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RESEARCH

The embira bark fiber: a sustainable Amazon tape

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Abstract
The embira bark fiber is routinely used in Brazil to construct simple structures because of its ease of extraction, flexibility, and considerable strength. It plays an important role, somewhat similar to duct tape, and is commonly used for temporary repairs and tying objects. The flexible bark is removed from the tree by making two cuts into it and manually pulling off the fibrous structure. Three similar but distinct embira bark fibers are characterized structurally and mechanically: *embira branca*, *embira capa bode*, and *embira chichá*. The bark separates readily into strips with thicknesses between 0.3 and 1 mm, enabling it to be twisted and bent without damage. The structure consists of aligned cellulose fibers bound by lignin and hemicellulose. Thus, it is a natural composite. The tensile strength of the three fibers varies in the range of 25 to 100 MPa, with no clear difference between them. There is structural and strength consistency among them. The mechanical strength of *embira branca* is measured for different fiber bundle diameters and is found to increase with decreasing diameter. Thermogravimetric analysis showed that degradation of the fibers initiates at 250 °C, consistent with other lignocellulosic fibers. X-ray diffraction identifies two major components: the monoclinic crystalline structure of cellulose and an amorphous phase; the crystallinity index is approximately 50%. The tensile strength shows significant variation, a characteristic of biological materials; this can be significantly improved by selective growing of embira-bearing trees.

Keywords Cellulose · Tree bark fiber · Mechanical properties · Natural lignocellulose fibers

1 Introduction

The engineering plastics developed in the last century exhibit excellent formability and reasonable mechanical properties. As a result, they are used in numerous applications. On the other hand, the careless utilization of polymeric materials generates an increase in pollution, such as microplastics, resulting in a negative environmental impact. In the face of this challenge, many researchers are developing environmentally friendly and sustainable materials as alternatives to synthetic ones. These natural fibers are increasingly used as insulation, reinforcement, and fillers for composites.

After World War II, glass fiber-reinforced polymeric resins were extensively used for the construction of ship hulls. Furthermore, these polymeric composites were utilized in the aerospace, energy, and automotive industries. Examples of polymeric fibers that are widely used in ropes, fabrics, or as components of rigid composites are polyester, polypropylene, nylon, Dyneema, polyester, sisal, and cotton. Of these, the latter two are naturally produced. In the past decades, a new class of environmentally friendly polymeric composite materials has gained attention with the use of natural lignocellulosic fiber reinforcement. These new composites have already been widely used in non-structural automotive parts [1, 2] and as reinforcement for cement and concrete [3, 4]; they exhibit promising performance for personal ballistic protection [5, 6]. Moreover, environmentally friendly composites are also investigated for use in biodegradable resins combined with lignocellulosic natural fibers [7, 8].

A large number of natural fibers have been studied and characterized, such as sisal [9, 10] and jute [11, 12], which

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are widely known and used. The elm (*Ulmus* sp.) bark fibers in Northern Europe and America have been used for ropes and clothes (Pasztory et al. [13]).

In Brazil, due to its abundant flora, numerous studies related to fibers have been conducted. In this scenario, the mechanical properties and structure of the seven-islands-sedge, originally from the southeast of Brazil were studied [14, 15] as well as babassu and carnauba fibers, from the Brazilian northeast [16, 17]. Many fibers from Amazonia such as ubim [18], açai [19], titica vine [20], and guaraman [21] have been explored. This fiber exhibits an outstanding tensile strength of approximately 600 MPa.

However, a widely used Amazonian bark-originated fiber, the embira, has not been yet studied. The embira has its name originating from the Guarani language, *mbira*, which means mooring. Several families of trees provide bark fibers. The embira fibers are commonly used by the Indigenous tribes and local communities for the manufacture of straw houses, arches, belts, and mooring ropes. The fibers are extracted from the stalk manually.

These trees grow in the Amazon Forest and belong to several families. The *sine qua non* requirement is that they have fibers along the longitudinal axis of the trunk and that they are from the inner part of the tree bark. The tree bark has two principal layers: the outer bark and the inner bark. There is a layer containing live cells, the cambium, sandwiched between the phloem and the sapwood layer. The phloem carries sugars from the leaves, while the sapwood layer (xylem) transports minerals and water to the top. The hardwood layer of the tree contains only dead cells, whose framework, consisting of cellulose walls, provides a rigid structure to it. The tensile strength of wood varies according to species, between 40 and 100 MPa.

The present research aims to investigate flexible fibers commonly known as embira extracted from tree bark for future applications as an engineering material. Fibers extracted from three trees were used, with common names of *embira branca* (*Family*: *Thymoliaceae*; *Daphnosis brasiliensis*), *embira capa bode* (*Family*: *Caesalpiaceae; Bauhinia acreana Harms*), and *embira chichá* (*Family: Malvaceae*; *Sterculia curiosa*).

We briefly review the principal findings of work on Amazonian lignocellulose fibers, also known by the acronym LCFs. Ubim fibers have a density of 0.955 g/cm^3 for smaller diameters (~0.5 mm) to 0.44 for larger diameters (0.6 mm). The mechanical strength was not determined [18].

A much more important product, the byproduct of the açai production, has been more systematically evaluated for possible reinforcement in cement. The production of this waste from the collection of açai is immense: 1 million tons per year. The fiber strength, although being modest (average of 17.8 MPa), can be an effective reinforcement at up to 3% if the fibers are properly treated with NaOH [19]. The density of the fibers is 1.37, and their average diameter is 0.12 mm.

The titica vine fibers have a much lower density, 0.5 to 0.6 g/cm^3, and a strength that is also modest: 26 MPa. The crystallinity index was found to be equal to 78% [20]. The guruman fibers, on the other hand, have a strength reported by Reis et al. [21] of 614 MPa and one of the lowest densities (0.5 to 0.64 g/cm^3) of all the fibers. Their diameter, ~16 µm, is also one of the lowest. Thus, this is one of the most promising LCFs. Other ultra-strong fibers are jute (597 MPa), ramie (685 MPa), hemp (539 MPa), sisal (478 MPa), and coir (135 MPa).

Although these lignocellulose fibers are used by Amazon inhabitants to make furniture, baskets, brooms, and in construction as ties between wooden beams, there is no application, to this day, where they are used as reinforcements in polymeric components. This is explained by the inexistence on polymers as natural resources in the Amazon.

There is a considerable current effort toward incorporating lignocellulose fibers into polymer-based composites. This work is reviewed by Kariman et al. [22] and Monteiro et al. [23], and we highlight a few prominent aspects. An important property of these natural fibers is sustainability, which is playing an increasingly important role in the industry. The replacement of synthetic by natural fibers can mitigate some deleterious environmental effects. It is recognized that natural fibers do not have the same strength as synthetic ones, such as Kevlar (aramid), Spectra, and Dyneema. However, they have a lower density, and their elastic modulus is comparable to those of synthetic fibers. Naik et al. [24] review their automotive applications. The Mercedes Benz A-class cars have a considerable number of natural fiber components, such as jute in the door panels, flax for engine and gearbox covers, and abaca, hemp, sisal, and wool in other places. The Porsche Cayman GT4 Club is the world's first car to use hemp and flax-reinforced composites in the exterior body. Another material combination in which natural fibers/polymer plies are combined with metallic sheets produces technologically important laminate composite using banana leaves [25]. They reach tensile strengths exceeding 120 MPa. The chemical treatment of the natural fibers is an important aspect in many applications. Parida et al. [26] report significant improvement of adhesion of fibers to the matrix using alkali treatment.

The majority of the natural fibers are used as reinforcement in composites. Since the major characteristic of the embira is its flexibility and ease of use and of being subjected to knots, this fiber has not received the same attention. The work presented here remedies this situation. It is hoped that this study will stimulate further research into flexible lignocellulosic bark-originated fibers that are indeed splendid examples of sustainable materials.

2 Materials and methods

2.1 Materials

The extraction method of the fibers was similar to the process described in the literature for natural lignocellulosic fibers (NLFs) [27–29]. One set of fibers (*embira branca*) was obtained from the Javary River in the State of Amazon; two sets came from the state of Acre, on the Moa River (*embira chichá* and *embira capa bode*). The outer bark layer is first separated from the inner bark; the latter forms the embira fibers which are used in the present investigation. Strips of the three embiras are shown in Fig. 1. The *embira capa bode* has a darker coloration and presents a more open weave. Otherwise, they are similar.

The more detailed portion of this work was conducted on *embira branca*. The ability to make knots is an essential feature of the three embira structures that we studied. This enables the embira to be effective in joining wood beams, e.g., for the construction of structures. The first step consisted of immersing the rigid bark in water to soften it and ease the separation of fibers (actually, fiber bundles). The separation was done manually without the need to use a cutting instrument. They were washed with DI water and placed in an oven at 70 °C for 24 h to remove moisture and dry.

2.2 Optical microscopy

After the *embira branca* bark fiber extraction and drying process, 100 samples were randomly selected. Optical microscopy (Zeiss axio) was employed to measure the fiber diameter through a magnification of × 5. The cross-section was approximated circular, and the measurement process involved the selection of five regions along the length of the fiber conducted by turning the fiber to 0 and 90°. On each position, three measurements were taken, and an average was acquired. After this procedure, a mean value for the diameter was calculated.

Due to the wide diameter variation, a distribution frequency was implemented adopting six diameter intervals, from 0.375 to 1.8 mm. The weight of the embira was measured using an electronic precision scale (0.0001 g), model HM-202. This procedure enabled the evaluation of the geometric linear density.

For the *capa bode* and *cichá embiras*, wider strips were tested. The lateral and thickness dimensions provided an area, from which an equivalent diameter was calculated.

2.3 Tensile testing

The ultimate tensile strength (UTS) of six different diameter intervals was determined through tensile tests carried out at room temperature (~ 25 °C). Mean UTS values were obtained for each interval, which were associated directly with the cross-section. Two sets of tests were conducted; the more detailed tests were the ones on *embira branca* via the standard ASTM D2101-95 [30]. To protect the ends of the fibers from slipping between the gripps of the equipment and crushing, adhesive tape was used. Additionally, paper frames measuring 10 × 10 cm were employed to safeguard the fibers before testing. The good adhesion of the fibers to the equipment's gripps prevented any fiber slippage during testing and premature rupture. An Instron universal machine, Model 3367 (with a cell load of 500 N) was used to run the tests with a crosshead velocity and gauge length of 0.2 mm/min and 20 mm, respectively. This provided a strain rate of 1.6×10^{-4} s^{-1}.

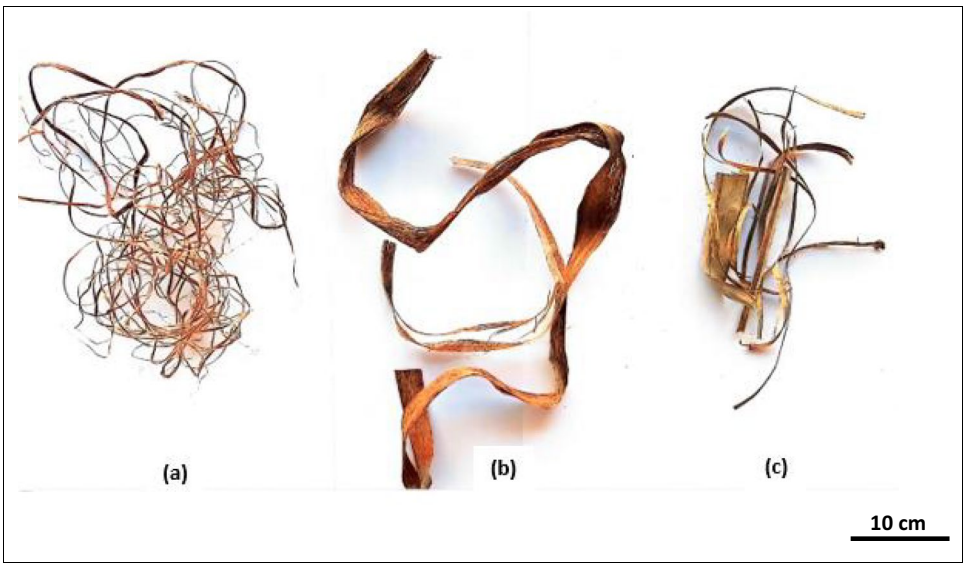

Fig. 1 Representative specimens of the three embiras studied: **a** *branca*, **b** *capa bode*, and **c** *chichá*

The second set of tests was conducted on the other two embiras (*capa bode* and *chichá*). Special grips with a self-tightening capability were used, and wider strips were tested. The strain rate was slightly larger, at $9 \times 10^{-4}\ s^{-1}$. An EMIC universal testing was used for these tests.

2.4 Weibull analysis

The UTS values attained were statistically interpreted using the Weibull analysis, based on the Weibull cumulative failure probability (F(x)), given by:

$$F(x) = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right] \quad (1)$$

where σ_0 is a normalizing parameter. The parameter m (commonly referred to as Weibull modulus) indicates the level of dispersion in the data being analyzed. It measures the degree of narrowness in the distribution [31].

2.5 Characterization

Microscopic analysis was used to evaluate the morphology of the fibers before and after tensile testing. The samples were coated with platinum to create electrical conductivity. The morphological analysis was performed using a scanning electron microscope (SEM) model FEI Apreo FE-SEM, operating at a voltage between 5 and 15 kV.

2.6 Thermogravimetric analysis (TGA-DTG)

The thermogravimetric analysis (TGA) was performed according to ASTM E 1131 [32], through a PerkinElmer Model *Pyris* 1 TGA. The fibers were crushed and inserted into a platinum crucible. The parameters adopted were a heating rate of 10 °C/min, a gas flow of 50 mL/min, a nitrogen atmosphere, and a temperature ranging from 30 to 600 °C.

2.7 Fourier transform infrared spectroscopy (FTIR)

Fourier transform infrared spectroscopy (FTIR) was performed to analyze the chemical bonding interaction of embira. The specimen was scanned from 4000 to 400 cm^{-1} and 32 scans using a PerkinElmer model Spectrum Two.

2.8 X-ray diffraction

The X-ray scan was performed using CuK alpha radiation in Bruker D2 Phaser equipment. The analysis was conducted at a scan rate of 0.05 (2θ/s), from 5° to 75°. The crystallinity index was calculated according to the procedure described by Segal et al. [33].

2.9 Preparation of specimens

To ensure the accuracy of the experimental work (XRD, TGA, FTIR, and tensile testing), the *embira branca* fibers were placed in a furnace at 60 °C to eliminate moisture. The ambient humidity in San Diego is between 60 and 70%.

3 Results and discussion

3.1 Structural and morphological characterization

An essential characteristic of the embira is its flexibility, making tying a simple procedure. This is demonstrated by the knot illustrated in Fig. 2a. This is helped by the geometry of the strips, which have a small thickness but are wide. This is indeed a "tape" geometry. Upon being subjected to bending, the fibers separate easily (Fig. 2b). This relaxes the inter-fiber shear stresses that develop upon flexure. The thickness of the individual tapes varies between 0.3 and 1 mm.

Figures 3, 4, and 5 show the longitudinal sections of three embira bark fibers at (from top to bottom) increasing magnifications. The geometry of fibers aligned with the longitudinal tree axis is common to the three embiras. There is a great degree of similarity among the three embiras. Figure 3 shows the *embira branca*. The embiras are composed of fiber bundles of ~ 400 μm in the case of the *capa bode embira* (Fig. 4), which consist of fibers with diameters of approximately 20 to 100 μm. These bundles are in the shape of flat tapes. There are open spaces between the bundles that alternate along the embiras. In addition to the fibers, there is a mucilaginous substance binding them together. The *chichá embira* is somewhat different (Fig. 5) and contains, very clearly, arrays of cuboidal features aligned and forming fibers with ~ 15–20 μm lateral dimensions. These have the distinct appearance of cells, cellulose forming the walls. Some of them are hollow, while others have the lateral wall folding inwards; this appearance is due to the shrinking of the inside material from drying. It is known that the cambium layer of the bark has live cells. The growth of this layer generates the phloem. Thus, we conclude that the fibers extracted from this bark contain this layer.

The three embiras have a lateral porosity created by the weaving of the fiber bundles, creating hollowed-out regions (porosity). Some evidence of the cellulose-based cells can also be found in Fig. 3c. So, as the cells undergo apoptosis, they generate the fibers, which retain their lateral dimensions of ~ 20 μm. These cell-originated fibers arrange themselves into fiber bundles, which have larger dimensions, as will become clear in the next section. Also present in the three embiras are thinner fibrils, with diameters of ~ 5 μm.

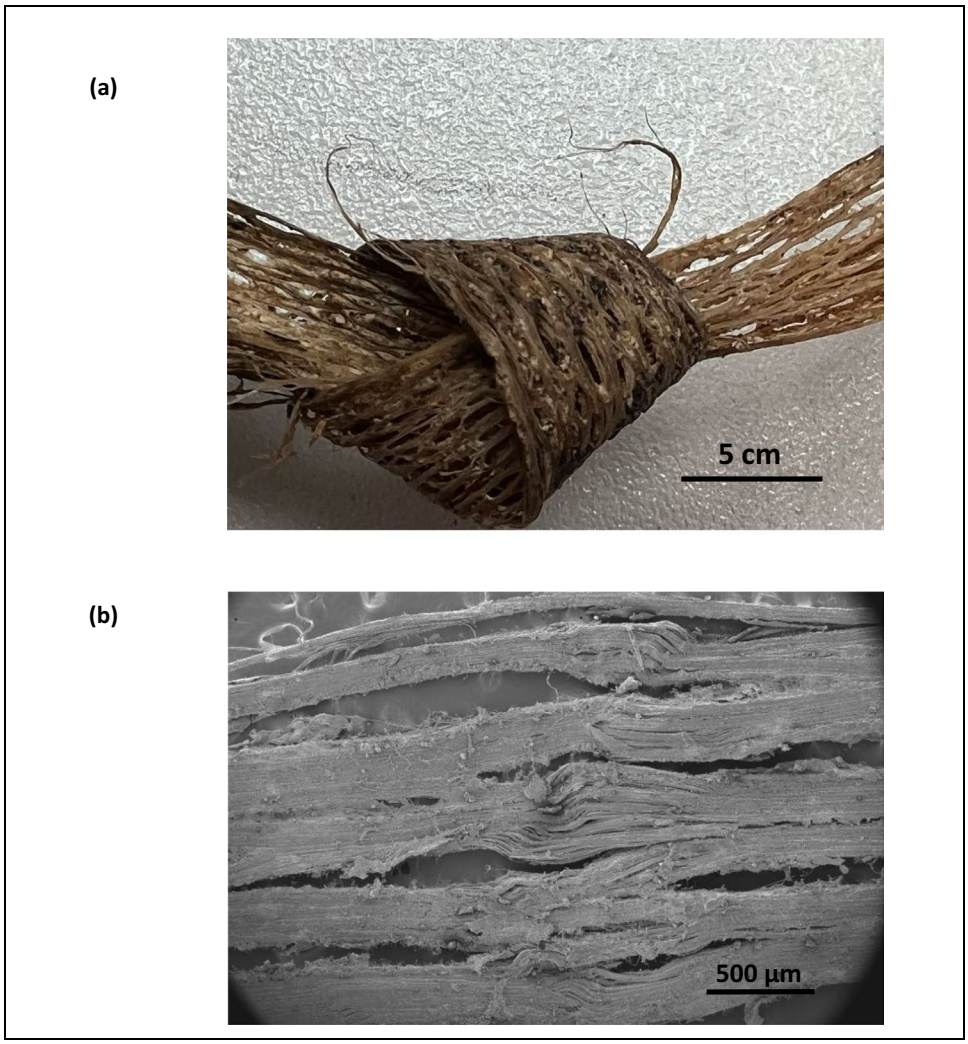

Fig. 2 The flexibility of *embira capa bode* enabled by thin tapes separating upon deformation. **a** Knot made with embira, demonstrating flexibility and ability of be deformed. The individual fiber layers, with thicknesses between 0.2 and 1 mm, readily separate, and can bend with ease. **b** Detail of tape subjected to lateral flexure, causing separation of the fibers in a microbuckling mode

3.2 Diametral variation

The properties of natural lignocellulosic fibers are directly affected by their extensive dimensional dispersion [34, 35]. Understanding the behavior of natural lignocellulosic fibers is crucial for their application in several industrial fields [36–39], including ballistic applications [5, 40, 41]. Different methods have been developed to yield better performance from these fibers, particularly in composite processing [42–44]. One important method is evaluating the diametral distribution in intervals since this parameter affects the density and mechanical properties of fibers [45–48]. Fibers in the lower diameter intervals are expected to perform better as reinforcement for the matrix [49].

Figure 6 displays the diameter variation based on six intervals. The diameter of fiber bundles ranges from 0.365 to 1.8 mm, with an average diameter of 1.078 ± 0.39 mm. Indeed, these are fiber bundles; each one is comprised of many fibers. The second interval (0.604–0.843 mm) has the highest frequency (40 fibers), while the last interval (1.560–1.8 mm) has the lowest frequency. This is likely due to the difficulty of obtaining fibers with larger diameters using the adopted methodology.

3.3 Density measurement

The same intervals were used to evaluate the behavior of the geometric linear density. Figure 7a depicts this correlation. This increase in density with decreasing diameter occurs due to the lower presence of internal defects, such as voids inside the fibers. Thicker fibers and bundles exhibit higher porosity content. This behavior directly impacts the density of natural lignocellulosic fibers [22, 50].

The density of fibers, ρ, increases as the diameter decreases, as depicted in Fig. 7b. This trend was also observed in the literature [1, 14, 51, 52]:

$$\rho = \frac{-0.84}{D} + 1.98 \tag{2}$$

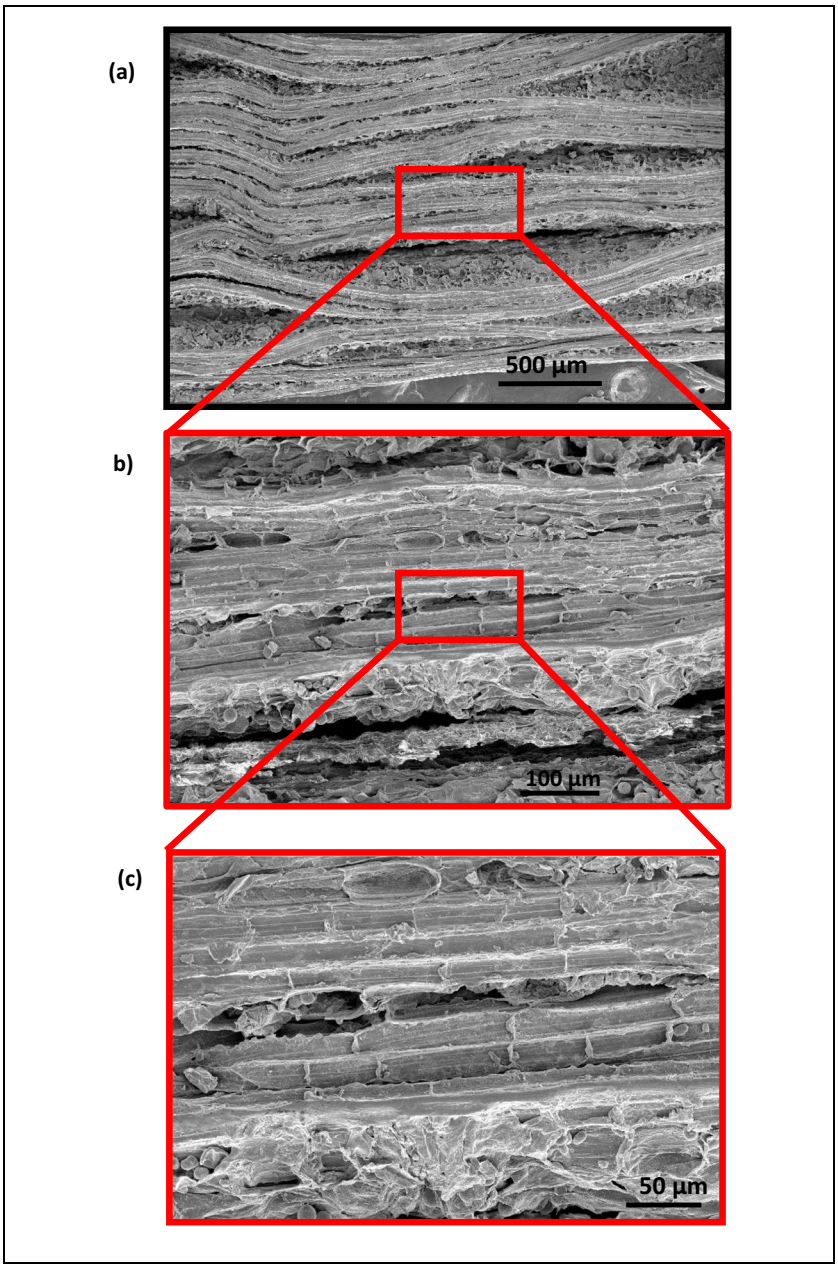

Fig. 3 *Embira branca*. **a** Overall view showing the formation of gaps through weaving of fiber bundles. **b** Closer view of a fiber bundle. **c** Close bonding between fibers

In Eq. 2, the density is expressed in g/cm^3, and the fiber bundle diameter is expressed in mm. The other parameters have, accordingly, compatible units.

3.4 Mechanical properties

3.4.1 Ultimate tensile strength

Many factors are known to affect the mechanical performance of these biological materials [53–55]: premature failure of the fibrils and fibers [56], quality of the soil, age, degradation, method by which the fibers were extracted from the plant, cellulose percentage, crystallinity index, and microfibrillar angle (MFA). Figure 8 shows the effect of fiber diameter on the ultimate tensile strength of *embira branca*. The other two embiras are also included but were tested less comprehensively. Nevertheless, the UTS of the three embiras is consistent: it varies from 36 to 106 MPa. The literature reports [57–60] that fibers with high cellulose content and low microfibrillar angle tend to exhibit better mechanical properties. The current UTS values are consistent with the tensile strength of wood, which varies in the same range. An important factor is that the number of flaws inside the fiber bundles decreases with decreasing diameter, at a constant concentration of them. This is the essence of the size dependence of strength of brittle materials. This

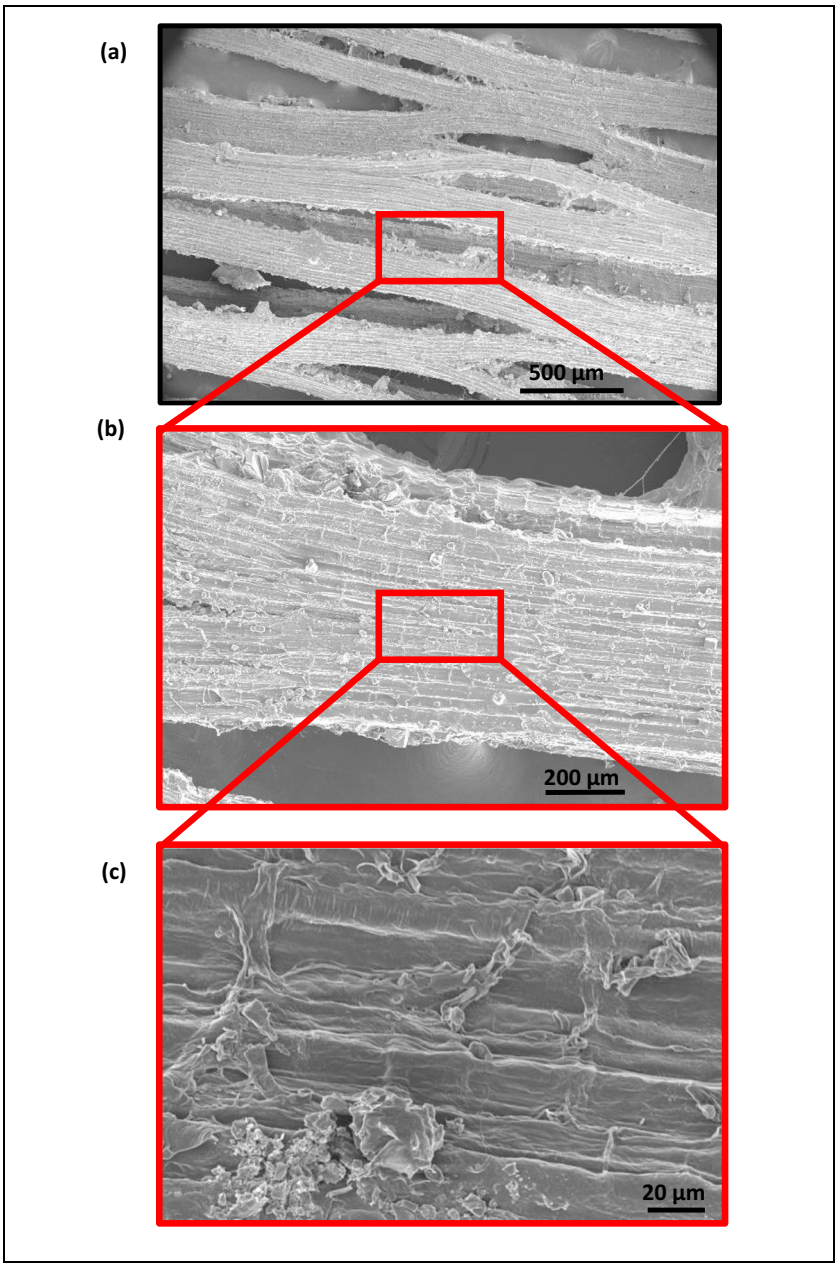

Fig. 4 *Embira capa bode*. **a** Overall view shows the formation of gaps through weaving of fibers. **b** Closer view of a fiber bundle. **c** Close bonding between fibers

increase is related to a greater degree of microfibrils inside the fiber structure [22, 61]. Furthermore, thicker fibers have a higher percentage of lignin than cellulose, resulting in a lower UTS. The experiments on the *embira branca* were repeated with 15 specimens of different diameters in order to ascertain whether the UTS values are reproducible; they are shown in Figure S1 and demonstrate the repeatability of our results.

Variations of the microstructural chemical composition, such as lignin, hemicellulose, and cellulose content in the root, stem, bark, or leaves, are known to affect the mechanical response of natural fibers [62, 63]. Figure 8b shows the Weibull-obtained values strength for the combined fibers, without differentiating their origin. This plot provides a measure of the range of UTS values as well as their variability, which is quite large ($m = 2.43$). This value would decrease significantly if the analysis were conducted for one size range of one single embira.

It is found that the UTS varies approximately with the inverse of the diameter, D. For UTS expressed in MPa and mm diameter units, it can be represented by the empirical relationship:

$$UTS = \frac{49.3}{D} + 4.33 \tag{3}$$

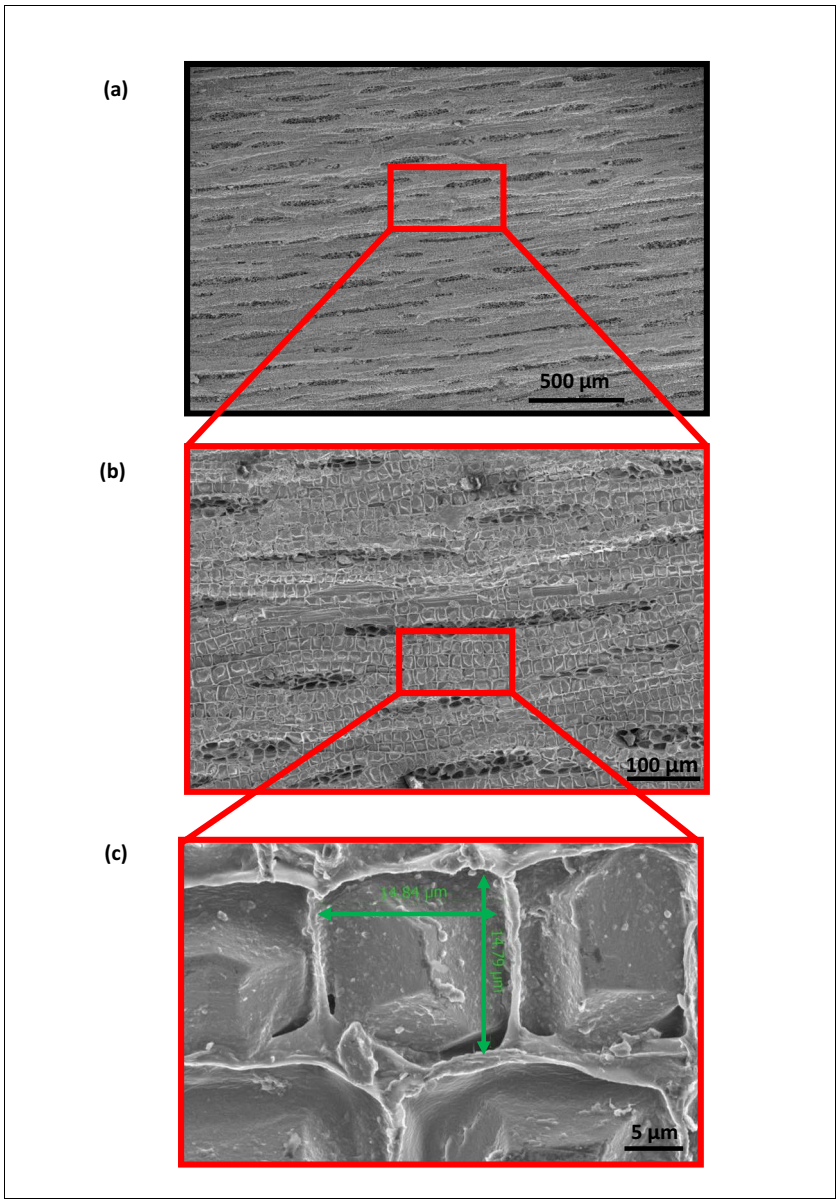

Fig. 5 *Embira chichá*. **a** Overall view shows the formation of gaps through the weaving of fibers. **b** Closer view of fibers showing that they are formed by aligned cuboidal units. **c** Cuboidal units with ~ 15–30 µm side

Table 1 compares the mechanical properties of some natural fibers. Babassu fibers, originating from Brazil, exhibit an ultimate tensile strength similar to embira. In general, synthetic fibers demonstrate remarkable strength, but their density is much higher than natural fibers. There are also natural fibers that have much higher tensile strength than embira, e.g., jute (390–770 MPa) [64] and *Cyperus platystylis* [65] (up to 770 MPa). Synthetic fibers also reach much higher strength, but the embira's ease of extraction and use, bending, and tying ability render it a valuable sustainable fiber, the "duct tape" of the Amazon [44, 66, 67]. Kompella and Lambros [68] performed a systematic investigation of the strength of cotton and vegetable fibers and the number of tests, a detailed description of a specially constructed testing machine, and Weibull analysis gives great credibility to their results. They obtained a mean strength for cellulose fibers taken from wood of 165 MPa; cotton exhibited a much larger mean strength of 495 MPa. The Weibull modulus was low for both wood-based ($m = 1.26$) and cotton-based ($m = 1.77$) cellulose. These values are consistent with the present result of $m = 2.47$. Ramie has a strength of 870 MPa ($d \sim 17$ µm), whereas coir, whose fibers have a diameter of 0.1 mm, exhibits a much lower strength (140 MPa).

The wide range of strength data shown in Table 1 and reported in the literature results from its dependence on the presence of defects and heterogeneities, degree of crystallinity, length, diameter of specimens, and a fraction of cellulose. While the lower values are easy to understand, the strength values above 1 GPa are difficult to fathom, especially in view of the constituent materials of

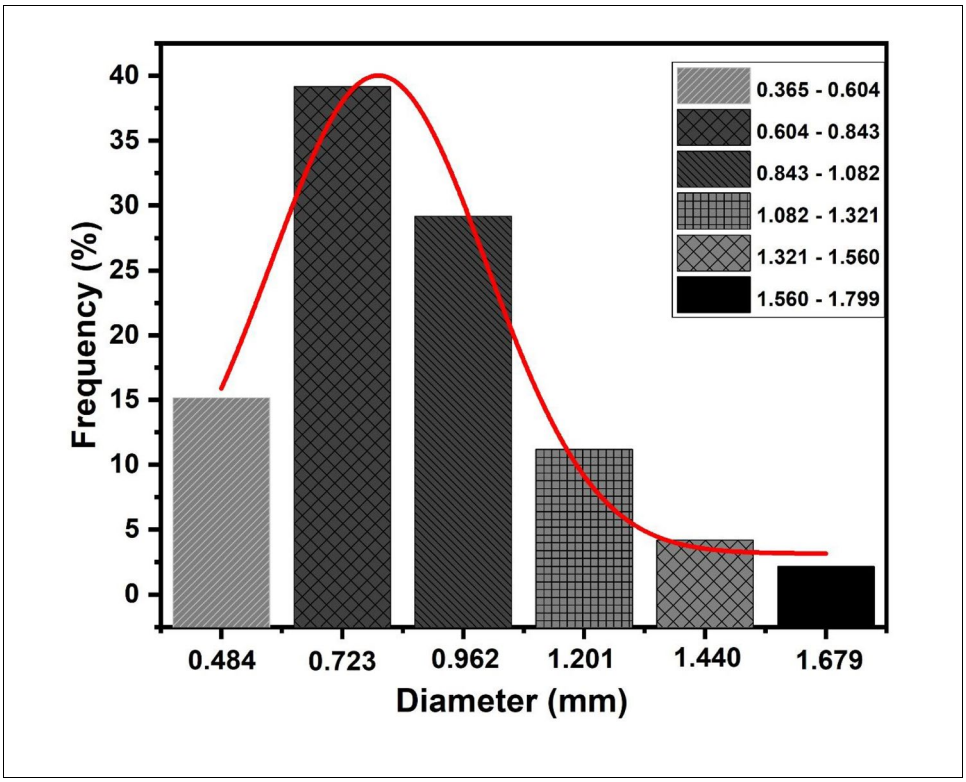

Fig. 6 Distribution frequency of *embira branca* fiber diameters; diameters for each range in insert (dimensions in mm). The highest frequency is observed for fibers in the 0.604–0.843 mm range

the fibers. Indran and Raj [69], Perimal et al. [70], and Chakravarthy et al. [71] present complete tabulations of the physical and chemical properties of natural cellulosic fibers.

The strength is dependent on specimen length, and comparison with other experimental results should take the dependence of strength on length into account. It is well known that the strength decreases with length. This should, in principle, follow a Weibull relationship. Indeed, the Weibull equation has a volume term.

3.4.2 Elastic modulus

Analysis of the elastic modulus as a function of mean diameter in each interval was also performed for the *embira branca*. The elastic modulus increases with the decrease in diameter (Fig. 9). The lower density is attributed to increasing porosity within the fibers. The elastic modulus increases from 0.5 GPa for 1.7 µm diameter fibers to 1.1 GPa for 0.5 µm. The elastic moduli of the *capa bode* and *chichá embiras* were also measured at the equivalent diameters tested and are consistent with the *embira branca*. They are 1.035 GPa and 1.67 GPa, respectively (Table 1). Kompella and Lambros [68] report a similar value for wood-based cellulose: 2 GPa.

3.5 Thermogravimetric analysis

Figure 10 and Table 2 show the results of TGA-DTG for the *embira branca* fibers. Microstructure degradation is divided into three stages. In the first step, there is a mass loss of 5.81% at 151 °C due to the moisture desorption on the surface of the fiber, which leads to dehydration. An unexpected drop in mass loss occurs between 233 and 357 °C. This range of temperature is associated with the second stage. Furthermore, at 250 °C, T_{onset} occurs. This temperature corresponds to the limit of thermal stability. After this point, the degradation of the components (cellulose, lignin, and hemicellulose) responsible for fiber formation occurs, leading to the production of volatile substances and consequent loss of mass. The maximum rate of degradation is observed at 334 °C; this is linked to the breakdown of hemicellulose [72, 73]. The second stage finishes when the mass loss reaches 60.7%. In the third stage, between 357 and 516 °C, a mass loss of 97.5% takes place. A peak temperature is observed at 457 °C, which corresponds to the final lignin degradation. After that, there is no mass loss until 600 °C; only ash content remains.

The comprehensive review by Karimah et al. [22] presents the chemical composition of ~ 40 natural fibers. The ash content of our specimens (Fig. 10) is ~ 2.5%. This compares with abaca, kenaf, *Phragmites communis*, and

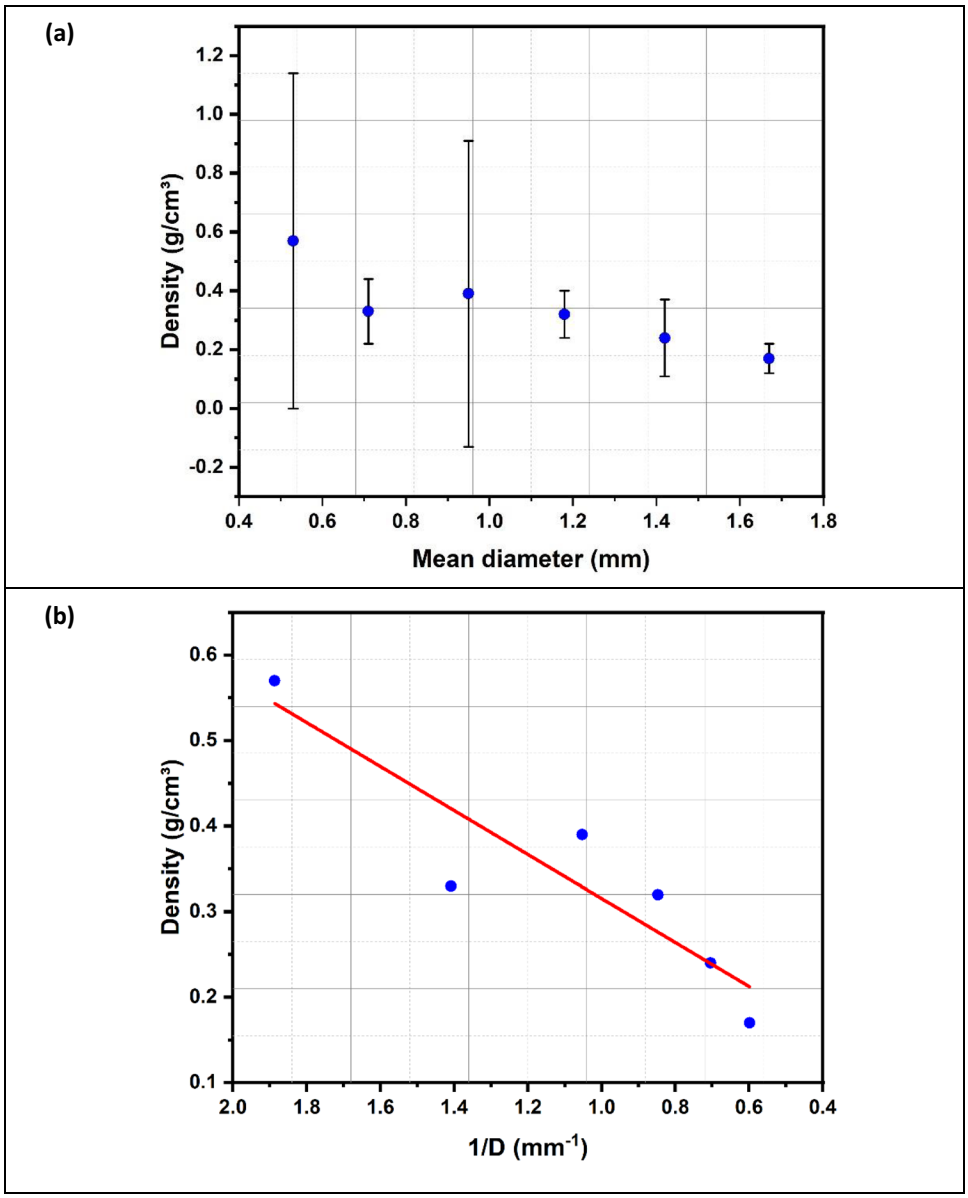

Fig. 7 **a** Variation of the density with the diameters for each interval for *embira branca*. **b** Mean densities as a function of 1/D

Citrullus lanatus. The cellulose, hemicellulose, and lignin contents of the 40 fibers vary widely, with cellulose being the largest fraction in general, followed by hemicellulose and lignin. In our case, the hemicellulose breakdown leaves 40 pct.

3.6 Fourier transform infrared analysis (FTIR)

Figure 11 shows the FTIR for the embira branca fibers. The results indicate that the embira fibers exhibit vibrational properties similar to other natural lignocellulose fibers [33, 74–77], which are composed of lignin, hemicellulose, and cellulose. In addition, Table 3 presents the functional groups, sources, and adsorption bands for the embira fibers.

The embira fiber spectrum presents a wide absorption range. The highest transmittance band is noted at 3290 cm^{-1}, corresponding to the OH stretching generated by cellulose and hemicellulose [33, 74, 78, 79]. The band at 2921 cm^{-1} belongs to the CH expansion [80]. On the other hand, the band at 1612 cm^{-1} concerns the carboxyl elongation of the carboxylic acid or ester group due to the water absorption inside the cellulose [81]. The band at 1426 cm^{-1} is attributed to CH_2 by symmetric bending and C = C elongation in aromatic groups of pectins, lignin, and hemicellulose [82]. At 1374 cm^{-1}, the absorption band is associated with the CH curvature of polysaccharides [83]. The band at 1247 cm^{-1} is related to the aromatic structures of lignin [84]. At 1020 cm^{-1}, the band is assigned to the stretching of C-O and O–H belonging to cellulose [85]. Finally, the absorption at

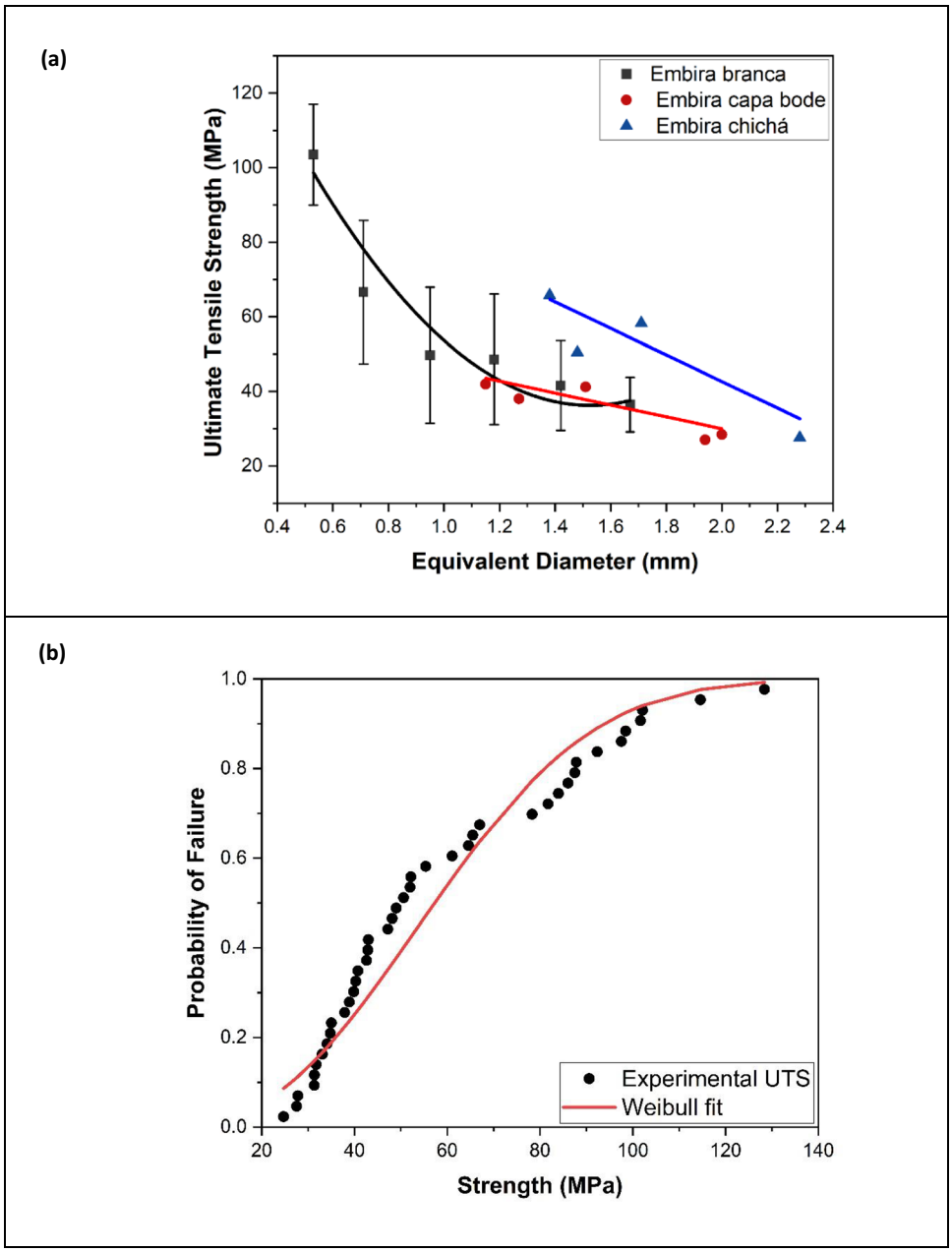

Fig. 8 **a** Variation of the UTS with mean diameters for each interval. **b** Plot of UTS of all specimens expressed as Weibull distribution ($\sigma_0 = 66.6$ MPa; $m = 2.43$)

517 cm^{-1} is due to cellulose out-of-plane bending of C–OH [86]. Thus, the spectrum shows the presence of cellulose, lignin, and hemicellulose.

3.7 X-ray diffraction

The diffractometer scan (Fig. 12) shows two features: the presence of three peaks and a background of varying intensity. The latter is due to the significant presence of an amorphous phase; the former are the principal peaks of the I_β monoclinic cellulose structure. The three peaks at 16°, 22°, and 35° are marked in Fig. 12, together with their indices: (110), (200), and (004), respectively. Cellulose contains, by nature, both crystalline and amorphous regions. The index of crystallinity was calculated from Eq. 4, defined by Segal et al. [33]:

$$C = 100 \times \frac{I_{200} - I_{non-cr}}{I_{200}}[\%] \quad (4)$$

where C is the apparent crystallinity [%], I_{200} is the maximum intensity of the 200 peak at a 2θ angle of 22°, and $I_{\text{non-cr}}$ represents the intensity of the diffraction of the non-crystalline phase, which is taken at an angle of about 18° in the valley between the 200 and 110 peaks. The value obtained for C is 48.5%.

Table 1 Mechanical properties of natural lignocellulosic fibers

Fiber	UTS (MPa)	Strain at failure (%)	Elastic modulus (GPa)	References
Embira branca bark fibers	36–109	15–11	1.06 ± 0.27	This work
Embira capa bode	36.4 ± 8.4	-	1.035 ± 0.13	This work
Embira chichá	48.8 ± 15.0	-	1.67 ± 0.42	This work
Jute	390–770	19–27	1.8–1.2	[64]
Cocos nucifera	106	1–2	12–9	[88]
Cyperus platystylis R.Br	598-715	1.1–0.5	58.35–119	[65]
Cissus quadrangularis	1850–5330	3.6–11.4	56–131	[69]
Thespesia populnea barks	329–557	1.7–2.92	19.5–30	[87]
Derris scandens	437–785	3.39–9.1	4.8–22.1	[85]
Table Cissus vitiginea	315.47 ± 38	8.96 ± 1.5	6.05 ± 1.00	[71]
Celulose fibers (wood)	165	-	2	[68]
Coir (d ~ 0.1 mm)	140	15	-	[89]
Ramie (d ~ 0.017 mm)	870	1.2		

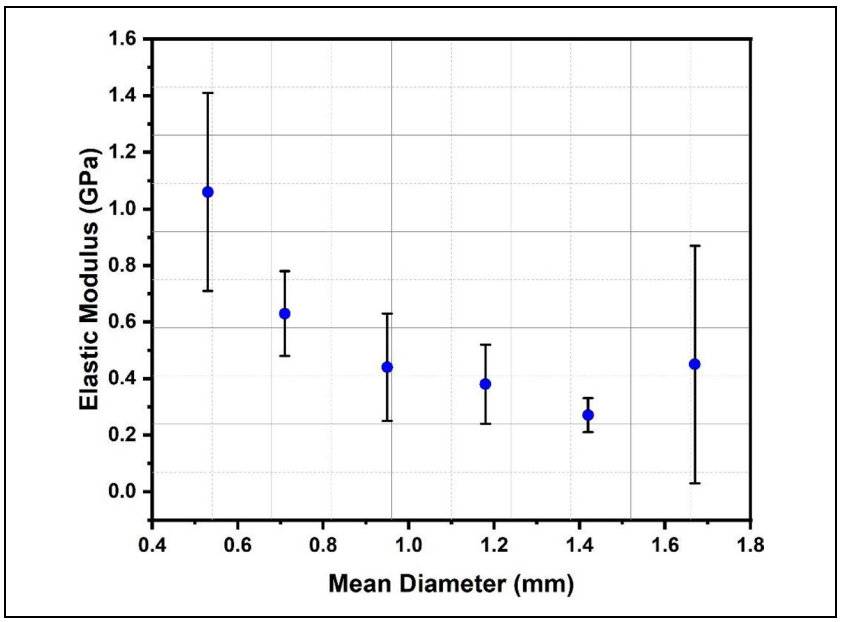

Fig. 9 Variation of the elastic modulus as a function of mean diameters for each interval for *embira branca*

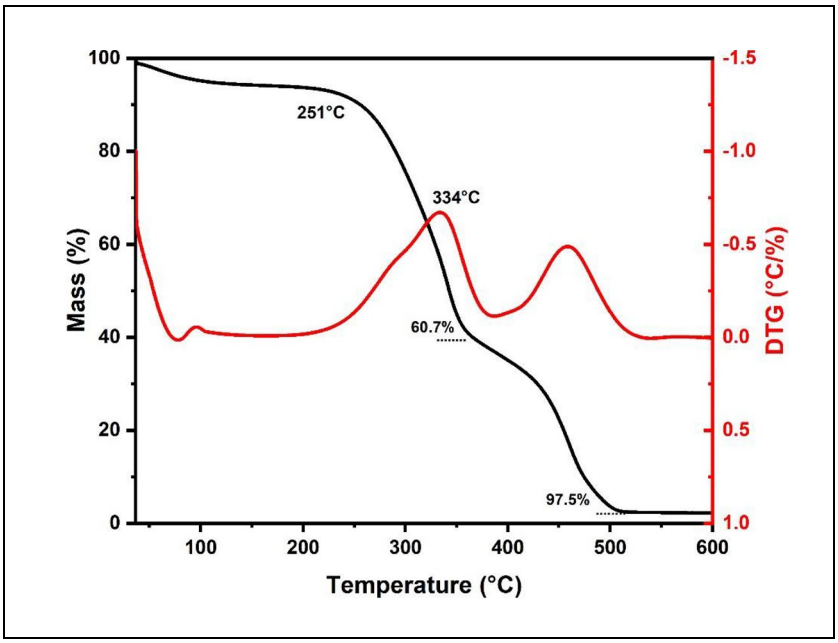

Fig. 10 TGA/DTG curves for the *embira branca* fibers

There is a significant similarity between the current and *Thespesia populnea* results. These results match the identification of the bark fibers of *Thespesia populnea* [87] from India, who report a crystallinity index of 48%. However, there are problems with the units in this work [87], the fiber bundle diameters being quoted in mm (100 mm!), whereas they should be in µm.

Table 2 TGA-DTG of *embira* bark fiber

Function-alization	Mass loss (up to 200 °C) (%)	T_{onset} (°C)	T_{max} of degrada-tion (°C)	Mass loss (up to 350 °C) (%)	Mass loss (up to 600 °C) (%)
Embira branca bark fibers	6.03	250	334	60.7	97.5

4 Conclusions

The embira strips from the western Amazon (Javary and Moa Rivers) are an important sustainable tape widely used in the region playing the role of a versatile material for many uses. Although the tree barks come from different families, their organization is similar: the fibers with a diameter of approximately 20 µm are aligned with the tree trunk axis and have similar organization. They form bundles which have elongated voids between them in a pattern by which fibers change bundles periodically, providing lateral stability. They present similar tensile strengths, varying between 25 and 106 MPa. Consistent with previous findings on lignocellulose fibers, the tensile strength increased with decreasing diameter, from 36 MPa (for fiber bundles with diameters in the 1.6 to 1.8 mm range) to 106 MPa (for fiber bundles with diameters in the 0.37–0.60 mm range). These values are consistent with the tensile strength of wood. The

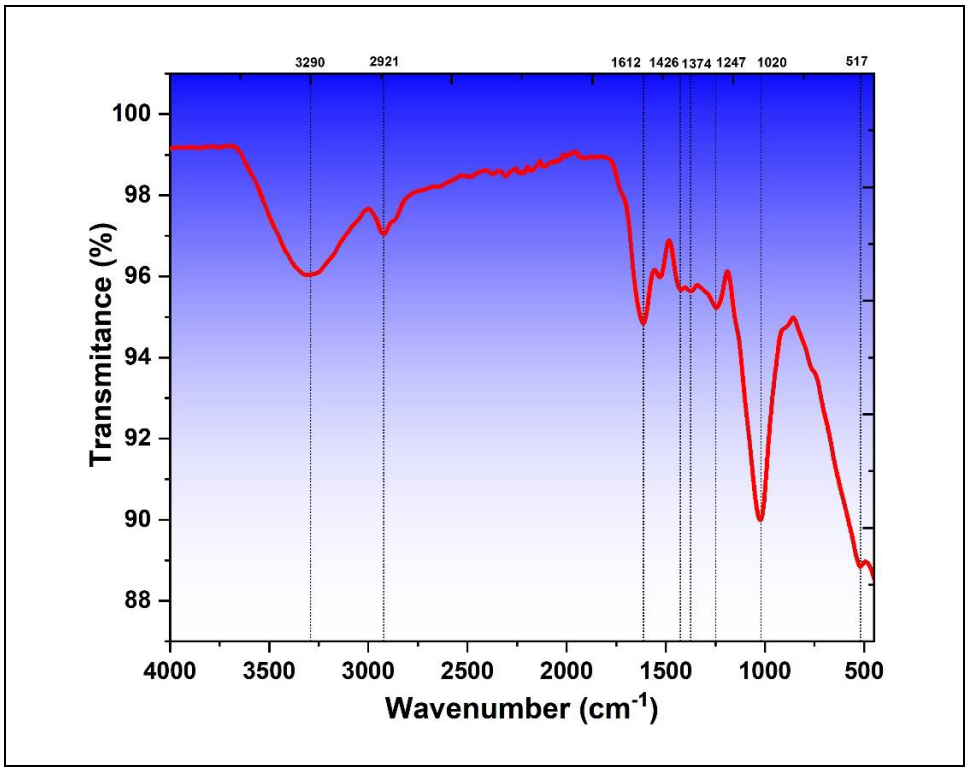

Fig. 11 Fourier transformation infrared (FTIR) spectrum of the *embira branca* fibers

Table 3 FTIR analysis

Absorption bands (cm^{-1})	Bands	Sources	References
3290	OH stretching	Cellulose, hemicellulose	[74]
2921	CH stretching	Cellulose	[80]
1612	OH bending of absorbed water	Water, cellulose	[81]
1426	HCH and OCH in-plane bending vibration	Cellulose	[82]
1374	In the plane CH bending	Cellulose, hemicellulose	[83]
1247	C = O and G ring stretching	Lignin	[84]
1020	C-O and O–H stretching	Cellulose	[85]
517	C–OH out-of-plane bending	Cellulose	[86]

individual fibers have an approximate dimension of 20 µm; thus, the thinnest fiber bundles tested, with a diameter of 5 mm, contain approximately 300 fibers. The relatively low tensile strength of *embira* bark fibers has two main origins: many fibers per bundle (over 300); and a large fraction of amorphous lignin (~0.5). Cellulose is the principal contributor to the tensile strength. Consistently with the increase in strength with decreasing diameter, the density and elastic modulus also increase. This suggests that the concentration of flaws and voids decreases as the diameter is decreased. X-ray diffraction and FTIR indicate that cellulose is the main crystalline constituent. The broad background in the X-ray scan suggests a significant fraction of the amorphous phase.

Although the research reported herein did not address these aspects, we suggest the use of chemical treatment of the fiber to enhance their properties and the further investigation of Amazonian bark fibers with greater strength and the growing of trees for the specific purpose of extracting the bark from which embira fibers are produced.

An important mechanism of deformation was identified: the buckling of the tree bark strips, generated in making knots, requires large shear strains, which are accommodated by the formation of plastic microbuckling regions through the separation of the fibers. Upon twisting or bending of the strips, the fibers separate, enabling ease of tying, which is important for their utilization.

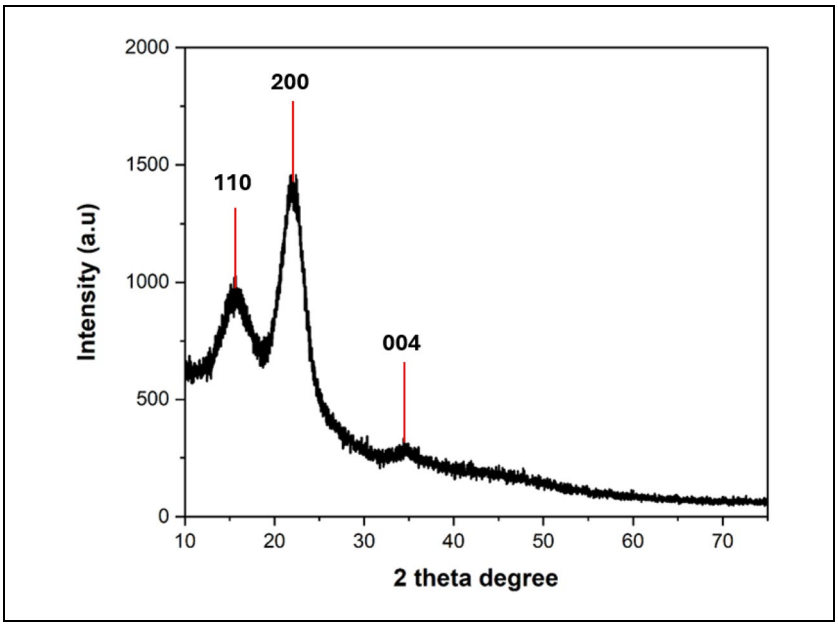

Fig. 12 X-ray diffractogram of *embira branca* showing crystalline cellulose peaks (monoclinic I_β) superimposed on the amorphous background

We feel that it will be possible to cultivate the trees in plantations and to produce bark in a more systematic manner. There is no risk of deforestation because the surfaces required are minimal, and the trees stay alive if the removal of bark is done correctly. This is an open area for future studies.

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Author contributions Sheron S. Tavares: Conceptualization, methodology, investigation, writing—review and editing.

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Henry A. Colorado: investigation, writing—review and editing.

Sergio Neves Monteiro: methodology, writing—review and editing.

Marc A. Meyers: Conceptualization, investigation, methodology, writing—review and editing, Funding adquisition, Supervision.

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Declarations

Competing interests The authors declare no competing interests.

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