Research Article
doi: 10.1590/01047760202228013035
vol(28), 2022

CERNE

Mechanical properties of the macaw palm endocarp aiming seedling production process

Fábio Lúcio dos Santos [1iD], Francisco Scinocca [1✤iD],
Paula Beatriz Martins Fonseca [1iD], Flora Maria de Melo Villar [2iD]

[1] Engineering Department, Federal University of Lavras, Lavras, Brasil
[2] Agricultural Engineering Department, Federal University of Viçosa, Viçosa, Brasil

TECHNOLOGY OF FOREST PRODUCTS

ABSTRACT

Background: The Macaw palm (*Acrocomia aculeata*) is a palm tree native to the Tropical America Forests. This palm has stood out due to its high potential for the production of oil for biofuels, being an excellent source of renewable energy. However, due to the rudimentary way of exploring the Macaw palm, mostly using native people labor, it is not possible to extract the maximum economical potential that this plant can provide. In order to use the Macaw palm in industrial scale, new strategies using high-performance machinery in several segments of the production chain should be employed.

Results: For that, its seedlings production must be broadly expanded, using modern techniques for its propagation and production on an industrial scale, since its present low germination rates when the natural way is employed. In this way, the present paper has the objective of establishing a database of the mechanical properties of the endocarp of the Macaw palm when submitted to compression efforts, typically used for removing almonds from the endocarp. The inherent variability of its mechanical properties was quantified, using three different crops sites.

Conclusion: Important information about the mechanical properties of the Macaw palm endocarp is presented, serving as guideline for future works to genetic improvement of the Macaw palm, in order to obtain fruits with less variability in the mechanical properties of the endocarp and consequently improve the production on an industrial scale.

Keywords: Pre-germinated seeds; Compression efforts; Macaw palm endocarp; Biodiesel; Renewable energy.

HIGHLIGHTS

Database to improve production on an industrial scale of Macaw palm seedlings using pre-germination techniques in laboratories;
Mechanical properties of the endocarp of the Macaw palm and its inherent variability;
Force and Energy needed to removing almonds from the endocarp, without damage;
Macaw palm plantation sites and its influence in the rupture force of the endocarp.

DOS SANTOS, F. L.; SCINOCCA, F.; FONSECA, P. B. M.; VILLAR, F. M. DE M. Mechanical properties of the macaw palm endocarp aiming seedling production process. CERNE, v.28, e-102819, doi: 10.1590/01047760202228013035

✤Corresponding author e-mail: francisco.scinocca@ufla.br
Submitted: 29/11/2021 Accepted: 09/08/2022

CERNE ISSN 0104-7760
UNIVERSIDADE FEDERAL DE LAVRAS

INTRODUCTION

The Macaw palm (*Acrocomia aculeata*) is a palm tree native to tropical jungle, covering all Tropical America Forests (Pimentel et al., 2018). In Brazil, the Macaw palm is found in great dispersion in the biomes of the Cerrado, Atlantic Forest, Amazon Forest and Pantanal (Lorenzi et al., 2011; Ciconini et al., 2013, Motoike et al., 2013; Evaristo et al., 2016b). This palm has stood out due to its high potential for the production of oil for biofuels, being an excellent source of renewable energy (Bergmann et al., 2013; Machado et al., 2016; Silva et al., 2016). Likewise, its co-products have great potential for use in different segments of agriculture, cosmetics and industry in general (Ferrari and Azevedo Filho, 2012; Cardoso et al., 2017). Furthermore, the Macaw palm has been studied extensively by researchers due to its rusticity, adaptability, carbon fixation capacity and the possibility of being cultivated in consortium with other species in Agrosilvopatoral Systems (ASPS) (Motoike and Kuki, 2009; Evaristo et al., 2016b; Cardoso et al., 2017; Castro et al., 2017). Therefore, the particularities of its culture have aroused great interest from companies in the agricultural and industrial sector (Pimentel et al., 2018).

Due to the rudimentary way of exploring the Macaw palm, mostly using native people labor, it is not possible to extract the maximum economical potential that this plant can provide, even the Macaw palm being found in almost all regions of Brazil (Motoike et al., 2007; Ciconini et al., 2013). Therefore, the development of technologies that contribute to the sustainable production these raw materials is essential, providing its use in different sectors of the agro-energetic business, as a source of their products and co-products (Lorenzi et al., 2011). In order to use the Macaw palm on an industrial scale, new strategies using high-performance machinery in several segments of the production chain should be employed. In this way, the rudimentary extraction must be replaced by rational crops (Motoike et al., 2007; Evaristo et al., 2016a; Velloso et al., 2017; Villar et al., 2017; Oliveira et al., 2018; Pimentel et al., 2018; Grupioni et al., 2020). Thus, the production of Macaw palm seedlings must be broadly expanded, using modern techniques for its propagation and production on an industrial scale, since its present low germination rates when the natural way is employed (Motoike et al., 2007; Pimentel et al., 2016; Pimentel et al., 2018).

Pre-germination techniques in laboratories and seedling nurseries have a high capacity for expansion in seedling production, when compared to natural production, particularly for the Macaw palm. Using advances and improvements in the seeding production techniques, a significant increase in the propagation and production of Macaw palm can be obtained. Regarding the germination process and the production of pre-germinated Macaw palm seedlings, Motoike et al. (2007) developed a protocol that allows the pre-germination in a large-scale production, with germination efficiency of 60 to 80%. These pre-germinated of the Macaw palm seeds have high rates of seedling establishment in nurseries (Pimentel et al., 2016).

According to Motoike et al. (2007), the germination and production process of pre-germinated of Macaw palm seeds has, as its first step, the elimination of the endocarp, after its drying and loosening of the almond. Currently, almonds are extracted from the endocarp manually, using mechanical action. This procedure requires labor, being performed by hand tools, such as hammers or ditches, which can cause damage to almonds. From this procedure, only uninjured almonds proceed to the germination process. In this way, becomes evident that the automation of the process of elimination of the endocarp can minimize problems related to the shortage of labor and associated with the rudimentary techniques employed, while giving the industrial scale to boost the Macaw palm as a prominent source for renewable energies. As an important hypothesis for the present research, the use of automated systems to eliminate the endocarp of the fruits of Macaw palm, thought a compression process seems to be quite promising. For that, the quantification of the inherent variability of the mechanical properties becomes very important.

Thus, the present research was developed with the objective of establishing a database of the mechanical properties of the endocarp of the Macaw palm when submitted to compression efforts, typically used for removing almonds from the endocarp. This work had contributed with the quantification of the inherent variability of its mechanical properties, which will serve as a reference for design machines and automation process, with an adaptive loading application. For that, three crops sites were analyzed and significant differences in their mechanical properties were identified. In the same way, the present research can also serve as reference to genetic improvement of the Macaw palm, in order to obtain fruits with less variability in the mechanical properties of the endocarp and, consequently, to improve the production on an industrial scale.

MATERIAL AND METHODS

Experimental approach

To determine the mechanical properties of the Macaw palm endocarp, the Germplasm Bank of the Federal University of Viçosa was used. Three different sites were used, as identified in Table 1.

Table 1. Sites identification and information.

Site	BGP 16-6	BGP 52-2	BGP 12-7
Identification	A1	A2	A3
Brazilian State		Minas Gerais	
Region	Martinho Campos – Abaeté	Rio Piracicaba-Alvinópolis	Ibiá- Araxá

The fruits arising from the three sites, according to Table 1, were separated and, later, went through a pulping process. From this process, the epicarp and mesocarp of the fruits were removed by mechanical action, leaving only the endocarp, according to (Figure 1a), where the seed of the fruit is contained.

The Macaw palm endocarps were dimensionally characterized, according to the size and shape. Thus, the endocarps could be considered as triaxial spheroids, as presented in (Figure 1 b). Three diameters were obtained, corresponding to the largest dimension (a), intermediate dimension (b) and smallest dimension (c). The dimensions of the endocarp were obtained using a digital caliper with a resolution of 0.01 mm.

The dimensions of the endocarp, according to Figure 1 (b), enable to obtain the sphericity (S) and the volume (V) for the endocarps, from the different sites studied, using the Equation 1 and 2. A total of 48 samples were considered for each of the evaluated site, presented in Table 1 (Mohsenin, 1986).

$$S(\%) = \left[\frac{(abc)^{1/3}}{a}\right]100 \tag{1}$$

$$V = \frac{\pi abc}{6} \tag{2}$$

To determine the endocarp average mass, a digital weight balance with an accuracy of 0.001g was used. The mass of the endocarps was obtained individually and, subsequently, the mean for each site was defined, considering the samples.

The sphericity, volume and mass data of the endocarps of the Macaw palm fruit were subjected to analysis of variance statistical test, according to a completely randomized design, with three treatments using the sites A1, A2 and A3, considering the significance level of 5% of probability. To assess the influence of the studied sites, presented in Table 1, on the sphericity, volume and mass averages of the endocarps, the Tukey Significant Difference (TSD) test was performed, with a significance level of 5% probability. Statistical analyzes were performed using the software R.

Later, the compression tests were performed using the universal testing machine INSTRON-EMIC 2320, using a load cell of 20kN. The samples were subjected to a compression load between two parallel flat circular plates, as presented in Figure 3. A constant deformation of small magnitude on the two opposite faces of the Macaw palm fruit were applied. The experiments were conducted using a loading rate between 5.0mm·min^{-1}, to 40.0mm·min^{-1}, increasing 5.0mm·min^{-1}, considering six (6) replications. The same procedure was conducted for the three sites. In this way, forty eight (48) samples for each site were experimentally tested, totalling 144 samples for the whole research. The experiment was monitored using the Bluehill 3 Software, managed by the computer coupled to the universal testing machine. In order not to damage the almonds, the experiment was automatically stopped, as soon as there was a drop of approximately 10% in the mechanical resistance, being this load being sufficient to break the endocarp only. This configuration was obtained in preliminary setup tests, without damage the almonds in the present research.

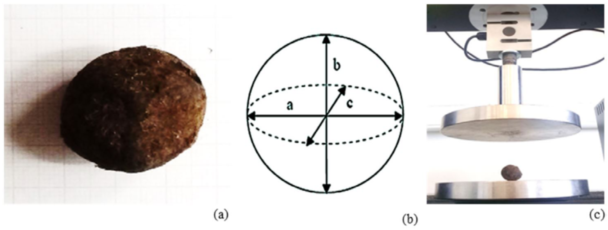

Figure 1. (a) Macaw palm endocarp after the pulping process; (b) Representation scheme of the orthogonal axes of the endocarp of the Macaw palm fruit: a, b and c represent the largest, the intermediate and the smallest dimensions, respectively; (c) Universal testing machine used for compression test of endocarp between two parallel flat circular plates.

From the compression tests conducted, important mechanical properties of the Macaw palm endocarp were collected until the break of endocarp, such as: break force, deformation, elasticity module and break off energy. This information will serve as guideline to design machines for its large-scale process for seedling production.

Statistical analysis

In a first step, an exploratory analysis of the data was carried out, to observe the data conditioning, as well as to avoid the existence of possible outliers. In the same way, an analysis to observe the existence of patterns was also done, using the histograms and other preliminary analyzes. In the sequence, the data of mechanical properties of Macaw palm endocarp referring to the breaking force, deformation, elasticity modulus and break off energy were evaluated from an experiment according to a completely randomized design, in a factorial scheme, considering the following factors: sites (A1, A2 and A3) and strain rates (5, 10, 15, 20, 25, 30, 35 and 40 mm·min^{-1}). The *Pearson* Correlations were performed in order to identify correlations between the Break Force and mass, Break Force and Volume and Break Force and Sphericity in the Sites A1, A2 and A3, considering a significance level of 5% of probability.

The present research had considered six repetitions, totalling 144 experimental units. The influence of the factors evaluated on the mechanical properties of the endocarp of the Macaw palm fruit stray efficiency, the data were submitted to analysis of variance test. The means of qualitative factors were compared using the Tukey Significant Difference (TSD) test, for a significance level of 5% probability. Statistical analyzes were performed using the computer program R.

Additionally, the geometric dimensions, volume and mass of the Macaw palm endocarp were also evaluated in order to investigate the existence of patterns or important information, which could be fundamental for the design of machines, selection or segregation of fruits with similar mechanical and geometrical characteristics in order to assist an easy-to-implement industrial selection.

RESULTS AND DISCUSSION

The Macaw palm fruits are composed of different structures such as the epicarp, mesocarp, endocarp and almond (Berton et al., 2013; Pires et al., 2013). The Table 2 shows the results for the physical properties (mass, volume and sphericity) of the endocarp of the Macaw palm fruit, according to (Figure 1a). The determination of these properties occurred after the despolping process, in which the epicarp and mesocarp of the fruit were removed mechanically.

Table 2. Physical properties results of the Macaw palm endocarp for the sites considered in the research: mass, volume and sphericity.

Sites	Physical properties					
	Mass (g)		Volume (cm^3)		Sphericity (%)	
	Average	Std	Average	Std	Average	Std
A1	9.09 a	±1.26	7.69 a	±1.03	91 a	±1.48
A2	11.51 b	±1.10	8.98 b	±0.67	88 b	±1.27
A3	14.33 c	±1.08	11.98 c	±0.90	89 c	±1.46

Means followed by the same letter, in the column, do not show significant difference according to the Tukey test at 5% probability.

There were significant differences between the sites studied and presented in Table 1 for the mass, volume and sphericity of the endocarp. Considering the average, the largest mass was obtained for in the A3; 57.6% greater than the average mass obtained for site A1, which presented the lowest average mass among the observed sites. Regarding the volume of the endocarp, there was a percentage difference of 55.7% between the sites A3 and A1, which had the highest and lowest volume, respectively. Despite the low percentage variation in sphericity, significant differences were found between all evaluated sites, this characteristic is desirable with regard to the design of machines for rupture of the endocarp of the Macaw palm fruit by mechanical action. The Pearson Correlations were performed and the results presented an absence of correlations.

According to Pires et al. (2013), there is a great variability in the biometry of the Macaw palm fruits, potential for biomass production and oil yield in different sites. However, according to the authors, the biometric characteristics of the fruits did not correlate with the oil contents. This variability between sites has also been observed in studies related to the study and determination of the mechanical properties of the fruit-rachilla system of the Macaw palm (Villar et al., 2017; Velloso et al., 2017; Rangel et al., 2019). With the compression experiments carried out during the present research, it was able to observe that variability can also be found in the endocarp mechanical properties. The break force required for rupture of the Macaw palm endocarp is shown in Figure 4.

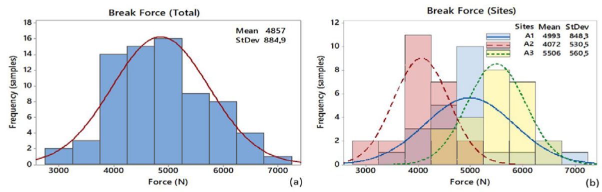

Figure 2. (a) Break Force (Total); (b) Break Force (Sites).

The Figure 2 (a) shows the strength required for the rupture, considering all three sites, A1, A2 and A3. Particularly, a huge dispersion is found, since a variation from 3000 N to 7000N can be found. In Figure 2 (b), it can be observed that the site A1 has greater dispersion, whereas sites A2 and A3 have less variability, with distinguished average in the break force. The Figure 3 presents the endocarp deformation during the breaking process. In details the Figure 3 (b) shows that the sites A1 and A3 presents similar deformation during the endocarp breaking process and a minor variation is presented by the site A2.

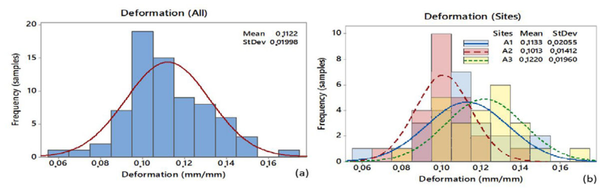

Figure 3. (a) Deformation (Total); (b) Deformation (Sites).

In the same way, the Elasticity Modulus present a huge dispersion, with the site A1 presenting a larger dispersion, as presented in Figure 4(a) and Figure 4(b), respectively.

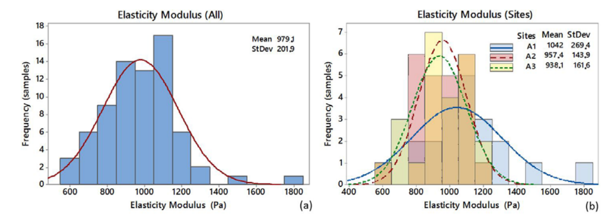

Figure 4. (a) Elasticity Modulus (Total); (b) Elasticity Modulus (Sites).

The Figure 5 presents the energy needed during the endocarp breaking process. The sites A2 present a minor energy dispersion for the process, as presented in Figure 5 (b) compared with the sites A1 and A3.

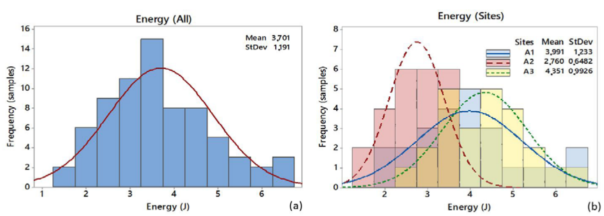

Figure 5. (a) Energy (Total); (b) Energy (Sites).

The weighting process of the Macaw palm fruit presents there were three distinguish mass ranges, as presented in Figure 6 (a) and Figure 6 (b). A mass decrease variation was observed at the same time that the average mass increase in the sites A1, A2 and A3, in that sequence.

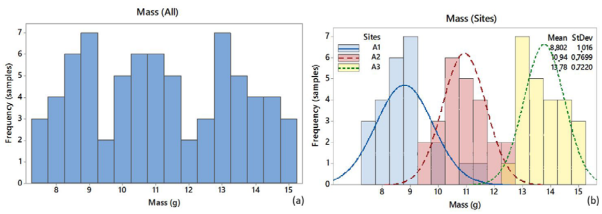

Figure 6. (a) Mass (Total); (b) Mass (Sites).

In Macaw palm endocarp dimensional measurement, it can be seen that site A1 has the greater sphericity in average, according to Figure 7 (a) has the largest radius variation in its average measurement dimension, as presented in Figure 7 (b).

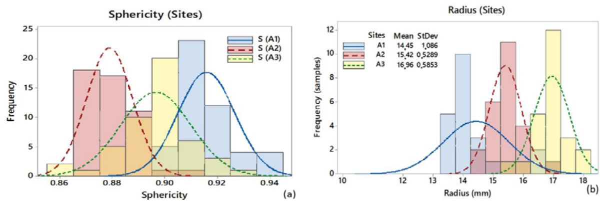

Figure 7. (a) Sphericity (Sites); (b) Radius (Sites).

Table 3 presents the result of the analysis of variance for the breaking force of the Macaw palm endocarp, considering the sites and deformation rate as factors. It was found that only the site factor showed a significant difference, with a significance level of 5% probability. The deformation rate factor did not show any significant difference, indicating that this factor, regardless of the level used, does not influence the rupture strength of the endocarp. This result is desirable and indicates that the design of machines for rupture of the endocarp can be conceived using higher strain rates, which would result in equipment with greater operational capacity. According to Grupioni et al. (2020), the understanding of the productive capacity and the factors that influence the process is fundamental to improve the performance of the machines, to produce in an industrial scale. In addition, efficient process mechanization requires operational planning and technical knowledge, which makes it possible to reduce costs (Oliveira et al., 2007; Santinato et al., 2015; Grupioni et al., 2020).

The effect of the sites factor on the rupture strength of the endocarp was studied using the Tukey test, for a significance level of 5% probability, as shown in Figure 8 (a). The site A3 presented the greatest average force required for the rupture of the endocarp, equal to 5592.9 N. The magnitude was 40.3% greater than the average force required for the rupture of the site A2 endocarps, which presented the lowest force demand, equal to 3987.1N. These results reflect the great variability that exists between the physical properties of the Macaw palm endocarp, which corroborates the results available in the literature for the mechanical properties of the Macaw palm fruit-rachilla system (Villar et al., 2017; Velloso et al., 2017 ; Rangel et al., 2019). Pires et al. (2013) observed a great variation in the biometric characteristics of the fruits of different fruits from the Brazilian Cerrado and from different biomes in the Pantanal. In this context, in the scope of machinery design, the machine design concepts must consider the significant variability of the physical and mechanical properties of the different sites at its seeds extraction.

The Macaw palm endocarp deformation during the compression test was evaluated considering the site and deformation rate factors. It was observed that only the site factor presented a significant difference. Table 4 shows the results for the Tukey test, in which the effect of the deformation and specific deformation of the endocarp was evaluated for the different sites.

Table 4. Compilation of results for the means of the different variables restored in the sites considered.

	Mechanical Properties	
Sites	Deformation (mm)	Specific deformation (mm/mm)
A1	2.10 ab	0.11 ab
A2	1.90 b	0.10 a
A3	2.27 a	0.12 b

Means followed by the same letter, in the column, do not show significant difference according to the Tukey test at 5% of probability.

The greatest deformation was observed for the site A3. Although, there are significant differences between the sites evaluated, it is possible to verify that the percentage variations between the sites were small considering the results for the specific deformation. It is noteworthy that these deformations were sufficient to promote the rupture of the endocarp, allowing the removal

Table 3. Result of the analysis of variance for force of rupture of the endocarp of the Macaw palm fruit considering the factors sites and deformation rates.

Variation Source	Degree of Freedom	Sum of squares	Mean square	F	P-value
Sites	2	25349198	1267499	30.89**	<0.001
Deformation Rate (DR)	7	3139671	448524	1.01^{ns}	0.383
S : DR	14	7416273	529734	1.29^{ns}	0.248
Residue	48	19694250	410297		
Sum	62	27110523			

** Significant at the 5% probability level, ns- not significant.

of the seed in an intact condition. For the production of pre-germinated Macaw palm seeds, the first step is the elimination of the endocarp (Motoike et al., 2007); in this process, the detachment of the almond occurs after drying process. Therefore, small deformations of the endocarp, combined with a low percentage variation of these deformations between the sites, can facilitate the process of mechanization and automation of the endocarp elimination, helping at the seedling production process.

It was not observed significant differences for the elastic modulus of the Macaw palm endocarp for the studied factors (sites and deformation rate). For sites A1, A2 and A3 the elasticity modules were 985.5, 926.3 and 929.9 Pa, respectively. These results indicate that despite the variability found in other mechanical and biometric properties of the fruits of the Macaw palm (Pires et al., 2013), the endocarp, regardless of the evaluated accessions, presented similar elasticity characteristics. It is noteworthy that this behavior, differs from other Macaw palm parts, such as the elasticity modulus of the spindle (Villar et al., 2017; Velloso et al., 2017; Rangel et al., 2019) and the elasticity module of the rachilla (Oliveira et al., 2018).

For the maximum energy of rupture of the endocarp, it is observed that only the sites factor showed significant differences. The Tukey test, for a significance level of 5% probability, was performed to verify the influence of accessions on the energy demand for endocarp rupture, as presented in Figure 8(b).

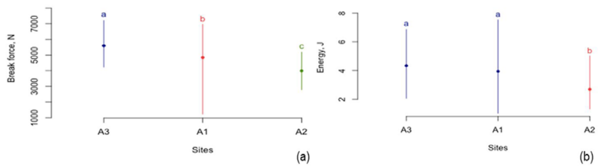

Figure 8. (a) Average breaking force of the Macaw palm endocarp in the different sites evaluated; (b) Maximum energy of rupture of the endocarp rupture (different sites).

The energy for endocarp rupture was 3.9, 2.7 and 4.3 J for the sites A1, A2 and A3, respectively. It was observed that the lowest energy demand for the rupture of the endocarps occurred in the site A2. Therefore, for the endocarp rupture of the sites A1 and A3, an increase at least of 44% was necessary. Thus, considering the results regarding the endocarp deformation, presented in Table 4, and the energy required for rupture, presented in Figure 5, it can be inferred that the material that constitutes the endocarp of the Macaw palm fruit tends towards a fragile mechanical behavior. Such mechanical behavior is characterized by small and even absent plastic deformations, in addition to low energy absorption capacity (Callister Jr., 2008).

With the results obtained in the present research, could be observed the inherent variability of the macaw palm endocarp, in a similar way to any biological products. The plants and consequently the fruits come from different regions with distinct edaphoclimatic characteristics. Additionally, considering the mechanization and automation of the endocarp elimination, aiming the seedling production process, this mechanical behavior represents an important information for the machine design concepts.

CONCLUSIONS

The physical properties of the Macaw palm endocarp, mass, volume and sphericity, showed significant variability between the sites studied; consequently, a variation of approximately 40% in the rupture force magnitude was found, when comparing the sites A1, A2 and A3. This variation is found in any type of biological product, especially when taking into account the variations of edaphoclimatic characteristics for each site (A1, A2 and A3).

The deformation rates did not influence the rupture force of the Macaw palm endocarp during the compression tests. For the mechanization process of eliminating the endocarp for the production of seedlings, the use of higher strain rates may favor the design of machines with greater operational capacity.

No significant differences were observed in relation to the modulus of elasticity of the Macaw palm endocarp. However, there were differences between the deformation and the energy required for the rupture. Due to the deformations and energy absorption capacity during the rupture process, it can be inferred that the Macaw palm endocarp tends to present a fragile mechanical behavior.

ACKNOWLEDGMENTS

The authors thank the Minas Gerais State Agency for Research and Development (FAPEMIG), and National Council for Scientific and Technological Development (CNPq), Brazil, for financial support.

AUTHORSHIP CONTRIBUTION

Project Idea: FLS, FMMV
Database: PBMF, FMMV
Processing: FLS, PBMF, FS
Analysis: FLS, FS
Writing: FLS, FS
Review: FLS, FS

REFERENCES

BERGMANN, J.C., TUPINAMBÁ, D.D. COSTA, O.Y.A., ALMEIDA, J.R.M., BARRETO, C.C., QUIRINO, B.F. Biodiesel production in Brazil and alternative biomass feedstocks. Renewable and Sustainable Energy Reviews, v. 21, p. 411-420, 2013. https://doi.org/10.1016/j.rser.2012.12.058.

BERTON, L.H.C., AZEVEDO FILHO, J.A., SIQUEIRA, W.J., COLOMBO, C.A. Seed germination and estimates of genetic parameters of promising Macaw palm (*Acrocomia aculeata*) progenies for biofuel production. Industrial Crops and Products, v. 51, p. 258-266, 2013. https://doi.org/10.1016/j.indcrop.2013.09.012.

CALLISTER JR., W.D. Ciência e engenharia de materiais: uma introdução. Editora LTC, 7a. edição. 705p. 2008.

CARDOSO, A., LAVIOLA, B.G., SANTOS, G.S., SOUSA, H.U., OLIVEIRA, H.B., VERAS, L.C., CIANNELLA, R., FAVARO, S. P. Opportunities and challenges for sustainable production of A. aculeata through agroforestry systems. Industrial Crops and Products, v. 107, p. 573-580, 2017. https://doi.org/10.1016/j.indcrop.2017.04.023.

CASTRO, C.A.O., RESENDE, R.T., KUKI, K.N., CARNEIRO, V.Q., MARCATTI, G.E.; CRUZ, C.D.; MOTOIKE, S.Y. High-performance prediction of macauba fruit biomass for agricultural and industrial purposes using Artificial Neural Networks. Industrial Crops and Products, v. 108, p. 806-813, 2017. https://doi.org/10.1016/j.indcrop.2017.07.031.

CICONINI, G., FAVARO, S.P., MIRANDA, C.H.B., TAPETI, C.F., MIYAHIRA, M.A.M., BEARARI, L., GALVANI, L., BORSATO A.V., COLNAGO L. A., NAKA, M.H. Biometry and oil contents of *Acrocomia aculeata* fruits from the Cerrados and Pantanal biomes in Mato Grosso do Sul, Brazil. Industrial Crops and Products, v. 45, n. 1, p. 208-2014, 2013. https://doi.org/10.1016/j.indcrop.2012.12.008.

EVARISTO, A.B., GROSSI, J.A.S., PIMENTEL, L.D., GOULART, S.M., MARTINS, A.D., SANTOS, V.L., MOTOIKE, S. Harvest and post-harvest conditions influencing macauba (*Acrocomia aculeata*) oil quality attributes. Industrial Crops and Products, v. 85, p. 63-73, 2016a. https://doi.org/10.1016/j.indcrop.2016.02.052.

EVARISTO, A.B., GROSSI, J.A.S., CARNEIRO, A.D.C.O., PIMENTEL, L.D., MOTOIKE, S.Y., KUKI, K.N. Actual and putative potentials of macauba palm as feedstock for solid biofuel production from residues. Biomass and Bioenergy, v. 85, p. 18-24, 2016b. https://doi.org/10.1016/j.biombioe.2015.11.024.

FERRARI, R.A., AZEVEDO FILHO, J.A. Macauba as promising substrate for crude oil and biodiesel production. Journal of Agricultural Science and Technology, v. B, n. 2, p. 1119-1126, 2012.

GRUPIONI, C.M.F., SANTOS, F.L., VELLOSO, N.S., VALENTE, D.S.M., PINTO, F.A.C. Macaw palm supply chain: Evaluation of a semi-mechanized fruit harvesting system. Industrial Crops and Products, v. 151, e112444, 2020. https://doi.org/10.1016/j.indcrop.2020.112444.

OLIVEIRA, E., SILVA, F.M., SALVADOR, N., SOUZA, Z.M., CHALFOUN, S.M., FIGUEIREDO, C.A.P. Custos operacionais da colheita mecanizada do cafeeiro. Pesquisa Agropecuária Brasileira, v. 42, n. 6, p. 827-831, 2007. http://dx.doi.org/10.1590/S0100-204X2007000600009.

OLIVEIRA, Z.R.C.R., SANTOS, F.L., VALENTE, D.S.M., PINTO, F.A.C., VELLOSO, N.S. Mechanical properties of the rachis from Macaw palm bunches. Acta Scientiarum. Agronomy, v. 40, e39504, 2018. http://dx.doi.org/10.4025/actasciagron.v40i1.39504.

LORENZI, G.M.A.C., PIMENTEL, L.D., PAULA, S.R., NEGRELLE, R.R.B., PAES, J.M.V. Prospecção da cadeia produtiva dos frutos da palmeira macaúba no estado de Minas Geais. Informe Agropecuário - EPAMIG, v. 32, n. 265, p. 41-51, 2011.

MACHADO, W., FIGUEIREDO, A., GUIMARÃES, M.F. Initial development of seedlings of macauba palm (*Acrocomia aculeata*). Industrial Crops and Products, v. 87, p. 14-19, 2016. http://dx.doi.org/10.1016/j.indcrop.2016.04.022.

MOHSENIN, N.N. Physical properties of plant and animal materials. New York: Gordon and Breach Publishers, 841p, 1986.

MOTOIKE, S.Y., LOPES, F.A., SÁ JUNIOR, A.Q., CARVALHO, M., OLIVEIRA, M.A.R. Processo de germinação e produção de sementes pré-germinadas de palmeiras do gênero Acrocomia. PI 0703180-7, 2007.

MOTOIKE, S.Y., KUKI, K.N. The potential of Macaw palm (Acrocomia aculeate) as source of biodiesel in Brazil. International Review of Chemical Engineering, v. 1, p. 632–635, 2009.

MOTOIKE, S.Y., CARVALHO, M., PIMENTEL, L.D., KUKI, K.N., PAES, J.M.V., DIAS, H.C.T., SATO, A.Y. A cultura da macaúba: implantação e manejo de cultivos racionais. Viçosa, MG: Editora UFV. 61p, 2013.

PIMENTEL, L.D., BRUCKNER, C.H., MANFIO, E.C., MOTOIKE, S.Y., MARTINEZ, H.E.P. Substrate, lime, phosphorus and topdress fertilization in Macaw palm seedling production. Revista Árvore, v. 40, n. 2, p. 235-244, 2016. http://dx.doi.org/10.1590/0100-67622016000200006.

PIMENTEL, L.D., FAVARO, S.P.; DIETRICH, O.H.S.; PRATES, G.C. Produção de mudas de macaúba diretamente em viveiro. Efeito de recipientes e substratos no desenvolvimento de mudas de macaúba Boletim de Pesquisa e Desenvolvimento 15 (ISSN 2177-0395), Brasília, DF: Embrapa Agroenergia. 22p. 2018. Available at: http://www.embrapa.br/agroenergia/publicacoes.

PIRES, T.P., SOUZA, E.S., KUKI, K.N., MOTOIKE, S.Y. Ecophysiological traits of the Macaw palm: A contribution towards the domestication of a novel oil crop. Industrial Crops and Products, v. 44, p. 200-210, 2013. https://doi.org/10.1016/j.indcrop.2012.09.029.

RANGEL, J.P., QUEIROZ, D.M., PINTO, F.A.C., SANTOS, F.L., VALENTE, D.S.M. Geometric, Physical and Mechanical Properties of the Fruit-rachilla of the Macauba Palm (*Acrocomia aculeata*) Considering Different Sampling Sites in the State of Minas Gerais in Brazil. Journal of Experimental Agriculture International, v. 38, n. 3, p. 1-6, 2019. https://doi.org/10.9734/jeai/2019/v38i330301.

SANTINATO, F., RUAS, R.A.A., SILVA, R.P., DUARTE, A.P., SANTINATO, R. Análise econômica da colheita mecanizada do café utilizando repetidas operações da colhedora. Coffee Science, v. 10, n. 3, p. 402–411, 2015.

SILVA, L.N., FORTES, I.C.P., SOUSA, F.P., PASA, V.M.D. Biokerosene and green diesel from macauba oils via catalytic deoxygenation over Pd/C. Fuel, v. 164, p. 329-338, 2016. https://doi.org/10.1016/j.fuel.2015.09.081.

VELLOSO, N.S., SANTOS, F.S., PINTO, F.A.C., VILLAR, F.M.M., VALENTE, D.S. Mechanical properties of the Macaw palm fruit-rachilla system. Pesquisa Agropecuária Tropical, v. 47, n. 2, p. 218-225, 2017. http://dx.doi.org/10.1590/1983-40632016v4745792.

VILLAR, F.M.M., PINTO, F.A.C., SANTOS, F.L., GROSSI, J.A.S., VELLOSO, N.S. Elasticity modulus and damping ratio of Macaw palm rachillas. Ciência Rural, v. 47, n. 2, 2017. e20160289, https://doi.org/10.1590/0103-8478cr20160289.