Research Article

Banana pseudostem fibers characterization and comparison with reported data on jute and sisal fibers

Ricardo Rodrigo Ramos Cecci[1] · **Adriano Alves Passos**[1] · **Thales Calmon de Aguiar Neto**[1] · **Leandro Alves Silva**[2]

Received: 19 June 2019 / Accepted: 26 November 2019 / Published online: 4 December 2019

Abstract
This work search for new environmentally friendly applications for the fibers of banana pseudostem. The morphological characteristics of the cellulosic fibers originated from pseudostem allows obtaining fabrics with good mechanical properties. Observing the potential of banana agribusiness disposal that MusaFiber Company realized, in this fibrous residue, an opportunity for the development of new products. Fibers were extracted mechanically from the banana pseudostems, then, the obtained fibers were characterized in relation to the diameter, tensile strength, elongation at break by tensile tests and its morphological structure by scanning electron microscopy. The mechanical tests revealed much better tensile strength (590 MPa) when compared to other natural fibers, such as jute (249 MPa) and sisal (350 MPa). The highest mechanical strength is due to the high degree of crystallinity of this fiber (~ 67%) calculated from the FTIR spectrum and to its morphology.

Keywords Ecological textiles · Banana pseudostem · Natural fibers · FTIR

1 Introduction

The study of *Musa x paradisiaca* pseudostems fibers was motivated by three main reasons: the growing environmental awareness, the enormous amount of pseudostem in the Brazilian banana production waste, and the historical use of fibers from *Musa* species in ancient and isolated societies with textile applications.

The 1950s were the start of the green revolution, which exponentially expanded the crop production worldwide [1]. Later in the 1970s, as a result of the growing demographic pressure in urban centres, and the oil crisis, global warming, waste generation and human caused pollution have taken a bigger role in economics, and the concept of sustainable development was forged [2]. The combination of a growing crop production and growing metropolises around the globe generated a main concern over the food waste destination, and how urban landfills would become unable to successfully process all this waste. Therefore, governments have invested in research to way find ways to reallocate this waste back in economics, and entrepreneurs have seen an opportunity to add value to their waste by finding new applications or new processing ways that allow further use of that waste as recycled or reused material.

Moreover, the sustainable fashion market is seeking to produce fabrics with ecological yarns to meet growing demand around the theme of sustainability. Some consolidated international brands have begun to invest in sustainable product lines. They were succeeding in developing fabrics that use raw materials different from traditional ones. *Taiwan's Singitex* company is manufacturing S.Cafe® fiber [3], through the recycling of coffee grounds. Big names like *North Face, Puma* and *Timberland* are already using the S. Cafe fabric. Another example is the company *Teijin*, which created the *EcoCircle*®, a Plantfiber

---

✉ Ricardo Rodrigo Ramos Cecci, rrcecci@cetiqt.senai.br | [1]Innovation Institute for Biosynthetic, SENAI CETIQT, Rio de Janeiro, Brazil. [2]MusaFiber Company, Bauru, Brazil.

SN Applied Sciences (2020) 2:20 | https://doi.org/10.1007/s42452-019-1790-8

bio-polyester. Nissan was one of the first companies to use the fabric for the upholstery of its Nissan Leaf electric car in 2014, [4].

Accordingly, this study seeks to address the Brazilian banana waste in ways to allow value addition to its market chain. In fact, banana is the second biggest fruit production in Brazil [5]. The banana pseudostem was estimated to exceed 20 million tons annually in Brazil only. In addition, the banana cultivated areas are often very poor, so adding value to its waste would mean increasing the amount of work, and the family revenue in those regions, such as Vale do Ribeira, in Brazil [6]. This amount of waste can be converted into fibers, researches indicate that it would take 37 kg of stems to produce 1 kg of fiber [7]. Furthermore, Vigneswaran et al. [8] outlined the historical use of banana fibers from mats, to recently developed composite packages and as clothing in Japan since 1600s. However, all the fabrics are handcrafted which does not allow a profitable and affordable scalability of banana fabrics.

The objective of this paper is to characterize the banana pseudostem fibers in order to base further research on how to process the fiber and scale up the production of banana fabrics.

2 Experimental

Banana pseudostems (*Musa x paradisiaca*) were collected from local cultivators, with about 2.5 m in length, 0.4 m of diameter and 40.0 kg in weight (Fig. 1a). Pseudostem barks were isolated from the inner layers manually in the laboratory and washed in distilled water to remove dirt and residues. The barks were dried at room temperature in an open environment for 24 h (Fig. 1b). For the mechanical extraction of the fibers, a Textilmaq defibrating machine (Fig. 1c), operating at a rotation speed of 600 rpm, was used to remove the non-fibrous parts of the barks leaving only the fibers that are used in the textile process for the yarn production. Lastly, these fibers were dried at room temperature and brushed (Fig. 1d).

The diameter test was performed at room temperature with a micrometer (Mitutoyo: External Micrometer series 102–311) throughout four different extents of the fiber. The tensile tests were performed in a calibrated Universal tensile testing machine, model Instron 23-5D, with a load cell of 500 N, provided by the Materials Engineering Department of USP São Carlos. Six samples were tested for elongation at rupture (εrup) and tensile strength ($\sigma_{máx}$). The fibers with a length of 30 cm were stretched at the speed rate of 30 mm/min. Test conditions were based on ASTM D2256 and ASTM D76 standards. Scanning Electron Microscopy (SEM) images were taken using a Hitachi TM3030 microscope of the Electronic Microscopy Laboratory (CETEM/UFRJ), operated at 15 kV in backscattered electrons (BSE) mode. FTIR spectroscopy was performed with a Agilent Cary 630 FTIR spectrometer over the range of 650–4000 cm^{-1}.

3 Results and conclusions

The samples of banana pseudostem defibrated fibers were assessed generating the average results and standard deviation presented in Table 1. In addition, the values obtained were compared with the theoretical values of the sisal and jute fibers. The different mechanical properties of the types of these fibers determine their application in the development of a finished product.

The average of maximum elongation obtained was 6.54% while the average of tensile strength was 570 MPa. The banana fiber showed to has higher tensile strength than jute (273 MPa) and sisal (350 MPa) fibers, being one

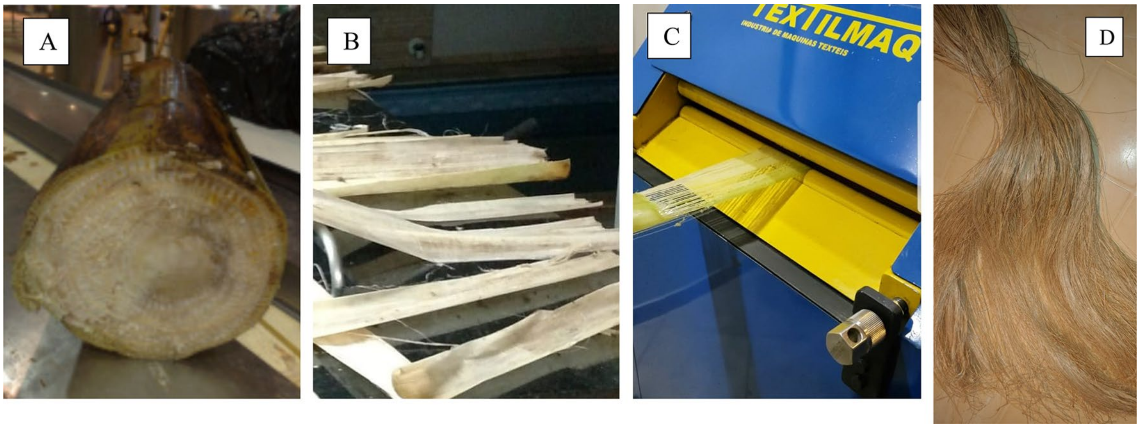

Fig. 1 **a** *In Natura* Banana pseudostem, **b** Fibrous barks removed from pseudostem during drying, **c** defibration machine input, **d** fibers obtained after defibration, drying and brushing

Table 1 Comparison between the mechanical properties of banana, jute and sisal fibers

Fibers	Diameter (μm)		Tensile strength (MPa)		Elongation at break (%)		Crystallinity (%)
	AVG	STDEV	AVG	STDEV	AVG	STDEV	
Banana [experimental]	110	0.9	570	12.1	6.54	0.4	67
Jute [9–11]	59.39	249	0.6	43			
Sisal [12, 13]	205	350	6–7	46			

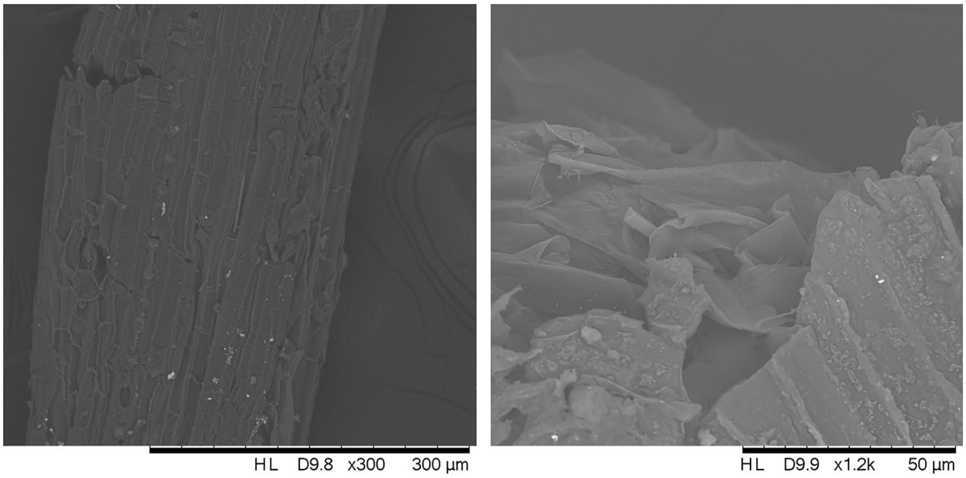

Fig. 2 SEM Images of the banana fiber. At left, the longitudinal-section, 300 times. At right, fracture-section, 1200 times

of the most important properties for yarn production. Low observed standard deviation values for all reported measurements suggest very homogeneous samples, which provides reliability in data assessment and repeatability of experimental results. The mean diameter obtained was 110 μm. The samples of banana fibers were observed to be thinner than sisal fiber (205 μm) and thicker than jute fiber (59.39 μm) reported in [9, 10, 13]. The diameter of the fiber is also an important property because thicker fibers hinder the spinning process, besides not allowing the production of thinner yarns.

Reported average diameter from banana, jute and sisal samples presented in Table 1 do not show a clear relation with its mechanical properties. However, an increase in crystallinity could explain the observed increase in samples' average tensile strength and elongation at break. Further crystallinity characterization, such as X Ray Diffraction, should be performed to better understand its relation with samples' mechanical properties.

Figure 2 shows the SEM images of raw Banana fiber at different magnitudes. (A) longitudinal-section shows that the unit cells with parallel orientation with tube-like structures composed of cellulose, hemicellulose and lignin. This structure contributes to the transportation of water and nutrients in the stem [14]. (B) fracture-section shows broken parts and entangled microfibrils of the fiber. It may be due to the extraction process of the fiber. Furthermore, the fiber exhibits a rough surface due to the presence of hemicellulose, lignin and waxy components present in the fiber [15].

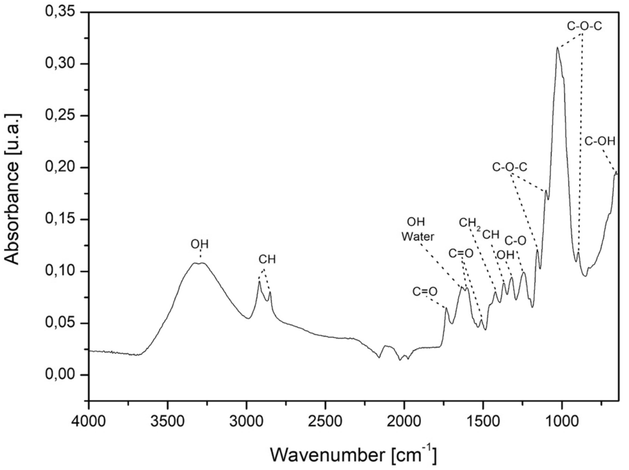

Fig. 3 FTIR spectrum of raw banana fibers, over the range of 650–4000 cm^{-1}

FTIR spectrum of raw banana fibers is shown in Fig. 3. A broad absorption band in the region of 3000–3500 cm^{-1} is associated with the presence of –OH stretching vibration found in the main organic constituents of pseudostems (α-cellulose, hemicellulose and lignin) [14]. Peaks around

2918 cm^{-1} and 2851 cm^{-1} are due to the asymmetric and symmetrical stretching modes of aliphatic –CH present in cellulose and hemicellulose [16]. Absorption bands at ~ 1733 cm^{-1} and 1244 cm^{-1}, associated with C=O and C–O stretching of the acetyl group due to hemicelluloses. The peak at ~ 1636 cm^{-1} could be attributed to –OH bending vibrations of absorbed water. The carbonyl (C=O) symmetric and asymmetric stretching conjugated with aromatic ring skeleton appears at ~ 1602 cm^{-1} and at ~ 1509 cm^{-1}, respectively, both attributed to aromatic characteristic of lignin. The absorption bands near 1423 cm^{-1} and 1367 cm^{-1} are associated with $-CH_2$ symmetric bending in lignin, cellulose and hemicellulose, and –CH symmetric deformation of cellulose and hemicellulose, respectively. The band at ~ 1319 cm^{-1} is related to the –OH in-plane deformation in cellulose [17]. The signature peak of β-glycosidic linkages of the cellulosic material is found at ~ 1155 cm^{-1} and at ~ 898 cm^{-1}, assigned to C–O–C symmetric stretching. The absorption peaks at ~ 1103 cm^{-1} and 1028 cm^{-1} arose due to the C–O–C pyranose ring skeletal vibration of cellulose [18] and asymmetric stretching of C–O–C in the cellulose and hemicelluloses [19]. The band located at ~ 655 cm^{-1} correspond to C–OH out-of-plane deformation in cellulose [20].

The α-cellulose content in the fiber and the formation of inter- and intra-molecular hydrogen bonds in the cellulose have a strong influence on its crystallinity, which in turn plays an important role on the tensile strength, elastic modulus and thermal stability of these fibers. These properties increase with increasing degree of crystallinity of the fiber. Das et al. [16] determined the degree of crystallinity (Xc) of raw fibers (*Musa sapientum L.*) by calculating the ratio of the intensities of the peaks located at ~ 1428 cm^{-1} and at ~ 898 cm^{-1} from the FTIR spectra (see Eq. 1). They obtained the value of 59%.

$$\mathrm{Xc} = I_{1428}/I_{898} \tag{1}$$

where Xc is the degree of crystallinity of the fiber.

According to Das et al. [16], the FTIR absorption band at ~ 1428 cm^{-1} is assigned to a symmetric $-CH_2$ bending vibration. This band is associated to the crystalline phase, so-called "crystallinity band". The FTIR absorption band at ~ 898 cm^{-1} is attributed to C–O–C stretching at β-glycosidic linkages, which is related to the amorphous phase, so-called "amorphous band". We have found the intensities of 0.079 for I_{142} and of 0.118 for I_{898}. As a result, we obtained the degree of crystallinity of 67% for the fiber samples. These results were shown to be higher than jute (43%) and sisal (46%) fibers, which may explain the higher mechanical strength of the banana fiber.

Table 2 shows the chemical composition of jute, sisal and banana fibers. It is noted that cellulose is the main constituent of natural fibers followed by hemicelluloses and lignin [24]. The variation in this composition occurs according to grooving (soil features, climate, aging conditions) and extraction methods conditions [21]. The contents of cellulose, hemicellulose and lignin present in banana fibers (Table 2) are very similar to those found for jute and sisal fibers [22–27], therefore do not allow any conclusion over fiber chemical content influence in mechanical data presented in Table 1.

Table 2 Reported data of chemical composition of the banana, jute and sisal fibers

Fibers	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Banana [22–27]	60–70	10–30	5–12
Jute [22–27]	50–70	12–20	5–21
Sisal [22–27]	60–74	10–20	7–11

Table 3 shows the typical FTIR absorption bands of jute and sisal found in the literature [12] and of banana fiber obtained experimentally. It is observed that the absorption bands are the same for all fibers.

Comparison between fiber absorption bands for similar functional groups in Table 3 also do not show evidence about how it could influence those fibers' mechanical properties in Table 1. However, as previously discussed in this article, the intensity of hydrogen-bond related peaks are better indication of fibers crystallinity, thus supporting its mechanical properties observed in Table 1.

4 Conclusions

Lignocellulose fibers were successfully extracted from *Musa x paradisiaca* mechanically. This study showed that there are substantial differences on the mechanical properties of banana fibers (570 MPa) in comparison to jute (249 MPa) and sisal (350 MPa) fibers, due to its high degree of crystallinity ~ 67% compared with jute (43%) and sisal (46%), even though they have similar chemical composition range and FTIR absorption bands. The obtained fibers proved to be one of the strongest natural fibers and could be used with reinforcing material in composites, as well as in packaging, clothing, carpets, ropes and also in the area of decoration and design. These preliminary testing for fiber extraction from the banana pseudostem reveal their potential applicability in the field of organic and ecological textiles and this market is continuously growing. Some of the key drivers of this growth are awareness of environmental sustainability and conservation, growing demand from emerging economies and consumer interest in clothing that uses environmentally friendly raw materials. Further tests in weaving process should be performed

Table 3 Reported FTIR absorption bands of jute and sisal fibers with experimental data of banana fibers

Functional Group	Peak range (cm^{-1}) jute fiber [12]	Peak range (cm^{-1}) sisal fiber [12]	Peak range (cm^{-1}) banana fiber [experimental]
OH stretching vibration of the water, and alcohol group	3374	3334	3000–3500
CH_2 stretching vibration	2708	3565	2887
Aromatic CH stretching vibration	2708	3298	2918, 2851
C=O stretching of the carbonyl group of lignin	1731	1754	1733
Aromatic ring skeletal vibration	1603, 1506	1721, 1456	1602, 1509
CH_2 bending	1459, 1355	1552, 1455	1423–1367
Phenolic CO of the lignin	1239	1119	1244
C–O–C stretching vibration	1067	1135	1028, 898

in order to produce ecological fabrics on a pilot scale and evaluate their properties, such as thermal, mechanical and wearability.

Acknowledgements The authors gratefully acknowledge the engineering department of materials of the University of São Paulo (USP São Carlos) by the provided infrastructure.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Patel R (2013) The long green revolution. J Peasant Stud 40(1):1–63
2. Nations U (1987) Report of the world commission on environment and development: our common future. Oslo: United Nations
3. Fashion United (2017) Sustainable textile innovations: coffee ground fibre. https://fashionunited.uk/news/fashion/sustainable-textile-innovations-coffee-ground-fibre/2017061624856
4. Innovation In Textiles (2012) Bio-polyester used in mass produced electric car. https://www.innovationintextiles.com/biopolyester-used-in-mass-produced-electric-car/
5. Andrade P (2017) Análise da conjuntura agropecuária safra 2016/17. Secretaria da Agricultura e do Abastecimento, pp 1–9
6. Junior IPB, Oliveira SS, Lima IG, Gomes A, Masuko FK, de Oliveira MG (2018) Preço na bananicultura: um estudo dos fatores que influenciam o preço da banana da região do Vale do Ribeira/sp. Revista Gestão em Foco-Edição 10:88–100
7. Lewin M (2006) Handbook of fiber chemistry. CRC Press, Boca Raton
8. Vigneswaran C, Pavithra V, Gayathri V, Mythili K (2015) Banana fiber: scope and value added product development. J Text Appar Technol Manag 9(2):1–7
9. Pereira TVC, Fidelis MEA, Gomes ODFM, de Andrade Silva F, Filho RDT (2012) Investigação da influência morfológica via análise de imagens na resistência à tração de fibras naturais. In: 67° ABM International Congress, Rio de Janeiro, pp 4172–4184
10. Pires EN, Merlini C, Al-Qureshi HA, Salmória GV, Barra GM (2012) Efeito do tratamento alcalino de fibras de juta no comportamento mecânico de compósitos de matriz Epóxi. Polímeros Ciência e Tecnologia 22(4):339–344
11. Zafar MT, Maiti SN, Ghosh AK (2015) Effect of surface treatment of jute fibers on the interfacial adhesion in poly(lactic acid)/jute fiber biocomposites. Fibers Polym 17(2):266–274
12. Boopalan M, Umapathy MJ, Jenyfer P (2012) A comparative study on the mechanical properties of jute and sisal fiber reinforced polymer composites. Silicon 4:145–149
13. Idicula M, Neelakantan NR, Oommen Z, Joseph K, Thomas S (2005) A study of the mechanical properties of randomly oriented short banana and sisal hybrid fiber reinforced polyester composites. J Appl Polym Sci 96(5):1699–1709
14. Pereira ALS, Nascimento DM, de Sá M, Filho MS, Cassales AR, Morais JP, Paula RC, Feitosa JP (2014) Banana (Musa sp. cv. Pacovan) pseudostem fibers are composed of varying lignocellulosic composition throughout the diameter. BioResources 9(4):7749–7763
15. Deepa B, Abraham E, Cherian BM, Bismarck A, Blaker JJ, Pothan LA, Kottaisamy M (2011) Structure, morphology and thermal characteristics of banana nano fibers obtained by steam explosion. Bioresour Technol 102(2):1988–1997
16. Das D, Hussain S, Ghosh AK, Pal AK (2018) Studies on cellulose nanocrystals extracted from *Musa sapientum*: structural and bonding aspects. Cellul Chem Technol 52(9–10):729–739
17. Das D, Mukherjee M, Pal AK, Ghosh AK (2017) Extraction of xylem fibers from *Musa sapientum* and characterization. Fibers Polym 18(11):2225–2234
18. Pappas C, Tarantilis PA, Daliani I, Mavromoustakos T, Polissiou M (2002) Comparison of classical and ultrasound-assisted isolation procedures of cellulose from kenaf (*Hibiscus cannabinus* L.) and eucalyptus (*Eucalyptus rodustrus* Sm.). Ultrason Sonochem 9(1):19–23
19. Johar N, Ahmad I, Dufresne A (2012) Extraction, preparation and characterization of cellulose fibres and nanocrystals from rice husk. Ind Crops Prod 37(1):93–99
20. Etaati A, Pather S, Rahman M, Wang H (2015) Ground hemp fibers as filler/reinforcement for thermoplastic biocomposites. Adv Mater Sci Eng 2015:513590
21. Bongarde US, Shinde VD (2014) Review on natural fiber reinforcement polymer composites. Int J Eng Sci Innov Technol 3(2):431–436
22. Marella JBR, Madireddy S, Maripi AN (2014) Production of pulp from banana pseudo stem for grease proof paper. Int J Eng Res Gen Sci 2(1):1–17
23. Sánchez C (2009) Biotechnology advances 27°. Lignocellulosic residues: biodegradation and bioconversion by

fungi. Research Centre for Biological Sciences, Universidad Autónoma de Tlaxcala, Tlaxcala, pp 185–194

24. Pujari S, Ramakrishna A, Kumar MS (2014) Comparison of jute and banana fiber composites: a review. Department of Mechanical Engineering, A.U College of Engineering, Visakhapatnam, Andhrapradesh, India. Department of Mechanical Engineering, Vardhaman College of engineering, Hyderabad, Andhrapradesh, India
25. Khan MZH, Sarkar MAR, Ibne F, Al Imam MD, Malinen A (2013) Fiber morphology and pulping study of banana pseudo-stem. Int J Fiber Text Res 3:31–35
26. Fávaro SL, Ganzerli TA, Neto AGVC, Silva ORRF, Radovanovic E (2010) Chemical, morphological and mechanical analysis of sisal fiber-reinforced recycled high-density polyethylene composites. eXPRESS Polym Lett 4(8):465–473
27. Mwaikambo LY, Ansell MP (2002) Chemical modification of hemp, sisal, jute, and kapok fibers by alkalization. J Appl Polym Sci 84(12):2222–2234