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Methods for separating the lignocellulosic fibers from the açaí pulping waste: quality for kraft pulping

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TECHNOLOGY OF FOREST PRODUCTS

ABSTRACT

Background: Converting açaí waste fibers into kraft pulp and paper demands high amounts of preserved fibers. Manual removal preserves the fibers, but mechanical methods are faster. Therefore, this work aimed to compare three methods to extract açaí fibers from the seed's surface concerning efficiency and fiber quality for cellulose pulping.

Results: Açaí waste fibers have ≈ 34 % of cellulose and ≈ 61% of non-cellulose structural components (based on extractive free mass) and ≈ 6% of non-structural extractives and ashes (based on total mass). They occur united into bundles that dissociate into short (388 µm) fiber cells. Their pulp-paper quality indexes were aspect ratio (31.8-41.2), wall fraction (52.8 %), flexibility coefficient (47.2 %), boiler index (0.6), Runkel index (1.2), and Mulsteph index (0.8). The manual removal preserved the fibers but had the lowest efficiency (0.1 g/min). The food processor provided intermediate preservation of the fibers and efficiency (0.5 g/min). Despite the highest efficiency (3.9 g/min) of the hammer mill method, the friction with the hammers damaged the fibers and increased the levels of extractives from 4 to 8% and hemicelluloses from 34 to 40%.

Conclusion: Açaí waste fiber bundles are dissociable into short fibers and have a favorable chemistry for kraft pulping and developing cellulose products. The fiber morphology is not ideal, but not limiting, demanding adjustments in the future kraft pulping parameters. The extraction of the fiber by the food processor is recommended, which is manageable to the local communities to support an integrated bioeconomy of the açaí waste.

Keywords: Non-wood fibers, short fibers, kraft cellulose, mechanical fiber separation, pulp-paper indexes.

HIGHLIGHTS

The chemistry and morphology of açaí fibers suggest suitable pulping and papermaking
The separating method of the waste açaí fibers from the seeds affects their quality
Manual removal is the slowest method but fully preserves açaí fiber integrity
Between the faster mechanical methods, the food processor keeps the açaí fibers better.

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INTRODUCTION

Euterpe edulis Martius, *Euterpe precatoria* Martius, and *Euterpe oleracea* Martius from the *Arecaceae* family are the açaí species commonly found in the Amazonia (Lorenzi et al., 2010). In the Eastern Amazon, the açaí mainly comes from *E. oleracea*, (Vaz and Nabout, 2016), with the river estuary as the origin center (Costa et al., 2024).

In 2022, Brazil produced 1.699.588 t of açaí fruit harvested from about 233.363 ha. The highest productions came from Pará with 1.595.455 t harvested from 224.004 ha and Amazonas with 90.616 t harvested from 5.890 ha (IBGE, 2024).

The de-pulping waste accounts for about 81% of the total processed mass, with surface fibers making up approximately 3% by weight of the açaí waste (Bufalino et al., 2018). They compose a vascular tissue of a monostelic network inside the inner parenchyma that forms a densely packed layer (Schauss, 2011). These fibers can be partially detached during or after fruit processing and have been referred to as "fiber bundles" (Oliveira et al., 2019).

Some notable applications for the mesocarp fibers include cellulose nanofibrils for reinforcing chitosan-based nanocomposite films (Braga et al., 2021a), cellulose nanostructured films (Braga et al., 2021b), reinforcement in cement-based mortars (Azevedo et al., 2021), a component of sand-asphalt mixtures for paving (Silva et al., 2017), and reinforcement in coating mortars (Marvila et al., 2020).

Besides the aforementioned applications, studies with the açaí fibers could be expanded for pulping and papermaking to replace other commonly used fibers (Saeed et al., 2017; Nayak and Bhushan, 2019). Non-wood fibers, such as those from açaí wastes, offer several advantages over wood, such as simplified pulping, high-quality bleached pulp, and the development of special papers with exceptional properties (Laftah and Rahman, 2016; El-Sayed et al., 2020).

Various factors must be evaluated when selecting lignocellulosic fibrous resources for papermaking purposes, such as the chemistry and morphology of the fibers, including measured length, width, wall thickness, and lumen diameter (Pereira et al., 2021), besides the cellulose extraction method based on the desired properties of the paper (Mboowa, 2024). The ideal non-wood fibers for pulping are those with similar chemical composition to wood fibers (Li et al., 2021). The lower the lignin content, the better, since this component must be removed during pulping causing the less possible degradation of cellulose (Luan et al., 2022).

In this sense, expanding the use of açaí lignocellulosic fibers for the pulp and paper industry can help address the future fiber shortage, but requires new characterizations focusing on such applications. For instance, besides the chemical and morphological traits, it is necessary to determine morphological indexes (aspect ratio, wall fraction, flexibility coefficient, Boiler index, Runkel index, and Mulsteph index) that indicate the fiber potential.

Moreover, it will be necessary to develop efficient methods to separate large amounts of the fibers from the seeds to supply future pulping and paper industries. Such efficiency must consider practicality regarding fiber yield and time to obtain significant amounts while preserving the fiber properties that are relevant for papermaking. The hypothesis is that manual removing can preserve the fiber integrity but is unfeasible for removing great amounts of fibers faster, which mechanical methods can overcome. On the other hand, mechanical removal methods will possibly damage the fibers and adversely affect future papermaking. Despite possible damage to the fiber bundles of the wastes through mechanical removal, the fiber cells that compose the bundles are only isolated by chemicals and are expected to be kept the same regardless of the fiber-seed separation method. Therefore, this work aimed to compare three methods to extract açaí fibers from the seed's surface concerning efficiency and fiber quality for future cellulose pulping.

MATERIAL AND METHODS

Collection and preparation of the açaí fibers

The açaí waste was collected from a commercial establishment at Belém, PA, Brazil, located 20.49 m above sea level (1°26'15.7"S 48°27'48.7"W), after the pulp (juice) extraction from the açaí fruit (*E. oleracea*). The seller acquires the açaí fruits from plantations of Embrapa cultivar namely BRS Pai d'Égua located 30.04 m above sea level (1°22'00.9"S 48°19'13.3"W), cultivated on "terra firme" (non-floodable lands). After collection, the material was washed with running water, dried in an oven at 40 ºC for 24 h, and stored in plastic bags. Washing and drying were carried out to avoid decay and to allow fiber removal.

Separating the açaí fibers from the seeds by three methods

The following methods were used to remove the surface fibers from the açaí seeds: a) Manual Removal, b) Hammer Mill Processing with an SL-33 SOLAB® mill, and c) Food Processor-assisted Removal with a plastic blade attached to a RI7632 Philips Walita® processor (650W), operating at speed 2. After processing in the hammer mill, the material (fiber + seed) was sieved using an A-200 RETSCH sieve shaker. A 4-mesh sieve was placed on top to retain whole seeds, while a 10-mesh sieve was positioned underneath to collect broken seed pieces. Below those, the base of the sieves (without openings) was placed to collect the fibers (Figure 1).

Yield and efficiency of the methods for removing açaí fibers

The difference in mass of the seeds before and after the fiber extraction and the time to remove the fibers were obtained to calculate the yield (Equation 1) and efficiency (Equation 2) of each method. The fibers of all three methods showed moisture content (based on dried mass) of about ≈ 8% after removal.

$$Y = \frac{(ISM - FSM)}{ISM} \times 100 \quad (1)$$

where: *Y* is the fiber yield (%), *ISM* is the initial seed mass (g), and *FSM* is the final seed mass (g).

$$E = \frac{FM}{T} \quad (2)$$

where: *E* is the efficiency (g/min), *FM* is the fiber mass (g), and *T* is the time to remove fibers (min).

The parameters were calculated considering three removals per treatment. The manual removal was performed by the same person.

Chemical composition of the açaí fibers

For the chemical analysis of the fibers, 100 g of each removal method was used. The fibers were crushed using a basic analytical mill (A11, IKA®), and the fractions retained between 40 and 60 *mesh* sieves were selected. Three repetitions were run for each parameter and analysis.

Total extractives based on total mass were determined following the NBR 14853 (ABNT, 2010) standard. The material was subjected to extraction with a 2:1 (w/v) toluene and ethanol solution for 8 h, followed by extraction with ethanol for 6 h, and 1 L of boiling distilled water. Moisture content analysis was carried out at the same time to allow the calculation of the extractive content based on the fiber's dry mass.

The ash content based on total mass was determined according to the TAPPI T 413 om-17 (TAPPI, 2017) standard. Moisture content analysis was carried out at the same time to allow the calculation of the ash content based on the fiber's dry mass. The porcelain crucibles containing 2 g of material each were placed in a Muffle Furnace (n2020, Magnu's®) at 105°C for 10 min. Then, the temperature was increased to 325°C to burn the sample and kept for 1 h. Next, the temperature was raised to 525°C for 1 h, and finally to 900°C for 4 h.

The Browning (1963) method was used for holocellulose determination. 3 mL of 20% sodium chlorite solution and 2 mL of 20% acetic acid were added to 2 g of extractive-free material, previously dried in an oven (103±2 °C for 24 h). The material was heated at 70°C in a water bath (Luca-157/36, Lucadema®). After each 45 min, an additional 3 mL of 20% sodium chlorite solution and 2 mL of 20% acetic acid were added. This operation was repeated four times after the initial application. Subsequently, the solvent was filtered and the material was washed with three portions of 10 mL of methanol and 1 L of distilled water.

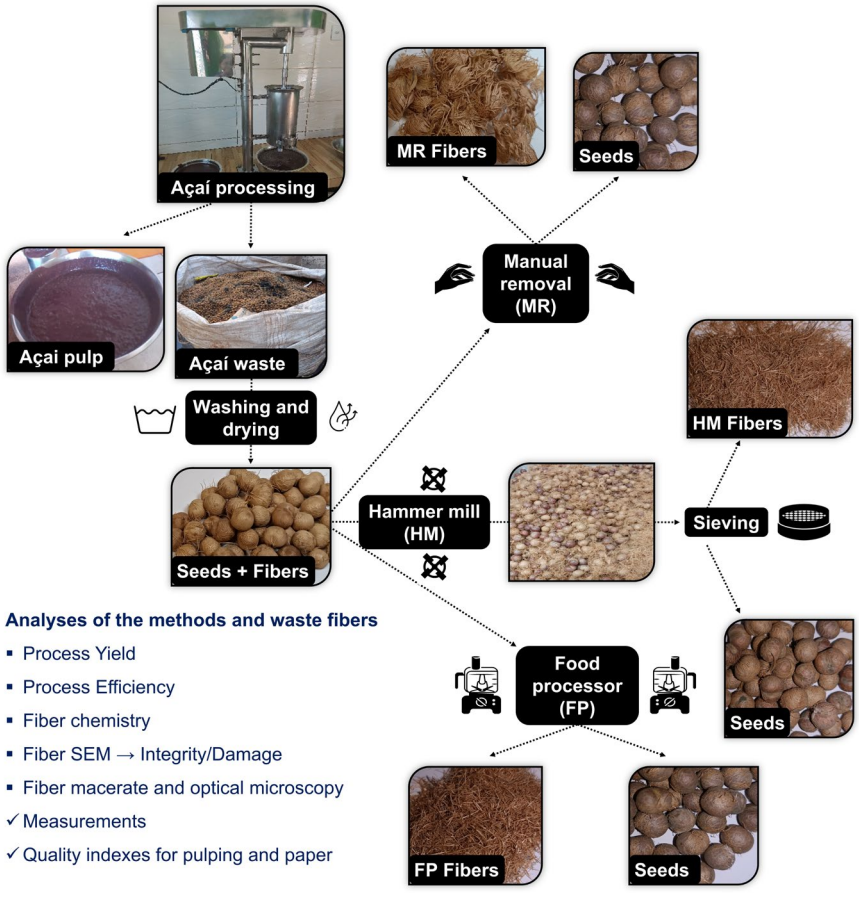

Figure 1: Açaí waste preparation and fiber removal by the three methods: MR: manual removal; HM: hammer mill; and FP: food processor.

The cellulose content was determined following the procedure described by Kennedy, Phillips, and Williams (1987) using 1 g per sample of previously dried holocellulose immersed in 15 mL of 24% KOH and shaken with a reciprocal shaking water bath (Luca-157/36, Lucadema®) at room temperature for 15 h. The cellulose content was determined based on holocellulose content, and then transformed to extractive-free based mass. The content of hemicelluloses was calculated by subtracting the cellulose content from the holocellulose content.

The analysis of insoluble lignin content was conducted following the procedures of the standard T222 om-15 (TAPPI, 2015). Extractive-free samples weighing equivalent to 0.300g were placed into test tubes. Subsequently, 3 mL of 72% sulfuric acid (cooled to 10 – 15 °C) was added to each sample and kept in a water bath at 30 ± 0.2 °C for 1 h. Afterward, the material was transferred to penicillin glasses with 84 mL of distilled water, sealed, and pressure-cooked for 1 h. The soluble lignin content was determined following the procedures specified in standard UM 250 (TAPPI, 2000). The analyses were performed in triplicate.

Scanning electron microscopy (SEM) of the açaí fiber bundles

The samples were placed on double-sided carbon adhesive tapes, previously fixed on aluminum sample holders (stubs), and covered with a thin layer of gold (20–30 nm). Two stubs per removing treatment were prepared. SEM micrographs were obtained using the scanning electron microscope Tescan Mira3 (TESCAN®), with a tungsten filament operating at 10 kV, a working distance of 10 mm, and a high vacuum of 10^{-3} Pa.

Morphology of the macerated açaí fibers

Macerated material analysis followed Franklin (1945) for fiber dimension measurements and was performed in triplicate. The samples were placed in small 20 mL glass containers filled with Franklin's solution macerating solution containing glacial acetic acid and hydrogen peroxide in a 1:1 (v/v) ratio.

Subsequently, the containers were sealed, and placed in an oven at 60 °C for 24 h until complete maceration of the samples. After this process, the dissociated material was washed with distilled water and stained with aqueous Safranin. For the measurement of dissociated cellular elements, temporary slides were prepared, and the measured anatomical traits were: fiber length (µm), fiber diameter (µm), and fiber lumen diameter (µm).

For each parameter, 50 measurements were performed per trait using a Trinocular Motic optical microscope. Fiber diameter and lumen diameter were measured using a 40x objective. After obtaining the images, the Motic Images Plus 3.0 software was used for quantitative parameter measurements. These parameters were used to calculate the fiber quality coefficients.

Quality coefficients of the açaí fibers for pulp and paper

The coefficients of fiber quality were calculated following the equations in Table 1.

Table 1: Coefficients of fiber quality.

Index	Equation
Aspect ratio	L/D
Wall fraction	$(2W/D) \times 100$
Flexibility coefficient	$(d/D) \times 100$
Boiler index	$(D^2 - d^2) / (D^2 + d^2)$
Runkel index	$2W/d$
Mulsteph index	$(D^2 - d^2) / D^2$

Where: L is the fiber length (µm), D is the fiber diameter (µm), W is the fiber wall thickness, and d is the lumen diameter (µm).

Statistical Analyses

Firstly, the data was checked by the Shapiro Wilk residual normality and the Bartlett variance homogeneity tests. When the data met the requirements (p-value ≤ 0.05 for both tests), one-way analyses of variance (ANOVA) were applied, and the means were compared by the Tukey test. The following variables meet the ANOVA requirements: ashes; soluble lignin; fiber length; fiber width; lume width; aspect ratio; Boiler index; and Mulsteph index. Welch's t-test was applied for check if there was difference among the treatments for the for the remaining variables that did not meet the requirements (p-value ≥ 0.05 for both tests), and the means were compared by the Fisher's LSD (Least Significant Different) test. All analyses were performed with the RStudio software version 4.3.2 at a 5% significance.

RESULTS

Yield and efficiency of the methods for removing açaí fibers

The fiber yield showed no differences among methods (see Figure 1). Nevertheless, the efficiency of the three methods varied, with the lowest and highest values for the manual and hammer mill removals, respectively (Figure 2).

Chemical composition of the açaí fibers

The content of extractives varied between the hammer mill and the other two methods, while the levels of hemicelluloses differed among the three methods. No statistical differences occurred for the remaining chemical analyses (Table 2).

Morphology of the açaí fiber bundles - SEM

The açaí mesocarp fibers are elongated structures with amorphous impregnations on the surface (Figure

3). The majority of manually removed fibers depicted a cylindrical shape and more homogeneous diameters than the other two methods, which showed some flattened and damaged fibers (Figures 3a-3c). The closer micrographs confirm that the fibers occur as bundles and that the mechanical methods cause their partial separation, unlike the manual removal (Figures 3d-3f). The hammer mill method damaged the fibers more severely than the food processor method. The fiber surfaces have many pits filled with a globular structure, some of which were missing in all fiber removal methods (Figures 3g-3i).

Morphology of the macerate of açaí fibers - optical microscopy

Regarding the morphological parameters, the length differed among the three methods. The highest length was found for manually removed fibers, while the fibers removed by the hammer mill had the lowest length. For the other parameters (width, lumen width, and wall thickness), there were no differences among the methods (Figure 4).

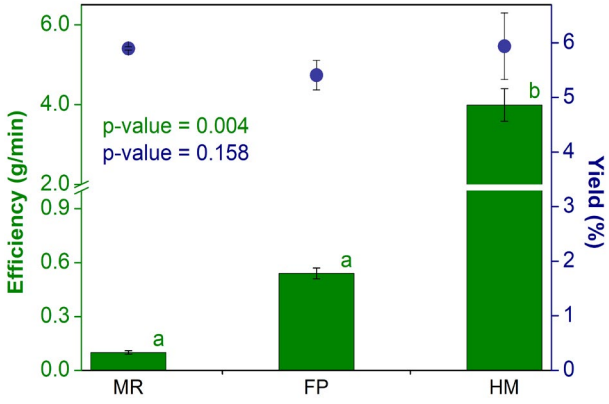

Figure 2: Yield and efficiency of the removing methods of açaí fibers at ≈ of 8% moisture content. M = manual; FP = food processor; and HM = hammer mill. Means followed by the same letter for the bars do not differ statistically by the Fisher's LSD at a 5% significance level.

The aspect ratio differed between the manual (highest) and hammer mill (lowest) methods. The aspect ratio considers the fiber length that varied according to the previous analysis; hence the results were coherent. Moreover, the Welch's t-test showed there is at least one difference among the methods, but the Fisher's LSD was unable to differentiate them. There were no differences among the extraction methods for the remaining methods (Table 3).

DISCUSSION

The similar yields showed that the three extraction methods were able to remove fibers equally close to the seeds' surface. On the other hand, the hypothesis of the slowest removal by the manual method was confirmed. The much higher efficiency of the hammer mill method probably prevented the statistic test to detect the difference between the food processor and the manual methods. However, the former removed 0.5 g of fibers per min, which is five times higher than the 0.1 g/min removed by the manual method. The longer friction time needed in the food processor and its plastic blade in comparison to robust metal hammers of the mill explains the different efficiencies between the two mechanical methods.

Unlike the food processor method, the hammer mill method was unable to provide fibers with the same chemistry of the manual method. The presence and different levels of seed traces in the fibers possibly explain the variations in chemical composition among the methods. A previous work showed that the seed showed a higher extractive content of 17% than the outer fibers of 13% (Monteiro et al., 2019), supporting the possibility of seed contamination in the hammer mill method with the highest extractive content (8%). Extractives are challenging for pulping during which they form complex substances named pitches (Singh et al., 2019) that deposit on machinery, reducing production and compromising the final product, besides increasing maintenance costs, and operational difficulties. Furthermore, a high extractive content influences pulping yield and increases solvent consumption (Vieira et al., 2021), especially the non-polar ones (Vieira et al., 2021). Therefore, the fibers removed by the hammer mill are potentially disadvantageous for the paper and pulp industry regarding the level of extractives.

Table 2: Chemical composition of the açaí fibers for the three extraction methods.

Method	Extractives^{tm}	Ashes^{tm}	Hem.^{ef}	Cellulose^{ef}	Lignin^{ef}	
					Soluble	Insoluble
	%					
MR	4.6±0.2^{a}	1.9±0.3^{a}	33.3±0.2^{a}	33.9±0.2^{a}	2.9±0.4^{a}	23.7±3.8^{a}
FP	3.9±0.1^{a}	1.6±0.1^{a}	34.3±0.3^{b}	34.0±0.3^{a}	3.2±0.2^{a}	23.0±4.8^{a}
HM	8.0±0.1^{b}	1.3±0.1^{a}	40.3±0.5^{c}	34.8±0.5^{a}	3.1±0.2^{a}	20.9±2.5^{a}
p-value	0.004	0.069	0.001	0.182	0.616	0.555

Hem. = hemicelluloses; M = manual; FP = food processor; HM = hammer mill; Component^{tm} = based on total mass; and Component^{ef} = based on extractive-free mass. Means followed by the same letter in the column do not differ statistically by the Tukey or Fisher's LSD at a 5% significance level.

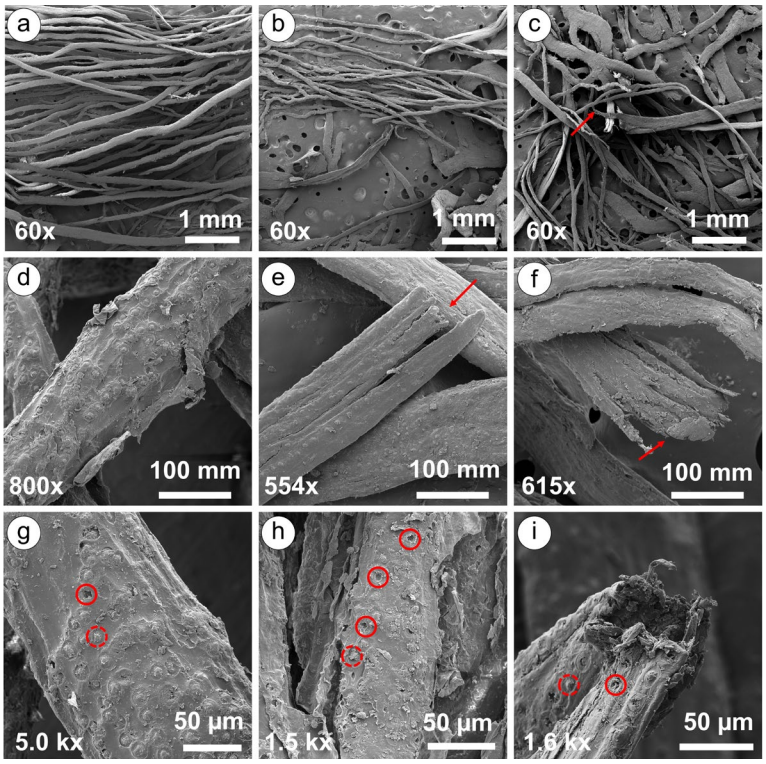

Figure 3: SEM micrographs of Açaí fibers: (a), (d), and (g) manually removed fibers (MR); (b), (e), and (h) food processor removed fibers (FP); and (c), (f), and (i) hammer mill removed fibers (HM). Dashed and full red circles respectively highlight silica-obstructed and unobstructed pit channels. Red arrows highlight fiber damage.

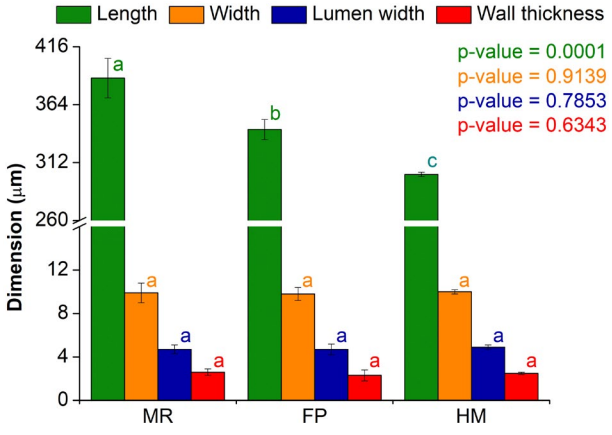

Figure 4: Morphology of the açaí fibers for the three extraction methods. M = manual; FP = food processor; and HM = hammer mill. Means followed by the same letter for each bar color do not differ statistically by the Tukey or Fisher's LSD at a 5% significance level.

Açaí fibers removed by the food processor and manually showed similar total extractive content to the 4.0% found by Silva et al. (2023). On the other hand, the extractive content of *Eucalyptus* spp., widely used in the cellulose industry, ranged from 2.3% to 3.0% (Vieira et al., 2021). Therefore, the extractive content of ≈ 4% is slightly higher, but probably no limiting for pulping of the açaí fibers.

Most typical woods destined for pulping exhibit ash content below 1.0%, but some agricultural wastes contain higher ash content, often silicates (Vieira et al., 2021). Ash content exceeding 1.0% can potentially influence reagent consumption and recovery, pulp yield, production costs, equipment wear, and maintenance (Pego et al., 2019). The açaí fiber ash content in this study was similar to the 1.4% reported by Santos et al. (2023) for the same fiber. Many silicon-rich structures were found on the surface of açaí fibers explaining their ash content, but a previous work showed they were mostly removed by alkali pretreatments (Oliveira et al., 2019).

The methods showed similar cellulose contents, but the hammer mill method depicted the highest hemicellulose content of 40.3%, exhibiting a substantial difference when compared to the manual removal (33.3%) and the food processor (34.3%). The higher polysaccharide level of the inner seeds (76%) concerning the outer fibers (45%) showed in the literature (Lima et al., 2021) once again support the possibility of seed contamination when the hammer mill was used, increasing the fibers' hemicellulose content.

Higher levels of hemicelluloses can hinder cellulose accessibility during pulping, given that it is located on the outer surface and interfibrillar space of cellulose fibers (Cebreiros et al., 2020). Therefore, the remarkably higher content in the fibers removed by the hammer mill is a potential drawback for future chemical pulping. Most hemicelluloses in açaí fibers are xyloses (Lima et al., 2021), hence similar to *Eucalyptus* spp., the main source of kraft pulping in Brazil.

Table 3: Pulp and paper quality coefficients of the açaí fibers for the three extraction methods.

Method	Aspect ratio	Wall fraction (%)	Flexibility coefficient (%)	Runkel index	Boiler index	Mulsteph index
MR	41.2±4.5[b]	53.6±0.8[a]	46.4±0.8[a]	1.2±0.0[a]	0.6±0.0[a]	0.8±0.0[a]
FP	37.1±3.4[ab]	52.8±2.7[a]	47.2±2.7[a]	1.2±0.1[a]	0.6±0.0[a]	0.8±0.0[a]
HM	31.8±0.4[a]	52.1±0.3[a]	47.9± 0.3[a]	1.1±0.0[a]	0.6±0.0[a]	0.8±0.0[a]
p-value	0.034	0.160	0.160	0.042	0.604	0.674

M = manual; FP = food processor; and HM = hammer mill. Means followed by the same letter in the column do not differ statistically by the Tukey or Fisher's LSD at a 5% significance level.

The lignin levels did not differ among the treatments. Low contents of lignin are beneficial since kraft pulping is based on efficient depolymerization and solubilization of lignin, while preserving cellulose the most (Henriksson et al., 2024). The insoluble lignin of açaí fibers in this study was similar to the 24.8% reported by Santos et al. (2023) for the same fiber. The total lignin content (insoluble + soluble) was 29.4% for *Eucalyptus pellita*, slightly higher than the values found herein for açaí fibers (Utami et al., 2023). Certain non-wood fibers exhibit elevated lignin levels, affecting the pulping process (Liu et al., 2018), but this was not observed for the açaí fibers.

The different microstructure of the fibers showed that the manual method preserved the fibers better, while the mechanical methods damaged them, but the food processor harmed them at a lower degree than the hammer mill. Besides, by manual removal, bundles were more homogeneous in cylindrical shapes and diameter, a favoring trait for solvent impregnation in pulping (Cáceres et al., 2015). On the other hand, the mechanical methods flattened the fibers with the hammers of the mill and the blades of the food processor. Fiber integrity is desirable for paper-high quality and strength (Retulainen and Keränen, 2017).

The globular structures in the pores of the fiber surface are composed of silica, an unwanted mineral for the production of paper, but removable by mild alkalinization (Oliveira et al., 2019). Therefore, probably removable by pressurized kraft pulping.

The macerates used to measure the morphological traits isolate the fibers from the original bundles and only entire cell fibers are measured; hence, the occasional damages observed in the bundles do not apply to this analysis. For this reason, the highest length found for the manual method is not supported by the same explanation and was not hypothesized. The occasional heterogeneity of the waste possibly caused this difference. Moreover, the manual removal achieves the fibers more closely attached to the seeds, unlike the other methods, possibly explaining the differences among the fiber average lengths.

Açaí waste fibers showed lengths below 2 mm; hence, are classified as short (Delzendehrooy et al., 2020). Short fibers often provide homogeneous and well-mixed pulps for manufacturing papers with smooth surface, high opacity, improved printing quality, and high flexibility. (Istikowati, 2023). The cell wall thickness affects the wettability and solvent penetration during kraft pulping, as well as the paper final quality (Rebola et al., 2020). Açaí fibers had cell wall thickness of ≈ 2.8 µm, which is similar to ≈ 3.0 µm found for two species of *Eucalyptus* from a 31-year-old plantation (Amorim et al., 2021). However, it was lower than the ≈ 5 µm found for *Arundo donax* cane (Garcez et al., 2022). Thinner walls lead to denser papers with high resistance to breakage and tension (Rebola et al., 2020).

Fiber and lumen widths are also relevant morphological properties that influence various paper properties, including slenderness, flexibility, and rigidity, in addition to affecting paper quality indices (Pego et al., 2019). The lumen width of açaí mesocarp fibers is smaller than 19.2 µm found for *Eucalyptus* wood commercial pulp (Silva et al., 2020).

The differences in fiber length resulted in different aspect ratios among the treatments, the only quality index that varied. Increases in aspect ratio improve the interlacing fiber of the paper (Chen et al., 2022a). Moreover, the larger the aspect ratio of the cellulose fibers, the larger the fractocohesive length, raising the flaw tolerance of the paper (Chen et al., 2022b). The açaí mesocarp fibers have a lower aspect ratio than those from commercial pulps of *Eucalyptus* (140.4) and *Pinus* (113.1) woods (Andrade et al., 2021), because they are shorter.

High wall fraction is related to more rigid fibers that are more resistant to collapse, resulting in paper with low fiber bonding (Silva et al., 2022). The value of approximately 54%, classify the fiber above the level (40%) recommended for proper cellulose quality (Foelkel and Barrichelo, 1975). Such fibers are categorized as having moderate stiffness, with low flexibility, challenging their interaction with other fibers, and decreasing paper strength. The cell wall fraction of açaí fibers was above the 34-42% range found for 36-month-old eucalyptus wood (Souza et al., 2021). Nevertheless, it was much lower than the 82% reported to non-wood culm fibers from *A. donax* cane (Garcez et al., 2022).

Higher flexibility coefficient characterizes more flexible fibers, which favor inter-bonding, thus enhancing paper strength. Higher values result in increased rupture resistance and decrease tensile strength (Pego et al., 2019). The flexibility coefficient of açaí mesocarp fibers is approximately 48%, which is lower than those of the conventional species of the paper and pulp industry, like 7-years-old *Eucalyptus* (52.7%) woods (Talgatti et al., 2020).

Typically, Runkel indices below 1 are excellently classified for paper, whereas indices from 1 to 2 are considered regular (Ogunleye et al., 2017). Açaí fibers had regular, but suitable for papermaking Runkel index. This parameter is associated with fiber stiffness, with higher

values indicating greater fiber rigidity, thus exhibiting a direct correlation with the final strength properties of the paper (Gonçalez et al., 2014). The Runkel index of açaí fibers surpasses 0.52-0.76 found in 36-month-old eucalyptus wood, the most used species to produce short cellulose fibers (Souza et al., 2021).

Boiler indexes below 0.5 are preferred for cellulose and paper production because they indicate a lower relative cell wall area, signifying thinner walls (Pego et al., 2019), however, all açaí fibers' indexes are above this value. Nonetheless, they were below 0.78, found for buriti palm (Pereira et al., 2003), and 0.84 reported to *Bambusa vulgaris* (Guimarães et al., 2010).

The Mulsteph index is linked to the potential for fiber collapse, as it represents the ratio of the relative cell wall area to the entire fiber (Pego et al., 2019). They were below 0.87, found for buriti palm (Pereira et al., 2003), and 0.91 found for *Bambusa vulgaris* (Guimarães et al., 2010).

When analyzing the potential of an alternative fiber for pulp and paper proposes, such indexes are highly relevant, but not determinant. Wood fibers are more likely to show ideal ranges of the indexes, unlike non-wood fibers, e.g. those from bamboo and sugar cane, which are raw materials for cellulose worldwide. The solution concerns adjusting the pulping variables (temperatures, pressures, solvents, etc) and blending them with other fibers to produce paper (Pego et al., 2019). However, the potential of açaí papers for such purpose surpassed many non-wood fibers of the literature.

This work is limited to the use of small-scale mechanical methods, but that could be converted into larger similar machines to fulfill the fiber-seed separation demands of industries in the Amazon. Nevertheless, some of the açaí waste is pulverized in the cities, farms and forest areas, where the three methods are simple and performable by any community in the Amazon to transform the açaí wastes into income for an integrated bioeconomy. At first, manual removal would be the safest in preserving the fiber integrity, but it could be unfeasible to obtain large amounts in a short time. Future works must advance for finding the best parameters for the kraft pulping of açaí waste fibers.

CONCLUSIONS

Macroscopic açaí waste fibers are cylindric bundles that, when dissociated, are converted into short and thin-walled fiber unit cells, such as the commercial ones used to produce refined cellulose products. Other favorable fiber traits for the pulp and paper industry are a high content of cellulose (≈ 34%) along with lower contents of extractives (≈ 4%) and lignin (≈ 27%). The quality indexes regarding the morphology are compatible to non-wood fibers for this purpose.

The manual removal preserved the fiber integrity and homogeneity the most, besides providing beneficial longer fibers. However, it took the longest to yield the same fiber mass as the others. The hammer mill method is the fastest but is not recommended because it significantly harms the morphology of the fiber bundles, besides increasing greatly its extractive and hemicellulose contents. The food processor balanced intermediate time efficiency with less damage to the fiber morphology than the hammer mill method, while keeping fiber chemistry. Therefore, it is the most feasible one.

This work will support the future kraft pulping and paper production with açaí waste fibers, a suitable possibility of adding value to this biomass at an industrial scale and, at the same time, involving the local community.

AUTHORSHIP CONTRIBUTION

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