipment for use in the harvest and post-harvest operations based on knowledge of the physical and mechanical properties of structures that compose the bunches. In this way, fieldwork for the operator will be made safer, while reducing the contingent of labor and production costs associated with extraction.

In this context, and considering the potential of the crop, the aim of this work was to determine and evaluate the mechanical properties of rachis from macaw palm bunches in order to constitute a basis of knowledge for the design of harvesting and post-processing machines.

Material and method

Research was carried out from November 2015 to February 2016 using macaw palm bunches collected at the Active Germplasm Bank (BAG), located at the Experimental Farm in Araponga, Minas Gerais State, Brazil, at 20° 40' South latitude and 42° 31' West longitude. Samples of macaw palm rachis came from four sites: BGP 12 - Ibiá - Araxá; BGP 13 - Sítio Paraíso - Belo Horizonte; BGP 31 - Três Marias; and BGP 53 - Lavras - São João Del Rey.

Samples were always collected in the morning, and tests performed during the same day as collection. The ambient temperature of the laboratory was maintained at 20°C.

The water content, Poisson's ratio, shear strength, modulus of elasticity and compressive strength were determined for the samples at each stage of maturation. Immature fruits were considered to be in their maturation stage at 180 days and mature when natural detachment of fruits occurred.

Water content

To obtain the water content of the rachis samples, the direct method (Brasil, 2009) was used. First, the empty crucibles that would be used were weighed. Subsequently, the crucibles were weighed with the addition of a volume of 1 cm^3 chopped samples of macaw palm rachis (Figure 1). As established by the direct method, three replicates were then dried in an oven at 105 ± 3°C for 24 hours. Finally, the crucibles were weighed with the dried samples and the results recorded.

Figure 1. Crucibles containing chopped samples of macaw palm rachis with a volume of 1 cm^3.

Poisson's ratio

Poisson's ratio was determined using a machine universal testing INSTRON 3360 Series Dual Column Table Frames with Bluehill 3 software. The tests were performed employing four test bodies (Figure 2) at each stage of maturation. Test specimen composition was standardized at 12 cm of length, 2.50 cm of width and 0.50 cm of height.

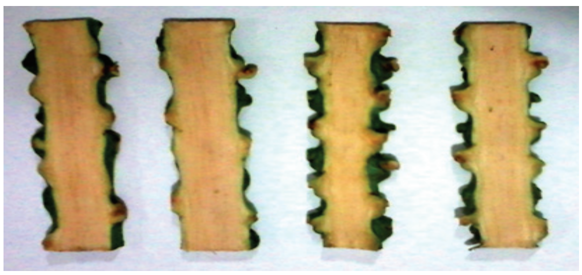

Figure 2. Test specimens of macaw palm rachis used to determine the Poisson's ratio.

The rachis test specimens were fixed directly to the universal testing machine by means of jaws of the equipment and subject to traction. The system displaced the sample vertically by 3.0 mm. The deformation was then measured transversally and longitudinally using a caliper rule of 0.01 mm resolution.

The Poisson coefficient was calculated by Equation 3.

$$\mu = \frac{-\Delta d}{\Delta l} \qquad (3)$$

where: μ = Poisson's ratio; Δd = specific transversal contraction, mm mm^{-1}; and Δl = specific longitudinal elongation, mm mm^{-1}.

Shear test

The shear test was also accomplished using the universal testing machine INSTRON 3360, configured to perform a compression routine with a velocity of 15 mm min.$^{-1}$. For this test, specimens were prepared from the upper third of the rachis (Figure 3) using lengths of 50 mm and actual cross sections of the rachis with average diameters of 25 mm.

Figure 3. Test specimens of macaw palm rachis prepared for shear test.

The shear tests were performed considering two conditions. In the first, a blade without a tensioner was fixed to the upper jaw of the testing machine, while on the lower jaw, a flat circular plate (Figure 4) was used. In order to allocate and support the specimens during the tests, an apparatus was developed and positioned over the flat circular plate (Figure 5).

Figure 4. Set up used for the shear test of macaw palm rachis.

For the second condition, the tests were performed using a blade with a tensioner, which was characterized by a 45° chamfer at its end (Figure 5).

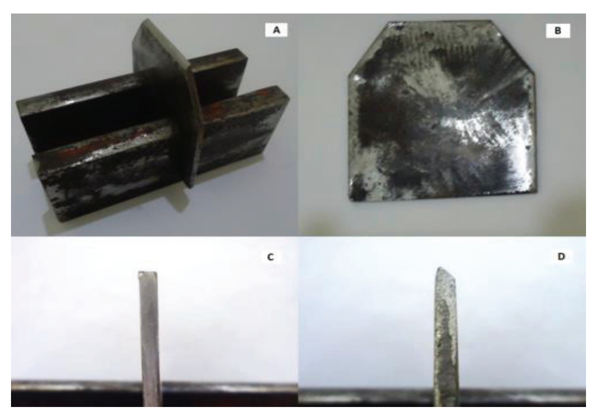

Figure 5. Apparatus developed for the shear test (A), blade used for test (B), without tensioner (C), and blade with tensioner and 45° chamfer at the end (D).

The test specimens were inserted into the fixed part of the apparatus. During the test, the downward movement of the upper jaw of the universal testing machine, where the test blade was fixed, provided a shearing force in the cross-section of the specimens; this force was monitored until the test specimen cut itself off.

From the maximum shear force and the cross-sectional area of the test specimen, shear stress of the macaw palm rachis was calculated (Equation 4).

$$\tau = \frac{F}{S} \quad (4)$$

where: τ = shear stress, MPa; F = shear force, N; and S = cross-sectional area of the test specimen, mm^2.

Compression test

The modulus of elasticity of the rachis was determined through a compression test, employing an INSTRON 3360 universal testing machine and using five cylindrical test specimens for all sites. These specimens were sourced from the lower third of the rachis, with a 20 mm diameter (rachis circular cross section) and 15 mm length (Figure 6).

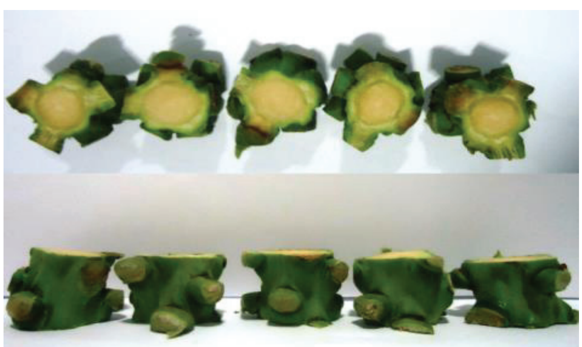

Figure 6. Test specimens of macaw palm rachis prepared for compression tests.

The tests were performed by means of compression, and the samples were placed between two parallel flat circular plates (Figure 7) and subjected to constant deformation at small magnitudes on the two opposite faces of the specimen. The constant deformation rate was 15.0 mm $min.^{-1}$, monitored by Bluehill 3 software and managed by the computer coupled to the universal testing machine. The elasticity modulus of the rachis was calculated using the tangent method. Additionally, compressive strength was determined.

Statistical analysis

The data for the water content, Poisson's ratio, shear test, modulus of elasticity and compressive strength of the samples (test specimens) were submitted to analysis of variance, according to a completely randomized design and considering two stages of maturation (rachis from immature and mature fruits). The stage of maturation effect on the behavior of mechanical properties was studied using the Tukey test at a significance level of 5%. Statistical analysis was completed by the computer software Assistat Statistic version 7.7 beta (Silva & Azevedo, 2016).

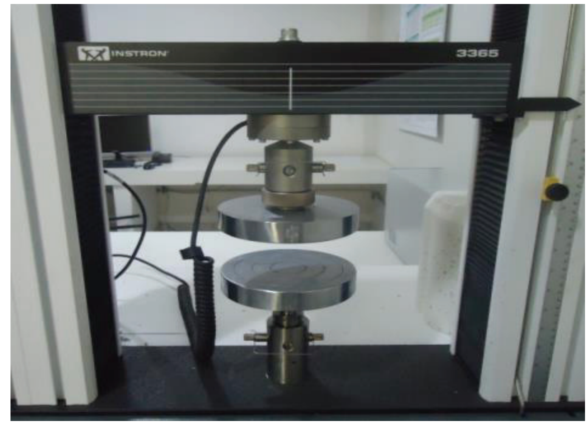

Figure 7. Equipment used for compression test of macaw palm rachis.

Result and discussion

Water content

After analyzing the average water content of the macaw palm rachis for the BGP 12, BGP 13, and BGP 53 sites, no significant differences were observed between the stages of maturation from immature to mature fruits (Table 1). However, for the BGP 31 site only, it is possible to confirm that from the immature to mature maturation stages, the average water content showed a slight decrease.

Table 1. Average water content (% w.b.) of the macaw palm rachis in immature and mature stages of maturation.

Sites	Average water content (%w.b.)	
	Immature	Mature
BGP 12	78.20 aA	80.55 aA
BGP 13	76.34 aA	78.10 abA
BGP 31	77.84 aA	72.31 bB
BGP 53	82.72 aA	81.30 aA

Averages followed by the same letters (lowercase) in the columns do not significantly differ from each other by Tukey test at 5% probability. Averages followed by the same letters (uppercase) in the rows do not significantly differ from each other by Tukey test at 5% probability.

Comparing the average water contents for the same stage of maturation, it can be observed that there are no significant differences between sites in the immature stage. However, for the mature stage, it can be stated that the BGP 31 site has lower water content than the BGP 12 and BGP 53 sites.

With the physiological maturation of the fruits, the water content remained unchanged from the immature to the mature stages, which was expected due to the need for a water supply to maintain the fruits in bunches. Water content can influence the required shear strength to cut biological structures such as the macaw palm rachis. Taghijarah, Ahmadi, Grahderijani, and Tavakoli (2011) reported that when cutting sugarcane stalks with an average water content of 75.3% (% w.b.) and cross-sectional area of

453 mm^2, a shear strength of 3.64 MPa was necessary.

Poisson's ratio

The Poisson's ratios for stages of maturation and sites are presented in Tables 2 and 3, respectively.

Table 2. Poisson's ratio of macaw palm rachis in immature and mature stages of maturation.

Stages of maturation	Poisson's ratio
Immature	0.29 ± 0.14 a
Mature	0.31 ± 0.14 a

Averages followed by the same letter do not differ statistically from each other by Tukey test at 5% probability.

Table 3. Poisson's ratio of macaw palm rachis for the sites.

Sites	Poisson's ratio
BGP 12	0.32 ± 0.27 a
BGP 13	0.33 ± 0.27 a
BGP 31	0.35 ± 0.27 a
BGP 53	0.22 ± 0.27 a

Averages followed by the same letter do not differ statistically from each other by Tukey test at 5% probability.

There was no significant difference in the Poisson ratios in relation to the stage of maturation (Table 2) or site (Table 3). However, it can be observed that the Poisson ratios at the mature stage were higher than those found in the immature stage, meaning that for a given longitudinal deformation, the mature rachis of macaw palm presented greater deformation in the longitudinal direction when compared to the rachis of macaw palm in the immature stage.

Although there is no significant difference in the results, the BGP 31 site was the one that obtained the highest value of Poisson coefficient, 0.35, and the BGP 53 site obtained the lowest value, 0.22. This indicates that for the same longitudinal deformation, the BGP 31 site will deform more easily in the same direction than the other sites.

Comparing the results obtained with the fibrous biological materials analyzed by Ghavami and Marinho (2005), which found a Poisson coefficient of 0.26 for *Guadua angustifolia*, this value is below the value found for macaw palm rachis. In addition, Coelho et al. (2015), in a study of the "Catuaí Vermelho" coffee variety, obtained a Poisson's coefficient of 0.35 for coffee stems in the green and cherry stages of maturation. These results are by magnitude close to those obtained in the present work for macaw palm rachis.

Shear stress

The results for rachis shear stress are presented in Table 4. Two conditions were evaluated: the first with a cutting blade without a tensioner and the second with a cutting blade with 45° chamfer, characterizing a tensioner.

Table 4. Results for shear stress of macaw palm rachis with cutting blades without tensioner and a cutting blade with 45° chamfer.

Cutting blade	Shear stress (MPa)
Without tensioner	2.79 ± 0.54 a
With tensioner	0.90 ± 0.54 b

The averages followed by the same letter do not differ statistically from each other by the Tukey test at 5% probability.

For different cutting blades, a magnitude of 2.79 MPa was observed for the cutting blade without tensioner, while 0.90 MPa was observed for the cutting blade with 45° chamfer. Using a cutting blade with a tensioner required one-third of the applied force to cut the rachis of the macaw palm.

The results for shear stress considering the different stages of maturation are presented in Table 5.

Table 5. Shear stress of rachis at immature and mature stages of maturation.

Stages of maturation	Shear stress (MPa)	
	Without tensioner	With tensioner
Immature	2.55 ± 0.64 a	0.37 ± 0.17 b
Mature	3.02 ± 0.64 a	1.44 ± 0.17 a

The averages followed by the same letter do not differ statistically from each other by the Tukey test at 5% probability.

It was observed that there was no significant difference between the maturation stages. However, while using a tensioner and cutting blade with 45° chamfer, there was a significant difference between the stages of maturation (Table 5). Over time, the magnitude of shear tends to increase, which implies that the application of greater force is necessary to perform the same cut. For a cutting blade with a tensioner, it was observed that the shear stress magnitude increased approximately 3.9 times, reaching 1.44 MPa, for the mature stage.

The shear stress for the sites is shown in Table 6.

Table 6. Shear stress of the macaw palm rachis for the sites.

Sites	Shear stress (MPa)	
	Without tensioner	With tensioner
BGP 12	2.78 ± 1.62 a	0.86 ± 3.09 a
BGP 13	2.85 ± 1.62 a	0.92 ± 3.09 a
BGP 31	2.36 ± 1.62 a	0.96 ± 3.09 a
BGP 53	3.17 ± 1.62 a	0.87 ± 3.09 a

The averages followed by the same letter do not differ statistically from each other by the Tukey test at 5% probability.

From the results, it was observed that there was no significant difference between the evaluated sites or for the types of cutting blades used.

In a study carried out for bamboo species *Guadua angustifolia*, Ghavami and Marinho (2005) found an average shear stress equal to 2.02 MPa. This magnitude is very close to the results obtained for macaw palm rachis, which is also a fibrous biological material, for a cutting blade without tensioner. It can be inferred that the result found by Ghavami and Marinho (2005) is in the interval between the values obtained from the different cutting blades analyzed in this research.

Compression test

Modulus of elasticity

For the modulus of elasticity, significant differences were observed between the stages of maturation evaluated (Table 7).

Table 7. Modulus of elasticity of the macaw palm rachis in immature and mature stages of maturation.

Maturation stages	Modulus of elasticity (MPa)
Immature	51.97 ± 9.18 a
Mature	37.93 ± 9.18 b

The averages followed by the same letter do not differ statistically from each other by the Tukey test at 5% probability.

The modulus of elasticity for the immature stage was higher than that of the mature stage. There was a greater elastic deformation by the macaw palm rachis in the mature stage for the same tension applied.

Regarding the sites, no significant differences were determined for the modulus of elasticity (Table 8).

Table 8. Modulus of elasticity of different sites on macaw palm rachis.

Sites	Modulus of elasticity (MPa)
BGP 12	39.83 ± 18.23 a
BGP 13	39.40 ± 18.23 a
BGP 31	54.72 ± 18.23 a
BGP 53	45.85 ± 18.23 a

The averages followed by the same letter do not differ statistically from each other by the Tukey test at 5% probability.

Lobão, Lúcia, Moreira, and Gomes (2004) obtained a modulus of elasticity of 18342 MPa from compression tests in a study developed for the fiber of *Eucalyptus grandis* wood, with an average density of 0.88 g mL^{-1}. This magnitude is approximately 420 times greater than that reported for the macaw palm rachis, and it can be inferred that the macaw palm rachis is much more flexible than the *E. grandis* wood, which is mechanized from harvester heads that use knives to perform of the tree cutting (Leite et al., 2014). Therefore, these results suggest that the use of cutting blades assemble in a harvester head could be a solution for the harvesting of macaw palm bunches.

Compressive strength

In Table 9, the results for compressive strength are presented.

Table 9. Compressive strength of macaw palm rachis in immature and mature stages of maturation.

Stages of maturation	Compressive strength (MPa)
Immature	6.81 ± 1.03 a
Mature	3.34 ± 1.03 b

The averages followed by the same letter do not differ statistically from each other by the Tukey test at 5% probability.

The compressive strength of the immature stage was approximately twice that of the mature stage. Magnitude of compressive strength evidence the difficulty of compressing a certain body. In the case under study, the macaw palm rachis in the green maturation stage had a higher resistance to compression than the macaw palm rachis belonging to the mature maturation stage.

Regarding the values of compressive strength, no significant differences were found between sites (Table 10).

Table 10. Compressive strength of macaw palm rachis between sites.

Sites	Compressive strength (MPa)
BGP 12	4.86 ± 2.88 a
BGP 13	4.54 ± 2.88 a
BGP 31	5.98 ± 2.88 a
BGP 53	4.93 ± 2.88 a

The averages followed by the same letter do not differ statistically from each other by the Tukey test at 5% probability.

The compressive strength magnitude found by the present work, 5.10 MPa, is very close to the results found by Magalhães, Braunbeck, and Pagnano (2004) for the compressive strength of sugarcane, which obtained an average value of 4.9 MPa. These similar magnitudes are due to the fibrous structural similarities of sugarcane and macaw palm rachis.

Conclusion

The water content of the macaw palm rachis only showed a significant difference between maturation stages for the BGP 31 site. The Poisson coefficient was 0.29 for the immature stage of maturation and 0.31 for the mature stage. The cutting blade without a tensioner exhibits about three times greater magnitude of shear stress than the cutting blade with a 45° chamfer. The modulus of elasticity at the immature stage of maturation was higher than for the mature stage, at 51.97 MPa and 37.93 MPa respectively. The compressive strength for the immature stage of maturation was approximately twice that of the mature stage.

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