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ORIGINAL

Residue of açaí berry (*Euterpe oleracea*) management as a source of lignocellulosic material

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Abstract

The management of açaí berry palm trees consists in the maintenance of a few stems per individual, which generates a large amount of waste. This study aimed to assess some mechanical, physical and anatomical properties of the material from the *Euterpe oleracea* stem considering its dense peripheral zone and low-density center. The compression strength and stiffness, density, size of vascular bundles, proportional area of vascular bundles and fiber length were analyzed. The peripheral zone presented very distinct properties in relation to the center. While the former is considered adequate to be used as a source of lignocellulosic material, the latter is not. The compressive strength of the peripheral zone is equivalent to some commercial Amazon timbers of similar density and higher than bamboo. A linear model confirmed density as a viable property to predict resistance on the peripheral zone. The use of *E. oleracea* stems can stimulate the adoption of management practices to raise the açaí berry productivity and, together with sustainable practices that contribute to the species conservation, increase the income in the Amazon region, especially for those who depend directly on the açaí fruit production. Some studies are still necessary to understand the applicability of this material, but it has shown potential for the manufacturing of high added value products, such as furniture, frames for paintings, handicrafts and as substitute of imported bamboo products.

1 Introduction

Euterpe oleracea Mart. is a multi-stemmed palm tree species widely distributed on the flooded plains of the Amazon basin. Its fruit, called açaí berry, is an important food source for traditional people from the Amazon (Oliveira et al. 2002; Farias Neto et al. 2012). For a long time, extractive activities supplied the market with *E. oleracea* fruit and palm heart, but their crescent demand and the consequent increase in pressure on the natural ecosystems resulted in a change in the exploitation processes, from harvesting to management (Oliveira et al. 2002; Homma et al. 2006).

In the 1990s, the açaí berry started to be consumed in other regions of Brazil, sharply increasing the demand and consequently motivating the plantation of orchards in a system of rational production (Rogez 2000). After the description of functional chemical components in the composition of açaí berry, it gained the status of a "superfruit" (Yamaguchi et al. 2015), resulting in a second big increase in demand.

Besides genetic selection, management practices can improve fruit productivity by reducing the number of stems per clump (Aguiar et al. 2017), for a better space use of each stem, which lowers the competition for water, light and nutrients (Queiroz and Mochiutti 2012). Stems removed during management are used for walls, pillars and roof structures, usually in rustic buildings and without processing (Bentes-Gama et al. 2005).

The management of açaí production areas generates a lot of underused raw material, most of it left in the forest, despite the high potential for many different applications. Palm trees, as well as all monocotyledons, have a common characteristic, the absence of cambium (Kubitzki et al. 1998), meaning that they do not produce wood (Parthasarathy and Klotz 1976). Their stem consists of the primary plant body, fibrovascular bundles, containing xylem, phloem and fibers, immersed in a parenchymatous matrix (Zimmerman and Tomlinson 1972). The bamboo group is an example of well-succeeded monocotyledon, the stem of which is used

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in many engineered products, with applications similar to those of wood, as presented by Sharma et al. (2015).

Although less common than bamboo, some palm trees have also been studied for providing material from their stems for solid or glued products. Killmann and Fink (1996) provide a vast amount of information about the application of coconut palm (*Cocus nucifera*) stem, from the source and its processing to drying, gluing, and finishing. Peach palm (*Bactris* sp.) stem can also be applied to produce handicrafts, parquets, and other building materials, and according to FAO (1994), it has high strength and elasticity, as well as desirable aesthetics.

Palm tree stems present a peripheral zone with higher density in relation to the core and both having very distinct characteristics. In the case of the coconut palm tree, the peripheral zone is more than three times stronger than the core (Killmann and Fink 1996). This difference can only result in very distinct potential applications.

As well as for wood, understanding the mechanical properties of the *E. oleracea* stem is essential to find proper uses for it (Thelandersson and Larsen 2003), and identifying correlations between its mechanical properties and other characteristics enables the prediction of the material behavior using simpler methods.

The present study aims to assess the resistance to compression parallel to grain of the stem material from *E. oleracea* and seek for its correlations with physical and anatomical properties, considering the dense peripheral zone and the soft center.

2 Materials and methods

2.1 Material

The material was collected in the surroundings of Santarém city (2°26′35″S, 54°42′30″W), located on the confluence of the Tapajós and the Amazon rivers, in the Brazilian Amazon region. Six stems were collected, each one from a different individual, always from the center of the palm clump, where the straightest and oldest stems are found. As they grew in the wild, the age of the stems is unknown but was estimated between 8 and 10 years old. Stems were then taken to the carpentry to produce 15 mm × 15 mm × 600 mm slats from two different portions, the high-density peripheral zone and the low-density core (Fig. 1). Cross-section dimensions of the samples were limited to the thickness of the high-density peripheral zone.

Six specimens, measuring 15 mm × 15 mm × 45 mm, were produced from each slat as in the sequence presented in Fig. 2. Specimens A, C, and E were tested on compression load, and samples B, D and F were prepared for anatomical analysis. For all six stems, there were 18 specimens for each combination of zone (periphery/center) and type of analysis (mechanical/anatomical): 72 specimens in total. This methodology was chosen so that correlation tests could be made between the sample pairs (A–B, C–D, E–F).

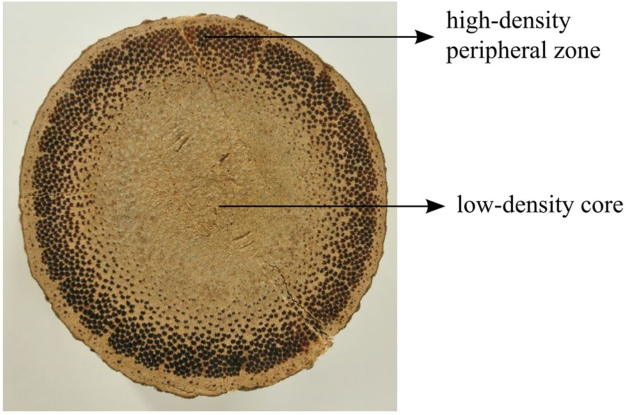

Fig. 1 Cross section of a 200 mm diameter *E. oleracea* stem, showing the two studied portions

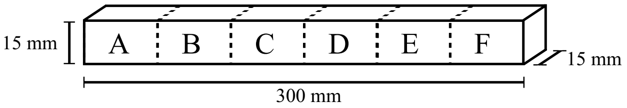

Fig. 2 Sampling methodology for each slat

2.2 Density and mechanical tests

The samples were submitted to the compression load test parallel to grain in a universal testing machine, model EMIC, with a load capacity of 300 kN at the Wood Technology Laboratory, Federal University of Western Pará, Brazil.

Resistance to compression parallel to grain is one of the most studied mechanical wood properties (Kretschmann 2010), and because it is not a compound stress, such as static bending, and simpler to test than shear parallel to grain, it was chosen for the first mechanical properties assessment of the material. The mechanical tests were conducted adapting the Brazilian Timber and Timber Structures Standard—NBR 7190 (ABNT 1997). As the material presents dimension limitations on the cross section, samples of 15 mm × 15 mm × 45 mm were produced, maintaining 3:1 ratio for height/width of the Brazilian standard.

All compression specimens were kept in an acclimation room at 25 °C and 65% air humidity, until the mass levelled, indicating they have reached 12% equilibrium moisture content (MC). After weighing the specimens in a semi-analytic scale, their volume was measured using a digital calliper with a precision of 0.01 mm. The density at 12% MC ($\rho_{12\%}$)

was calculated with the mass and the volume of the conditioned specimens.

2.3 Anatomy

The anatomy specimens were cut in two parts, one to measure the fiber length and another to analyze the cross-section features. To produce a plain cross-section surface, the specimens were sanded with sandpaper P60 and P100 and then polished with P200, P300, P400 and P500. Pictures were taken under a stereo microscope and analyzed on the free software ImageJ (Rasband 2011). The vascular bundle diameter and the percentage of bundle area were measured on the cross section. In addition, the fiber length was measured with the same software on macerate preparations, using the Franklin (1945) method to separate the cells. Histological slides from the material cross section were also produced to show the difference in the vascular bundle anatomy, although no quantitative analysis was undertaken.

2.4 Data analysis

Some descriptive statistics were used to describe each variable assessed on both stem portions. To check the hypothesis of the normal distribution and homoscedasticity of the data, the Shapiro–Wilk and the Bartlett tests were applied, respectively. As data presented both premises, the Student *T* test was chosen for comparing all variables between treatments. The relationships between variables were tested with the Pearson correlation test. Linear models were tested to seek variables that can be used for the prediction of compression strength. The free software R (R Development Core Team 2019) was used for all graphical and statistical analysis.

3 Results and discussion

It is clear that the materials from the peripheral zone and the center have completely different properties (Tables 1 and 2). The former has higher average values for all analyzed variables, with Student *T* test *p* values ranging from 0 to 0.00010. The variance is higher in the center samples except for fiber length and vascular bundle diameter, which were the variables with the smallest difference between treatments, respectively 42% and 27% higher in the peripheral zone than in the center. Density and vascular bundle area were respectively 3.5 and 3 times higher in the peripheral zone. The most discrepant values were those for the mechanical properties; while E_{c0} in the peripheral zone was 13 times higher than in the center, f_{c0} was virtually 17 times higher. The peripheral zone has a material of higher quality and homogeneity.

Fathi and Frühwald (2014) described, from a 40-year-old individual of *Cocos nucifera*, vascular bundles features

Table 1 Descriptive statistics for the variables from the peripheral zone

Peripheral zone ($n=18$)	f_{c0} (MPa)	E_{c0} (MPa)	$\rho_{12\%}$ (g/cm^3)	Fiber length (mm)	Bundle area (%)	Bundle diam (mm)
Mean	67.88	6551.7	0.876	2.60	43.05	0.829
Median	66.40	6134.9	0.872	2.47	44.13	0.855
Minimum	51.50	3824.7	0.706	1.77	34.03	0.582
Maximum	83.00	10969.9	1.114	3.71	54.16	1.012
Std. Dev	9.16	1938.4	0.101	0.65	6.52	0.124
Coef. Var	13.49	29.59	11.56	24.94	15.14	14.95

Table 2 Descriptive statistics for the variables from the center

Center ($n=18$)	f_{c0} (MPa)	E_{c0} (MPa)	$\rho_{12\%}$ (g/cm^3)	Fiber length (mm)	Bundle area (%)	Bundle diam (mm)
Mean	4.05	494.5	0.250	1.83	14.79	0.650
Median	3.19	416.1	0.237	1.85	14.78	0.667
Minimum	2.62	219.6	0.190	1.06	8.04	0.522
Maximum	8.09	982.0	0.321	2.36	23.20	0.744
Std. Dev	1.62	226.0	0.044	0.32	5.98	0.077
Coef. Var	40.14	45.69	17.68	17.36	40.44	11.78

very similar to *E. oleracea* on both stem portions. In the peripheral zone, *C. nucifera* presented, on average, 43.5% of vascular bundle area and 0.878 mm of bundle diameter, while in the center, 12.5% of vascular bundle area and a bundle diameter of 0.761 mm. Nevertheless, the density of *C. nucifera* is more than 9% lower in the peripheral zone and 36% higher in the center in comparison to *E. oleracea*. Likewise, compression strength is 23% lower in the peripheral zone and almost four times higher in the center.

When comparing with the results reported by Sulc (*apud* Killmann and Fink 1996), *E. oleracea* is still stronger in the peripheral zone, 57 MPa on average, although *C. nucifera* is a lot stronger in the center, 19 MPa on average.

In the oil palm tree (*Elaeis guineensis*), the peripheral portion of stem is again weaker than *E. oleracea*, 25% (Bakar et al. 2008) and 56% (Anon *apud* Lim and Gan 2005), on average. In the center, the cited authors found the same value and four times the strength of *E. oleracea*.

FAO (1994) confirms the high strength of peach palm stems; however, it does not provide values for any mechanical tests. The bamboo species *Guadua angustifolia* (Maya-Echeverry et al. 2017) and *Bambusa striata* (Dubey et al. 2017), with averages of 37.9 and 40.82 MPa, respectively, are also substantially weaker than *E. oleracea* peripheral zone on compressive load.

Compared to timbers, the peripheral zone is 40% stronger than the Mexican oak *Quercus laurina* wood, although only 9% denser (Ruiz-Aquino et al. 2018) and in the range of the average strength values of Amazon timbers with similar density, such as *Goupia glabra*, 54.4 MPa (ABNT 1997), and *Euxylophora paraensis*, 69.4 MPa (IBAMA 1997). The center, on the other hand, is a lot weaker than that of woods of the same density, such as *Paulownia tomentosa*, with an average of 22.14 MPa, (Koman et al. 2017), and *Ochroma pyramidale*, 27 MPa for a specimen of 0.265 g/cm^3 (Borrega and Gibson 2015), and 21.44 MPa, the average of two samples of 225 and 264 g/cm^3 (Silva and Kyriakides 2007).

Specific strength (the ratio between strength and density) is a way to compare materials of different densities, such as the ones described in the present study. While the center presented an average specific strength of 15.86 MN/kg, it was about five times higher, 77.6 MN/kg, in the peripheral zone.

It is believed that the difference found in the strength of both materials is due to the amount of parenchyma they have. The peripheral zone, with less parenchyma, has a mechanical behaviour closer to woods of the same density, whereas the center, with more parenchyma, is a lot weaker than any wood of similar density.

The distinct behavior of the two treatments is also believed to be related to the anatomic characteristics of the vascular bundles, where fibers (the cells specialized for the mechanical support) are found. Figure 2 displays the cross section cuttings from the peripheral zone and from the center. Not only the amount of fibers is a lot higher in the peripheral zone bundles, but the fibers also present a much thicker cell wall. In the peripheral zone, the vascular bundles reduced the amount of conductive tissue and proportionally produced more fibers; similar to what was observed on the self-sustaining phase of *Flagellaria indica* (Hesse et al. 2016). The better mechanical performance of the peripheral zone material has its origin in the optimization of the plant self-support. Palm tree stems are very often subject to bending stresses, and the zone of higher tension values, the periphery, also presents higher resistance and rigidity. A portion of distinct fiber cells, wider and with thicker cell walls from a peripheral zone bundle, can be observed in Fig. 3. No information was found in the literature about the formation of this extra layer, but there is strong evidence (Fig. 4) to believe this portion was later added by the differentiation of parenchymatous cells. This might be the explanation of a greater coefficient of variance in the bundle diameter and the fiber length in peripheral zone samples in relation to the center. An added tissue with a different origin could add variability, when the analysis does not consider both tissues independently.

Because of their contrasted properties, the materials from the peripheral zone and center have different applications. The peripheral zone showed high density and strength, with values similar to some commercial Amazon woods and probably has the same end uses. However, there is a dimension limitation: the average peripheral zone thickness ranges from 30 to 40 mm. Technology can be used to overcome this restriction, such as the gluing techniques used to produce glued laminated bamboo (Sharma et al. 2015). Glued slats with fibers parallel to each other can produce *E. oleracea* boards, which can greatly broaden the range of uses. These boards have potential to produce furniture, handcrafts, doors, windows, flooring, cutting boards, etc., although it is necessary to proceed with specific tests. Produced prototypes have shown a very interesting visual aspect (Balboni, unpublished), they have a fibrous texture similar to that found on glued bamboo, but with darker colors (Fig. 5). It would also be feasible to produce *scrimber* products, such as the one described by Sharma et al. (2015) for bamboo.

The center, on the other hand, is light and weak, suggesting uses without mechanical stresses, such as thermal insulation. Nevertheless, Cardoso-Junior et al. (2017) have demonstrated that this material has a high solar heat absorption, even higher than darker and denser materials, such as *Manilkara* sp. wood. The reason, as can be observed in Fig. 6, is the silica found in the parenchymatous cells surrounding the vascular bundles, a cell type called *stegmata*, found adjacent to fibers in many monocotyledons (Schmitt et al. 1995). Moreover, the center is of very low durability, the stems were taken to dry in a conditioning room with an equilibrium moisture content

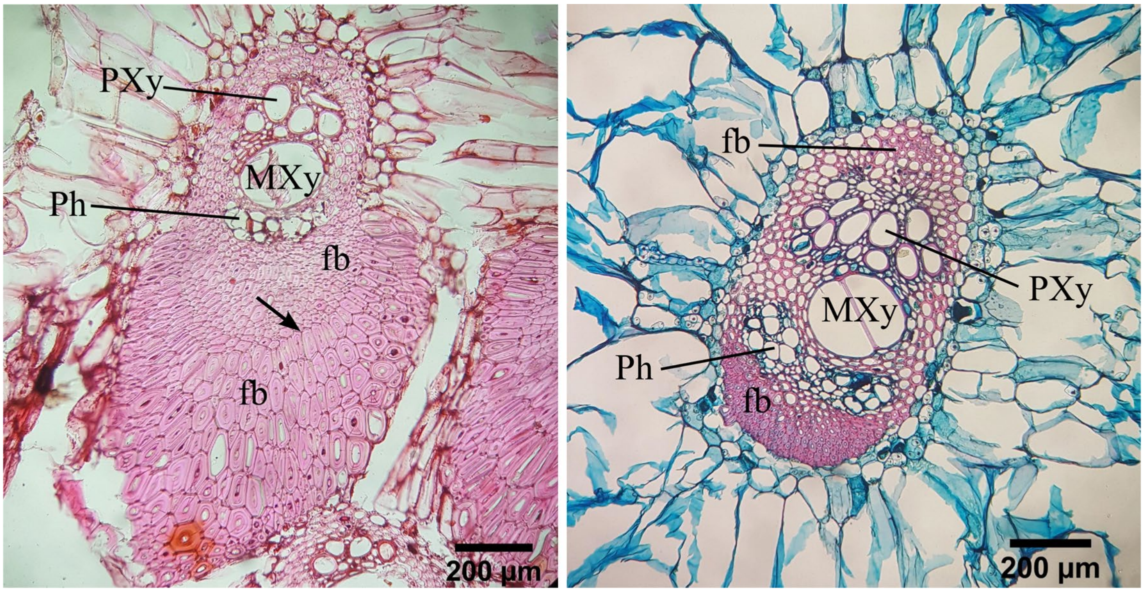

Fig. 3 Cross section cuts of vascular bundles from the peripheral zone (left) and from the center (right). *PXy* protoxylem, *MXy* metaxylem, *Ph* phloem, *fb* fibers. The arrow indicates the delimitation of the portion of distinct fiber cells

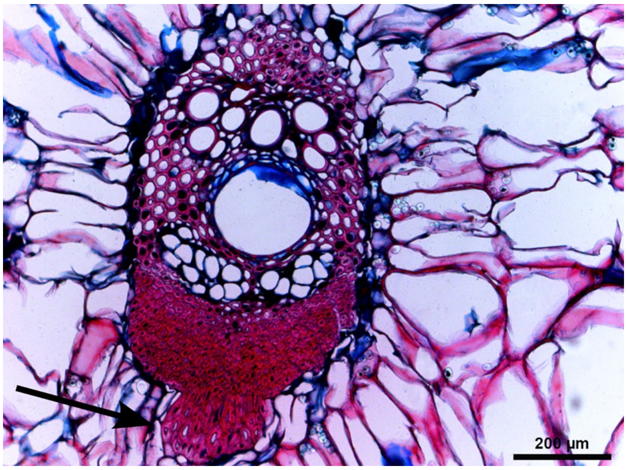

Fig. 4 Cross section cut: vascular bundle specialization with a fiber portion (arrow) believed to be differentiated from the parenchymatous cells

Fig. 5 Prototype of glued laminated *Euterpe oleracea* using the peripheral portion of the stem

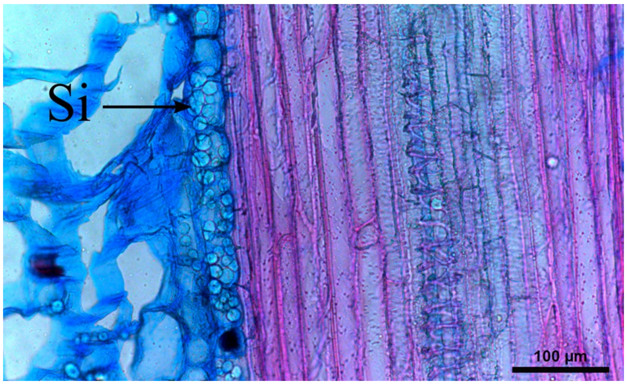

Fig. 6 Longitudinal cut: parenchymatous cells (stegmata) with silica (Si) in their lumen

of 12% straight after the harvesting and, in most of the cases, before the stems were dried, the center had already rotted because of its own moisture content. Consequently, it is recommended to use the material from the peripheral zone only.

The relationships between variables (Tables 3 and 4) reinforce the difference between materials, where only one pair of variables presented significant correlation on both treatments. Strong correlations indicate which variables can be used to build prediction models. Density, of both peripheral zone and center materials, has the highest correlation with compression strength. Amazon farmers can be instructed to use the stems with higher vascular bundle diameters, as it is a visual characteristic with high correlation to the compression strength, although lower than density.

Table 3 Correlation between variables from peripheral zone specimens

Peripheral zone ($n = 18$)

	f_{c0}	E_{c0}	$\rho_{12\%}$	Fiber length	Bundle area
E_{c0}	**0.592**				
$\rho_{12\%}$	**0.769**	0.203			
Fiber length	0.205	−0.318	0.364		
Bundle area	**0.497**	**0.577**	**0.477**	−0.076	
Bundle diam	**0.533**	0.198	**0.669**	**0.469**	0.373

Bold numbers represent significant correlations at $p < 0.05$

Table 4 Correlation between variables from center specimens

Center ($n = 18$)

	f_{c0}	E_{c0}	$\rho_{12\%}$	Fiber length	Bundle area
E_{c0}	0.453				
$\rho_{12\%}$	**0.806**	**0.612**			
Fiber length	0.12	0.017	0.19		
Bundle area	0.319	−0.058	0.352	0.195	
Bundle diam	−0.205	−0.437	−0.246	0.038	**0.577**

Bold numbers represent significant correlations at $p < 0.05$

The linear model of the material from the peripheral zone with the highest coefficient of determination (0.593) was between f_{c0} and $\rho_{12\%}$ ($f_{c0} = 6.88 + 69.66\rho_{12\%}$). The stems were collected in the wild and are represented by six individuals only, which explains the high variability. A bigger sampling will probably increase the model power to predict strength based on the density values. Even so, 60% of variation explained by one single variable is enough to consider density as an interesting non-destructive and faster method for selecting the studied material.

In Fig. 7, the data and linear model for *E. oleraceae* peripheral zone are displayed together with power models for softwoods and hardwoods (Kretschmann 2010). The model for *E. oleracea* peripheral zone is almost indistinguishable from the one for hardwoods, different from the softwoods model, which has a higher compression strength for the same density.

While softwoods have tracheids, palm trees are angiosperms and share the same load bearing cell type with hardwoods, the fibers (Parthasarathy and Klotz 1976), which can be the reason for such similarity. Another point is that softwoods, in general, have much less parenchyma than hardwoods. Morris et al. (2016) found an average of 7.63% of parenchyma on the cross section of conifers wood and 26.3% on angiosperms wood, a number that increases to 36.2% when considering wood of tropical angiosperms only. As *E. oleracea* presented 57% of parenchyma (the conductive tissue was computed in the vascular bundle area), a higher percentage than in hardwoods, another influence might stem from the fiber morphology.

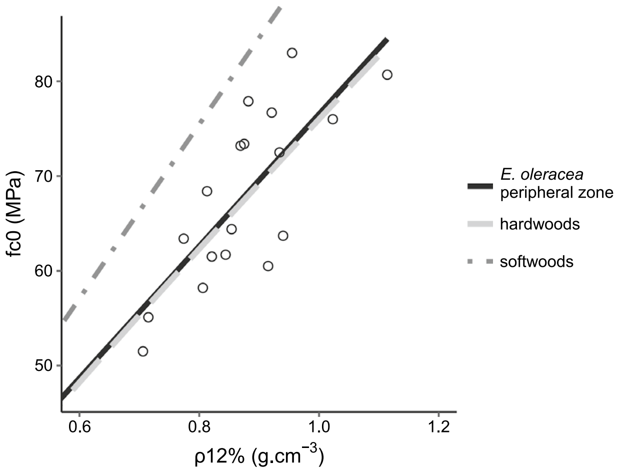

Fig. 7 Linear model of compression strength (f_{c0}) and density at 12% MC ($\rho_{12\%}$) of peripheral zone specimens and power models for softwoods and hardwoods (from Kretschmann 2010)

The same load bearing cell type and the high amount of parenchyma area on the cross section are the probable explanations for the specific strength in *E. oleracea* peripheral zone to be much closer to hardwoods than to softwoods. Yet it is important to highlight that softwoods do not usually reach the density values found in *E. oleracea* peripheral zone.

The applications of *E. oleracea* stems presented a much higher potential than *E. guineensis*, the stem of which is not recommended for load bearing uses because of its low density and strength (Lim and Gan 2005). Moreover, Bakar et al. (2008) reported the need for research to overcome several problems of *E. guineensis* stem, such as low durability and strength, as well as high shrinkage, with frequent occurrence of collapse, and poor machinery characteristics, even when considering only the peripheral portion of the stem.

Unlike *E. guineensis*, *C. nucifera* is probably the most succeeded palm tree species in regard to the use of stem as a source of lignocellulosic material. It is vastly used in the Philippines for a wide range of products, such as furniture, structures and flooring (Killmann and Fink 1996; Bailleres et al. 2010). The biggest advantages of *C. nucifera*, when comparing to *E. oleracea*, are the larger diameters, allowing the production of wide boards, and the steadier gradient of properties on the stem cross section (Parthasarathy and Klotz 1976). However, *E. oleracea* has a peripheral zone with higher strength and density than *C. nucifera*, which can result in higher quality products when glued accordingly.

The potential shown by the peripheral zone material from *E. oleracea* stem can be used by industries located in the Amazon region, using a residue to generate income and enter the niche, today occupied by imported bamboo products.

Additionally, it can be used in favor of the açaí berry producers. If well organized, the market of *E. oleracea* stem products can work as an additional income source and stimulate the management of açaí palm trees to improve fruit productivity. Certified high added value products, such as furniture, picture frames, and handicrafts, made with these residues can also be used as a tool for improving the life quality of people from the Amazon, mainly those who depend on the açaí berry production.

To promote the use of residues from the management of *E. oleracea*, especially the peripheral zone of the stem, some evaluations are still necessary. The potential of engineered products has to be assessed through the glueability of the peripheral zone material, mainly in uses subject to mechanical stresses, such as furniture and structures. Static bending strength and stiffness, hardness, workability and primary processing yield are other fundamental subjects to be analyzed.

The durability of the material also deserves attention, especially knowing that the center portion rots easily. Although it was observed that the peripheral portion is in a very good state even when the stems are in contact with the water and the soil, experimental trials should be undertaken in order to assess the material durability accordingly.

It is of great relevance to understand the amount of residue produced and its potential with the adoption of management in new natural areas and the increase in planted areas. Caution is recommended in the promotion of the use of this material in order not to stimulate improper removal of more stems than necessary. The replacement of a continuous income, such as fruit production, by unsustainable profits with stem products, can promote an overexploitation with undesirable consequences to the people and to the environment, such as reported by Vallejo et al. (2014) in Colombia.

4 Conclusion

The materials from the *E. oleracea* stem presented distinct properties: the peripheral zone has high potential to be used as a lignocellulosic material, whereas the center does not. The peripheral zone has properties similar to some high-density timber species and with the proper techniques to overcome the dimensional limitations, it can be used in the same manner. Density can be a non-destructive method for the selection of peripheral zone material with the highest resistance.

Additional studies are suggested to assess the possibilities of products made with *Euterpe oleracea* stem peripheral zone and their quality.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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