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Properties of an Amazonian vegetable fiber as a potential reinforcing material

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ABSTRACT

The jacitara palm (*Desmoncus polyacanthos* Mart.) is widely used by the artisans of the Amazon Basin region of Negro River, Brazil, and is known to provide excellent fiber characteristics and appearance. However, there is a lack of technical/scientific information about this important vegetable fiber. The objective of this study was to evaluate the main properties of jacitara fibers for their future technological application as reinforcement in composites. Anatomical, ultrastructural, chemical, physical and mechanical tests were performed. The coefficient of rigidity, fraction wall, Runkel index and aspect ratio results showed the potential of the jacitara fibers as reinforcement in composites. The range of the microfibrillar angle of the fibers was 12.8–16.5°. The average contents of cellulose, hemicellulose, lignin, extractives and mineral components were 66.9%, 18.4%, 14.7%, 11.6% and 1.8%, respectively. Fibers extracted from the bottom or from the medium part of the jacitara stem showed higher modulus of elasticity (1.9 GPa and 1.7 GPa, respectively) and tensile strength (74.4 MPa and 70.6 MPa, respectively) than that extracted from the upper part. The properties of the jacitara fibers are in the same range of other lignocellulosic materials. The experimental results in the present work contribute to the widespread use of the jacitara fibers as a source of raw material that may be used to engineered composites and new materials for different applications in the near future.

1. Introduction

Vegetable lignocellulosic macrofibers are widely available from annual plants in most developing countries. They present several interesting advantages, particularly their low real (1.3–1.5 g/cm^3) and apparent density (0.4–1.5 g/cm^3), high specific stiffness (1.1–80.0 GPa) and strength (0.1–3.0 GPa), biodegradability, their renewable character, their low processing energy in the case of chopped natural fibers, and their availability everywhere at modest cost and in a variety of morphologies and dimensions (Davies et al., 2011; Jarabo et al., 2012). For example, fibers from monocots presents average fiber lengths and width varying from 1.1 to 2.7 mm and 8 to 30 μm respectively (Ilvessalo-Pfäffli, 1994). In general these fibers are narrow, thick-walled, accompanied by thin-walled fibers with varying shapes of fibers ends (tapering, oblique and blunt).

All these properties make the vegetable lignocellulosic fibers convenient materials for matrix reinforcement, such as polymeric composites or fiber-cement applications, as witnesses the significant number of recent reviews and special issue publications (Peijs and Baillie, 2003; Savastano Jr. and Warden, 2005; Belgacem and Gandini, 2008; Sabu and Pothan, 2008; Savastano Jr. et al., 2010).

Vegetable fibers can be classified according to their origin: from phloem or liber (e.g. jute and malva), from leaves (e.g. sisal and curauá), from seeds (e.g. cotton), from fruit (e.g. coconut), from grass and reed (e.g. palm trees, rice and corn) and from xylem or woody material. Among the vegetable fibrous species, the most used and studied in Brazil are the *Eucalyptus* genus (mostly used as cellulose Kraft pulp), as well as bamboo (Guimarães Jr. et al., 2010), sugar cane bagasse, sisal and coconut coir husk fibers (Motta and Agopyan, 2007; Savastano Jr., 2000; Savastano Jr. and Warden, 2005; Savastano Jr. et al., 2010).

A prior knowledge of the morphology, chemical composition, and physical and mechanical properties of the vegetable fibers is essential for evaluation of their potential for different applications, of their capacity for a later industrial upscaling or for assessing

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the highest reinforcing potential of the fibers (e.g. improving their interaction with the composite matrix).

Jacitara (*Desmoncus polyacanthos* Mart.) is a very common palm species (Arecaceae family) native from Amazon Basin region of Negro River, Brazil. The stem fibers of jacitara are widely used by traditional Amazonian communities for production of handicraft utensils and instruments widely commercialized in South America, and also play an important cultural role for local communities. The jacitara stem has similar morphology and quality to the Asian rattans (*Calamus* spp.), which are species of great importance to the rattan and furniture industry, worldwide known by the quality of their fibers. However, there is a general lack of technical and scientific information about the jacitara palm fibers. Therefore, the objective of this study was to identify the main fiber morphological characteristics, the chemical composition, the physical and mechanical properties of the jacitara stem fibers, with the aim of exploring new applications for this Amazonian species.

2. Experimental

2.1. Material

The jacitara (*D. polyacanthos* Mart.) stems were collected in the district of Novo Airão, Amazonas State, Brazil. The usable length of the collected stems was obtained from the plant stem close to the ground and below the crown of each individual leaf. Samples for anatomical/morphological characterization were taken at five different height positions of the usable jacitara trunks: bottom (0%), 25%, medium (50%), 75% and top (100%), as depicted in Fig. 1.

2.2. Anatomy of the stem and fibrovascular bundles

The cross-section of the bottom of the jacitara stem was sectioned in a sliding microtome and using a type C razor blade steel. 10 μm thick slices were obtained. Staining of the sections was performed with safrablau (safranin 0.1% and astrablau 1%). Semi-permanent histological slides were observed in a Ken-A-Vision Model TT 1010 light microscope.

2.3. Fiber morphology

The separation of the anatomical elements (maceration) of the material extracted from the five height positions was performed using a method adapted from Franklin (1945). The macerated material remained in the oven at 60 °C until the complete individualization of the anatomical elements. Histological semi-permanent slides were prepared with the macerated material for measuring the following properties: overall fiber diameter (*fd*), lumen diameter (*ld*) and fiber length (*L*). Due to the absence of specific standard for monocots, the anatomical classification of the fibers was performed according to Coradin and Muñiz (1992) and International Association of Wood anatomists (IAWA Committee, 1989). Measurements of the dimensions of the fibers, as anatomical elements, were performed in a light microscope Ken-A-Vision Model TT 1010 with image analysis software (WinCeLL Pro, Regent Instruments Inc.). It was used around thirty measurements of fiber length, diameter and fiber lumen diameter, in each height position.

2.4. Anatomical parameters

From the values of overall fiber diameter (*fd*) and lumen diameter (*ld*) of the individualized fibers, it was calculated the anatomical parameters: wall thickness (WT), wall fraction (WF), coefficient of rigidity (CR), Runkel index (RI) and aspect ratio (AR). The wall thickness represents the average fiber cell wall thickness (Eq. (1)) while the wall fraction (Eq. (2)) indicates the volume occupied by the fiber wall in relation to the total fiber volume (Paula and Silva Jr., 1994). The coefficient of rigidity (Eq. (3)) and Runkel index (Eq. (4)) are used in the pulp and paper industry for checking the resistance of the fiber to the forces applied to the paper formation. The ratio of fiber length/fiber diameter, referred to as aspect ratio (Eq. (5)) consists of one parameter widely used to evaluate reinforcing fibers for composite materials and should be equal to or greater than 100 (Halpin and Kardos, 1976). These parameters provide useful information for evaluation of the potential of the vegetable fibers as reinforcement.

$$\text{WT}\ \ (\mu\text{m}) = \frac{fd - ld}{2} \tag{1}$$

$$\text{WF}\ \ (\%) = \frac{2 \times \text{WT}}{fd} \times 100 \tag{2}$$

$$\text{CR}\ \ (\%) = \frac{ld}{fd} \times 100 \tag{3}$$

$$\text{RI} = \frac{2 \times \text{WT}}{ld} \tag{4}$$

$$\text{AR} = \frac{L}{fd} \tag{5}$$

where *fd* is the overall fiber diameter (μm), *ld* is the lumen diameter (μm) and *L* is fiber length (μm).

2.5. Microfibrillar angle of the fiber

Microfibrils designate long flexible micro or nanofibers consisting of alternating crystalline and amorphous cellulose chains. According to Wimmer et al. (2002), the microfibrillar angle is one of the most important ultrastructural aspects of the fiber cell wall. The angle formed by microfibrils with the fiber axis is related to the strength of the individual cellulose fiber. The orientation of microfibrils toward the S2 layer can be associated with high tensile strength of the fiber. Lower values of microfibillar angle correlate with high tensile strength (Foelkel, 1977). The determination of the microfibrillar angle was carried out for fiber samples from the bottom (0%), medium (50%) and top (100%) positions of the jacitara plant (Fig. 1). The fractions of the stem at each position were sectioned at the tangential plane in a sliding microtome, using a type C razor blade steel. Each sample was composed of a mixture of histological sections with 10 μm thick, obtained from five different individuals of jacitara trunks. For dissociation of the anatomical elements the sections were soaked in a 1:1 (v/v) solution of hydrogen peroxide and glacial acetic acid at 50 °C for approximately 30 h, similarly to the procedures reported in Ribeiro et al. (2011). It was used a microscope with polarized light and a turntable with the scale ranging from 0 to 360°. Thirty fibers of each sample were measured for determination of the microfibrillar angle, following the methodology described by Leney (1981).

2.6. Chemical composition of the fibers

The contents of cellulose, hemicelluloses and lignin of the jacitara stems for chemical characterization (retained on the 60 mesh sieve) were obtained on the extractives-free samples, and they were determined according to the methodology described by Silva and Queiroz (2002). The determination of the extractives content and mineral/ash content followed the NBR 14853 (ABNT, 2010) and NBR 13999 (ABNT, 2003) standards, respectively.

2.7. Physical and mechanical properties

2.7.1. Thermal degradation

A representative compound sample of the jacitara fibers retained on the 270 mesh sieve was prepared for the

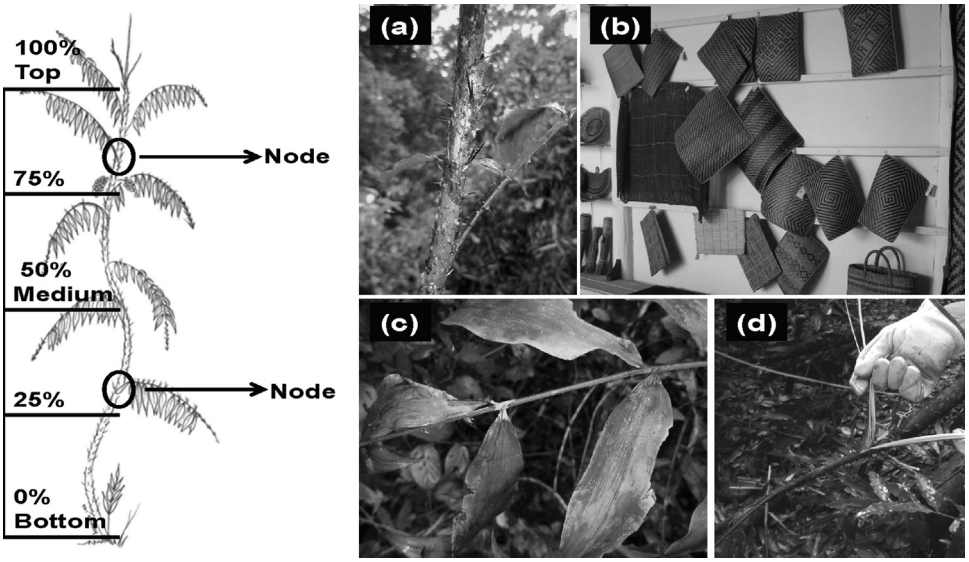

Fig. 1. Left: scheme of the sampling along the usable length of the jacitara stem. Adapted from Quiroz et al. (2008). Right: images of the palm plant (a), handcraft utensils (b), leaves (c) and fiber extraction (d).

thermogravimetric analysis (TGA) in a DTG Shimadzu 60AH thermal analyzer. Two replicates were used. Samples of about 4 mg were heated at 10 °C/min, under nitrogen flow of 50 mL/min.

2.7.2. Tensile strength and modulus of elasticity of the fibers

Eleven specimens constituted of jacitara fiber bundles with 15 cm length, and corresponding to the bottom (0%), medium (50%), top (100%) and node positions were extracted from the jacitara trunks for mechanical tests.

The tensile strength and modulus of elasticity (E) of the jacitara fiber bundles were obtained from the tensile test parallel to the fiber axis, as described by Motta and Agopyan (2007). The samples for the tensile test were subjected to oven drying at 60 ± 2 °C for approximately 36 h. After preparation, the cross-section area of the fiber bundle specimens was measured. The cross-section area of the testing specimen of jacitara fiber bundles was considered with an elliptical shape.

The tensile test of the fibers was performed using a universal testing machine with a load cell of 1 kN, loading rate of 0.4 mm/min, 20 mm length between jaws and claws under pneumatic pressure of approximately 2 kN. After completion of the mechanical test, the moisture content of the samples was determined (Vital, 1997).

2.7.3. Analyses of the fractured surfaces

Fractured surfaces of the fibers after the tensile test were observed in a LEO Evo40 XVP scanning electron microscope (SEM) and Software Leo User Interface (version Leo 3.2). Samples were gold coated before SEM analyses.

3. Results and discussion

3.1. Anatomy of the stem and fibrovascular bundles

Each fibrovascular bundle includes a single prominent metaxylem vessel (P, Fig. 2a, c and d), however, there may be multiple prominent vessels, with only of phloem strand, normally with a double or triple series of wide sieve cells (arrow 2, Fig. 2), protoxylem elements surrounded by and separated from the metaxylem by parenchyma (arrow 4, Fig. 2) and wide or narrow series of fibers. The phloem strands are enclosed by a band of sheathing fibers, which are continuous around the phloem side of the bundle. The phloem is generally viewed in opposite disposition to the protoxylem within each bundle. The wide metaxylem vessels with uniformly and continuously pitted walls are remarkable. Perforation plates of central vessel elements are always scalariform (arrow 5, Fig. 2). Peripheral bundles have wide series of fibers (F, Fig. 2a–c) and relatively narrow protoxylem elements (arrow 4, Fig. 2c). The inner side of the bundle, i.e. in the internal part of the jacitara stem, presents narrow series of fibers and large protoxylem elements (arrow 4, Fig. 2d).

3.2. Morphology of the fibers and anatomical parameters

The morphological properties and anatomical parameters of the jacitara fibers at different height positions are summarized in Tables 1 and 2. The average fiber diameter was around 16 μm. According to the classification of IAWA Committee (1989), the jacitara fibers should be classified as thin fibers. The jacitara fibers present length greater than 2 mm for all height positions studied, and may be classified as long fibers according to the classification of Coradin and Muñiz (1992). The average wall thickness of the jacitara fibers is higher than 5 μm, with the exception of top position (100%). IAWA Committee (1989) classifies vegetable fibers as: (i) very thin-walled, whose fiber lumen is three or more times

Table 1
Morphological properties of the individualized jacitara fibers at the different height positions.

Dimensions	Height	Range	Mean ± sd
Overall diameter, *fd* (μm)	0%	10.1–23.5	16.1 ± 0.8
	25%	10.2–24.3	16.7 ± 2.0
	50%	10.6–23.7	16.5 ± 0.5
	75%	10.9–25.9	16.7 ± 0.9
	100%	10.4–24.7	17.0 ± 1.2
Lumen diameter, *ld* (μm)	0%	1.6–10.6	4.0 ± 1.8
	25%	1.6–11.3	4.1 ± 2.8
	50%	1.7–10.9	4.7 ± 2.3
	75%	2.1–14.4	5.7 ± 3.2
	100%	4.1–17.9	9.2 ± 3.0
Length, *L* (mm)	0%	1.4–3.7	2.3 ± 0.4
	25%	1.5–4.4	2.6 ± 0.3
	50%	1.4–4.2	2.6 ± 0.2
	75%	1.3–4.3	2.4 ± 0.2
	100%	1.3–4.0	2.3 ± 0.3

sd: standard deviation.

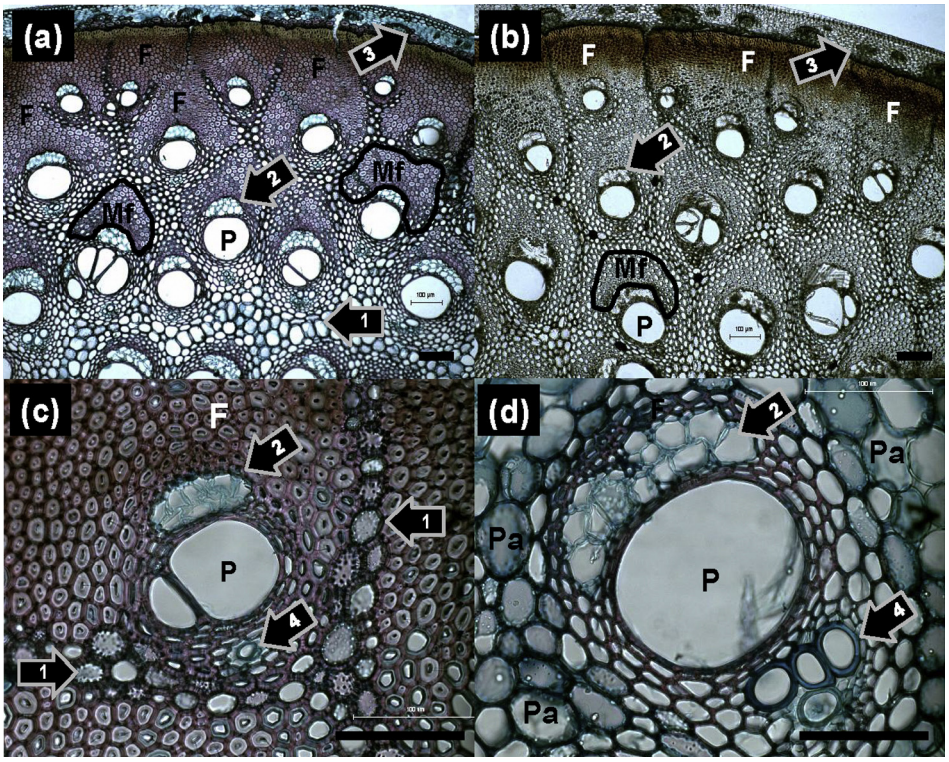

Fig. 2. *Desmoncus polyacanthos*. General features of the stem anatomy. Light microscopy images of the colored cross-section (a), the fresh cross-section (b), the outermost fibrovascular bundle (c) and innermost fibrovascular bundle (d) of the jacitara stem with identification of the different types of anatomical elements: parenchyma cells (Pa, arrow 1), the phloem cells (arrow 2), epidermis (arrow 3), protoxylem (arrow 4), pore or vessel element of metaxylem (P) with scalariform perforation plate (arrow 5), fibers (F) and macrofiber formed by the bundle of individual jacitara fibers (Mf). In image (e) visualizes vessel element in macerated material. Scale bar is 100 μm.

wider than the double of the wall thickness; (ii) thin to thick, when the fiber lumen is less than three times the double of the wall thickness; and (iii) very thick-walled, whose fiber lumen is almost completely inaccessible. From the relation among the lumen diameter and wall thickness, it can be stated that jacitara fibers have thin to thick walled fibers. Guimarães Jr. et al. (2010) encountered, for *Bambusa vulgaris*, values of fiber length (2.29 mm), fiber diameter (13.93 μm), lumen diameter (3.81 μm) and thick cell wall (5.06 μm) very close to those observed for the jacitara fibers.

Table 2
Anatomical parameters of the jacitara fibers at the different height positions.

Parameters	Height	Range	Mean ± sd
Wall thickness, WT (μm)	0%	3.8–8.3	5.9 ± 0.7
	25%	3.3–8.5	6.1 ± 1.3
	50%	3.6–8.4	5.7 ± 1.3
	75%	3.3–7.5	5.3 ± 1.2
	100%	2.4–5.3	3.6 ± 1.0
Wall fraction, WF (%)	0%	50.6–90.1	73.8 ± 9.1
	25%	49.5–88.9	72.5 ± 13.9
	50%	48.9–87.3	69.0 ± 13.7
	75%	40.0–84.5	62.9 ± 16.1
	100%	28.0–65.0	43.4 ± 14.8
Coefficient of rigidity, CR (%)	0%	11.1–49.7	24.6 ± 9.1
	25%	11.1–50.5	24.1 ± 13.9
	50%	12.7–51.1	27.8 ± 13.7
	75%	15.5–60.0	32.8 ± 16.1
	100%	35.0–72.0	53.0 ± 14.8
Runkel index, RI	0%	1.1–10.1	4.1 ± 1.5
	25%	1.1–11.7	4.5 ± 2.0
	50%	1.1–8.4	3.5 ± 1.5
	75%	0.7–8.1	2.9 ± 1.3
	100%	0.5–2.6	1.1 ± 0.9
Aspect ratio, AR	0%	103–169	140 ± 24
	25%	129–181	157 ± 21
	50%	145–180	157 ± 13
	75%	123–160	144 ± 15
	100%	108–170	139 ± 24

sd: standard deviation.

The average values of wall thickness (WT), wall fraction (WF) and Runkel index (RI) decreased toward bottom to top position. The highest values of these parameters were obtained at the positions of 0% and 25% of the jacitara stem. The lowest values for these parameters were observed at the top position (100%), due probably to the fact that this portion is composed of younger tissues (Tomlinson, 1990).

Jacitara fibers present more than 50% of wall fraction, with exception to the 100% height position. Thus, the thicker the fiber cell wall (i.e. the higher wall fraction) the higher the amount of cellulose, hemicellulose and lignin and lower is the void content in the individual fiber (Paula and Silva Jr., 1994). Jacitara fibers at the 0–75% height positions presented more than 60% of wall fraction, which may be considered as a characteristic of stiffer fibers (Guimarães Jr. et al., 2010). The results of coefficient of rigidity (CR) and Runkel index (RI) corroborate with that statement. For example for paper industry, fibers with a CR above 75%, characteristically exhibit a high degree of fiber collapse/hornification, improving contact surface between fibers. This is because the relationship between the lumen diameter and the fiber diameter is greater. Therefore, the higher that ratio the lower is the stiffness and the higher is the flexibility of the fiber (Nisgoski, 2005). The Runkel index showed values above 2 for the 0–75% height positions. The smaller the Runkel index, the greater the potential of entanglements between the fibers. In fact, the reinforcing potential is controlled by the ability of the fiber to form a percolated network held by strong hydrogen bonding interactions that contribute to increasing the stiffness as well as the reinforcement potential

Table 3
Microfibrillar angle of the jacitara fibers.

Height position	Microfibrillar angle (°)	
	Range	Mean ± sd
0% (bottom)	9.0–17.0	13.0 ± 2.1
50% (medium)	11.0–21.0	16.0 ± 3.3
100% (top)	9.0–22.0	17.0 ± 3.2
Node	10.0–19.0	15.0 ± 2.9

sd: standard deviation.

into polymeric composites (Malainine et al., 2005; Pullawan et al., 2010). The effect of reinforcement in composites depends, among other factors, on the fiber morphology (diameter and length). The use of fibers with higher aspect ratio may allow obtaining stiffer but more brittle composites. The aspect ratio of the jacitara fibers showed values above 100, for all positions along the stem. The higher the aspect ratio, the greater the ability of the fiber for reinforcing the composite (Rabello, 2000). When using macrofibers (commercial monocots fibers) with long lengths and small diameters, the more efficient is the reinforcement of the composite, since the increase in aspect ratio results in increased strength and stiffness of the composite (Santos et al., 2009).

3.3. Microfibrillar angle

The largest microfibrillar angle values were found at 50% (medium) and 100% (top) positions (Table 3). The values of microfibrillar angle at these positions were 16° and 17° respectively. The range of the microfibrillar angle in mature wood is of 5–20° for hardwoods fibers (Donaldson, 2008). The values of microfibrillar angle found for the jacitara fibers are also similar to the values found by Satyanarayana et al. (2007) when studying different non-woody fibers from Brazil, such as sisal (20°), jute (17.1°) and curauá fibers (18.8°). Lower values of microfibrillar angle are correlated with high axial tensile strength and stiffness (Savastano Jr., 2000; Wimmer et al., 2002; Donaldson, 2008).

3.4. Chemical composition

Table 4 presents the chemical composition of the jacitara fibers. The high cellulose content may contribute to the tensile strength of the fibers. Cellulose microfibrils are the structure of the plant cell wall (mainly the S2 secondary wall layer), and consequently exercises great influence on the physical and mechanical properties of the fibers. The hemicellulose content was almost 20%, which act as the matrix responsible for the connection between the cellulose and lignin in the fiber cell wall (Sedlmeyer, 2011). The lignin content of the jacitara fibers was around 15%, which also provides strength and cohesion to the lignocellulosic fibers.

The high content of extractives present in the jacitara stem can be visualized by the presence of the brown color cells in the epidermis of the stem's cross-section in Fig. 2. These extractives may be associated with the adaptation of this palm species to resist during partial water submersion through the water flood seasons of the Amazon climate. Therefore, these extractives are expected to protect the jacitara fibers from weathering degradation.

3.5. Physical and mechanical properties

3.5.1. Thermal degradation

The TGA and DTG curves of the jacitara fibers are presented in Fig. 3. As observed in the DTG curves, the decomposition of the jacitara fiber occurred essentially in two stages. The first stage was at temperatures between 40 and 100 °C, correspondent to the mass loss of around 10% from volatile substances (e.g.

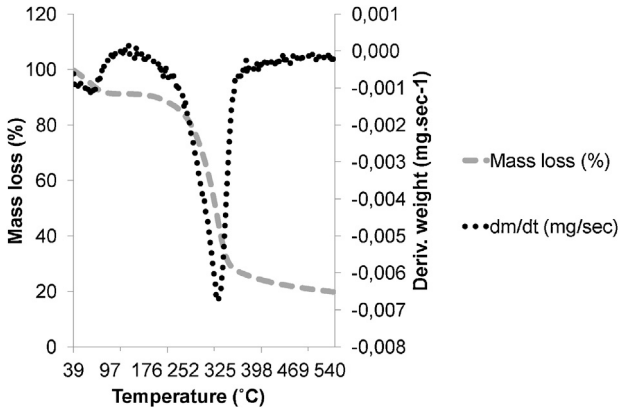

Fig. 3. TGA and DTG curves obtained for the fibers of the stem of jacitara in nitrogen atmosphere.

extractives) and moisture in the samples. The second and dominant thermo-gravimetric (DTG) peak, with mass loss of around 60%, was observed at around 330 °C, responsible for the maximum rate of mass loss of hemicelluloses (normally in the range of 225–325 °C), lignin (in the range of 250–500 °C) and cellulose (in the range of 305–375 °C) as reported by Prins et al. (2006). This observation may not limit the use of jacitara fibers for extruded or injected polymeric composites or for particleboards since the main polymer matrices and particleboards production do not require processing temperatures above 300 °C. No thermal event was observed at temperatures higher than 400 °C.

3.5.2. Mechanical properties

The moisture content in the jacitara stem specimens during the tensile test was of approximately 9%. The typical stress vs. strain curves obtained for each height position are presented in Fig. 4. The stress–strain curves of the jacitara stem specimens are similar to other materials that present the so-called bi-elastic behavior, such as steel materials (Timoshenko, 1966). The first linear region of the curves was used to calculate the modulus of elasticity (E). In the second region of the curves it is observed a stabilization of the stress during the increase of the strain, probably due to the slipping process (arrows in Fig. 5) through the fibrovascular bundles during the application of the stress or due to the rupture of the parenchyma cells (arrows 1 in Fig. 6), which presents thin cell wall (sometimes

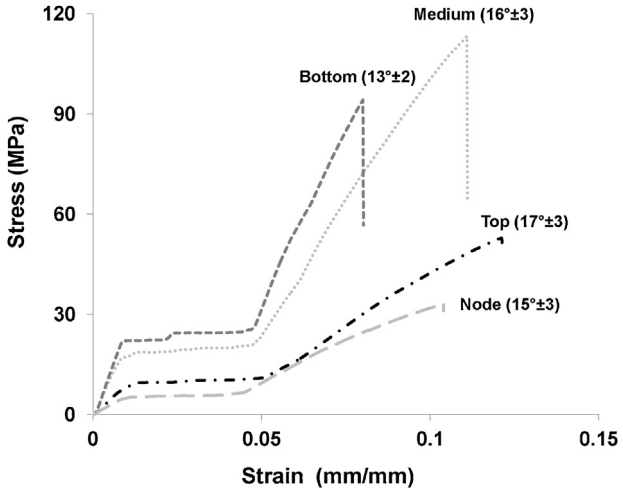

Fig. 4. Typical stress–strain curves of the jacitara specimens at the different height positions. Microfibrillar angle values and its standard deviation in each position of the jacitara stem are in parentheses.

Table 4
Chemical composition of the jacitara fibers and some reinforcing fibers.

Components	Jacitara		Bagasse (wt%)	Bamboo (wt%)	Sisal (wt%)	Curaua (wt%)	Coir husk (wt%)
	Range (wt%)	Mean ± sd (wt%)					
Cellulose[a]	66.1–67.8	66.9 ± 0.9	55.2[d]	26–43[d]	65.0[d]	73.6[d]	43–53[h]
Hemicelluloses[a]	16.8–19.4	18.4 ± 1.4	16.8[d]	30.0[d]	12.0[d]	9.9[d]	14[h]
Insoluble lignin[a]	14.2–15.3	14.7 ± 0.6	25.3[d]	21–31[d]	9.9[d]	7.5[d]	38–41[h]
Extractives[b,c]	10.8–12.3	11.6 ± 0.6	31.7[e]	13–19[f]	9.3[g]	–	2.3[g]
Minerals[c]	1.3–2.0	1.8 ± 0.3	0.8[e]	–	1.9[g]	–	1.3[g]

sd: standard deviation.
[a] Determination done using three replicates.
[b] Extractives soluble in ethanol toluene + ethanol + water.
[c] Determination made using five replicates.
[d] Faruk et al. (2012).
[e] Paula et al. (2011).
[f] Brito et al. (1987).
[g] Salazar and Leão (2006).
[h] Satyanarayana et al. (2007).

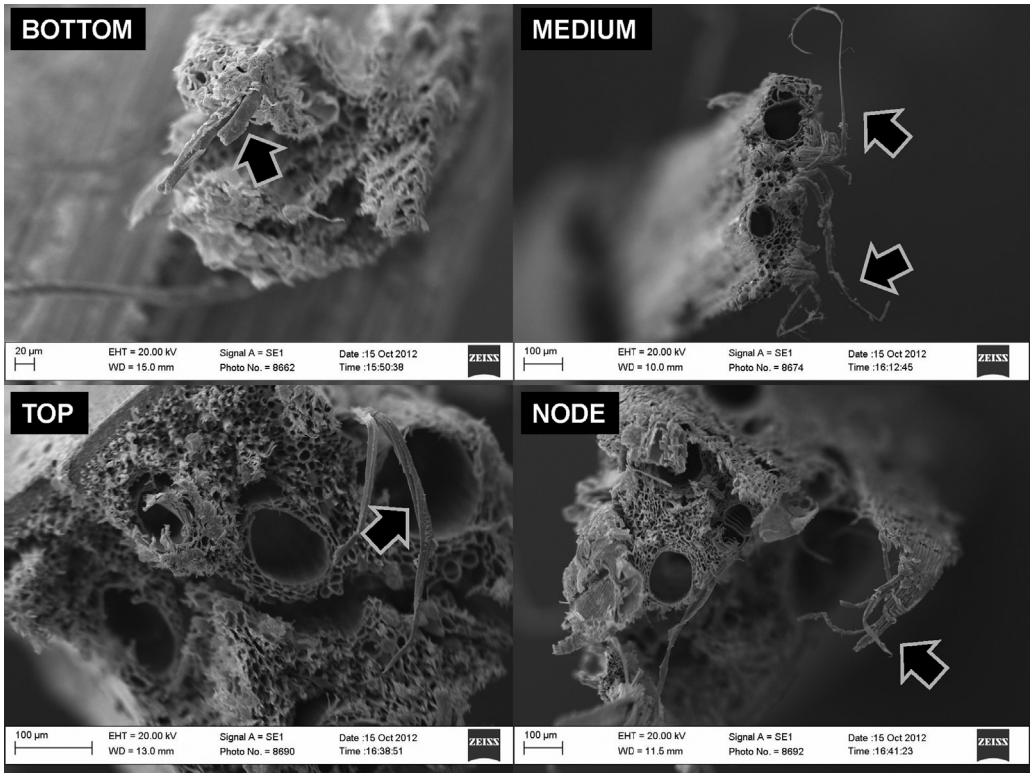

Fig. 5. Scanning electron microscopy (SEM) images of the fracture surface of the jacitara fiber (in all height positions of the plant) after mechanical test. Arrows indicate the presence of unbroken fibers.

just the primary wall) and vessel structures (arrows 2 in Fig. 6) in the stem specimens. The tensile strength (TS) is achieved at the end of this second elastic region.

The highest values of tensile strength (TS) and modulus of elasticity (E) observed in Table 5, were obtained for the specimens extracted from the bottom (TS = 74.4 MPa and E = 1874.2 MPa) and medium positions (TS = 70.6 MPa and E = 1687.6 MPa) of the jacitara plant. The results are comparable with that presented in the literature for bamboo (TS between 140 and 230 MPa and E between 11,000 and 17,000 MPa), for bagasse (TS = 290 MPa and E = 17,000 MPa), Sisal (TS between 511 and 635 MPa and E between 9400 and 22,000 MPa), curauá (TS between 500 and 1150 MPa and E = 11,800 MPa) and coir husk (TS = 175 MPa and E between 4000 and 6000 MPa) by Faruk et al. (2012). Deviations from values and stress–strain curves reported in the literature are the result of different testing conditions, such as: clamping length, type of

Table 5
Mechanical properties of the jacitara fiber bundles.

Variables[a]	Height position	Jacitara	
		Range (MPa)	Mean ± sd (MPa)
Tensile strength (TS)	0% (bottom)	54.7–113.2	74.4 ± 16.9
	50% (medium)	35.6–105.8	70.6 ± 21.1
	100% (top)	29.1–71.3	46.1 ± 11.4
	Node	24.2–47.9	38.3 ± 6.8
E	0% (bottom)	1145.3–2488.4	1874.2 ± 385.7
	50% (medium)	770.2–2806.4	1687.6 ± 694.9
	100% (top)	399.3–1053.3	782.1 ± 193.2
	Node	423.1–1057.1	761.8 ± 214.2

E: modulus of elasticity (MPa); sd: standard deviation.
[a] Properties determined using around 10 replicates.

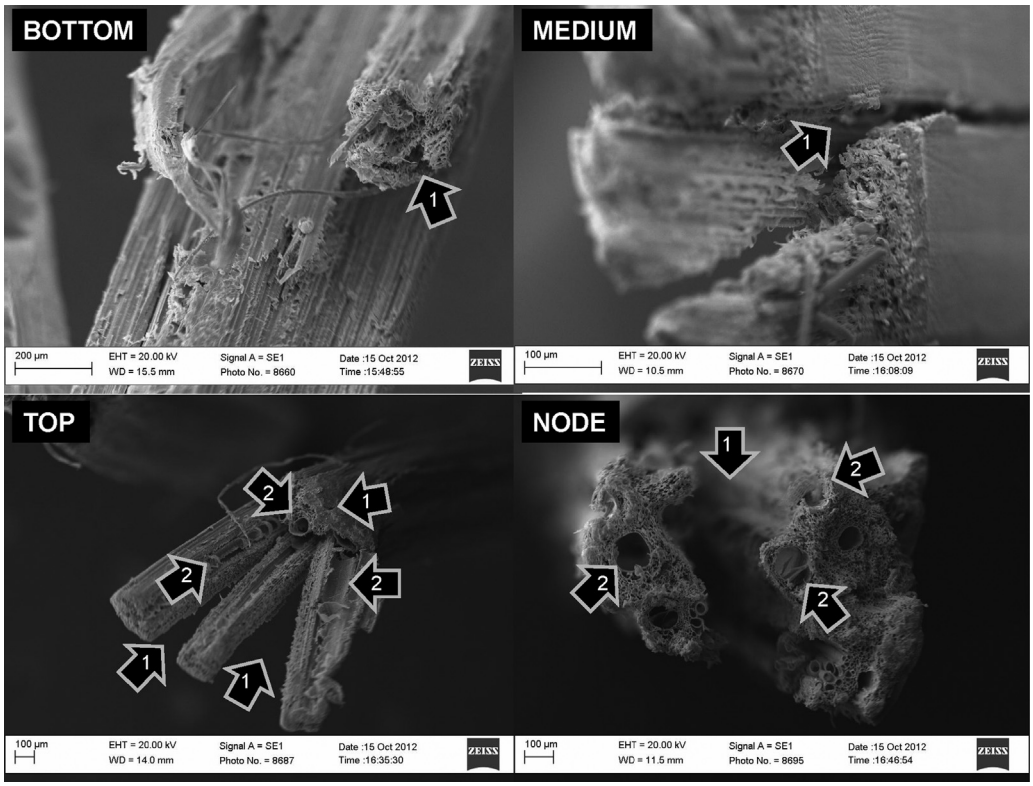

Fig. 6. Scanning electron microscopy (SEM) images of the fracture surface of the jacitara fiber (in all height positions of the plant) after mechanical test. Arrows 1 indicate that rupture occurred in regions with cells containing only primary wall, vessels and parenchyma cells. Arrows 2 indicate the vessels or pores presents in the rupture region.

specimens (individual fibers or fiber bundles), if tested in composites or as dry fibers, and others (Herrmann et al., 1998; Riedel and Nickel, 2002). In the present work, the tested specimens were not individual macrofibers but a group of different macrofiber bundles, strongly united, and concentrated near to the epidermis of the jacitara trunk. The industrial application of vegetable fibers usually require standardized dimensions, mainly when the mechanical properties of the products are the bottleneck (Jarabo et al., 2012).

4. Conclusion

The knowledge of the characteristics of the jacitara fibers is important to previously evaluate their possible applications in composites based on different types of matrix. The results of coefficient of rigidity, fraction wall, Runkel index and aspect ratio of the fibers showed their potential as reinforcing materials in composites. The microfibrillar angle of the fibers was in the range between 12.8° and 16.5°. The average contents of cellulose, hemicelluloses, lignin, extractives and mineral components were 66.9%, 18.4%, 14.7%, 11.6% and 1.8% respectively. The thermal decomposition of the jacitara fiber occurred essentially in two stages (40–100 °C and at around 330 °C, with reduction of 10–60% by mass respectively). The fibers of the bottom and medium parts of the plants showed the higher modulus (1874 MPa and 1688 MPa respectively) and axial tensile strength (74.4 MPa and 70.6 MPa respectively). The experimental results for tensile strength and modulus of elasticity were lower in comparison to the corresponding values referring to the main reinforcing fibers used in Brazil. Taking into account all the characteristics presented by the jacitara fibers and comparing them with other reinforcing fibers, it may be assumed that this important Amazon palm tree is a possible source of vegetable fiber similar to other species commercially exploited in the fiber market.

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