v. 4, n. 27, 2024

Journal of
**Engineering
Research**

Acceptance date: 28/11/2024

PIASSAVA FIBER: PRODUCTION CHAIN, PROPERTIES AND APPLICATIONS - A REVIEW

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DOI https://doi.org/10.22533/at.ed.3174272407118

Abstract: This review article investigates the production chain of piassava fiber, a natural fiber from different locations in Brazil, the two main ones being the *Attalea funifera* palm, found in the Atlantic rainforest of Bahia, and the *Leolpodinia Piassaba*, found in the Amazon rainforest in the Barcelos region. The article brings together analyses of the properties that make Piassava a valuable material for use in composites. Initially, the fundamental concepts related to the fiber are discussed, followed by a detailed analysis of the extraction and treatment process, which includes the cleaning and selection stages, carried out predominantly by women in local communities. The article also discusses the physical, mechanical and chemical properties of piassava, highlighting how these characteristics influence its use in composites and other materials. Studies show that the compressive and flexural strength of piassava composites can be optimized through treatments that improve adhesion between the fibre and the polymer matrix. In addition, the challenges faced in the production chain are presented, such as the variability in fiber quality and the need for appropriate chemical and physical treatments to improve mechanical performance. Finally, the article suggests directions for future research, emphasizing the importance of piassava as a sustainable alternative in a context of growing demand for environmentally friendly materials. It concludes that, with proper development, piassava fiber can play a significant role in the construction industry and other applications, promoting more sustainable and innovative practices.

Keywords: Piassava fiber, Sustainability, Natural composites.

INTRODUCTION

The growing demand for sustainable materials in construction has driven research and development into alternatives that reduce environmental impact and promote the efficient use of natural resources. In this context, plant fibers have stood out as a promising option due to their abundance, biodegradability and suitable mechanical properties for various applications. Among these fibers, Piassava fiber, obtained from palm trees native to Brazil, draws attention for its strength, durability and potential for reinforcement in composites and cementitious materials.

Despite this, its use remains predominantly in artisanal and low value-added uses, such as handicraft products, brooms and brushes. Compared to studies and applications of other fibers, Piassava is lagging behind in technological research.

This review article discusses the physical and chemical characteristics, mechanical properties and performance of Piassava fiber in different processes and applications, highlighting its role in the construction industry and in research into composite materials. The aim of this review is to serve as a theoretical basis for future applications of Piassava, as a starting point for researchers. By bringing together the various properties and possible applications suggested by different scientists in the field, the article points the way and suggests new scientific investigations.

The first section deals with crucial concepts on the subject, providing a theoretical framework for reading. This is followed by an overview of piassava fiber, covering advances and obstacles. This is followed by a discussion of the process of extracting and treating the fiber, pointing out the physical and chemical properties that are acquired through the various production routes for the material. Finally, the properties of the fiber and some of its industrial applications to date are highlighted.

Figure 01 - Piassava of the species Attalea funifera. Source: Amaral (2015)

BACKGROUND

NATURAL FIBERS

Natural fibers are renewable resources derived from plants or animals, offering advantages such as low cost, lightness, biodegradability and high specific properties (Luna & Lizarazo-Marriaga, 2022). They are classified into six main types: stem, leaf, seed, heartwood, grass and reed fibers, as well as other fibers such as wood and roots (Rowell, 2008). Natural fibers are increasingly used as reinforcement in composite materials due to their ecological nature, low carbon footprint and potential to create fully biodegradable composites. Often obtained as by-products of other processes, these fibers are more economical than high-performance synthetic fibers (Kotik, 2019). Natural fibers have varied mechanical, thermal and morphological properties, which influence their selection for specific applications and manufacturing processes. Their use in industrial parts is driven by the global demand for environmentally sustainable materials with shorter decomposition times compared to synthetic alternatives (Espinosa et al., 2019).

COMPOSITES

Composites are combinations of two or more materials, consisting of a matrix and one or more reinforcements. There are various types of composites, including glass fiber reinforced plastic (Queiroz et al., 2021), wood-cement (Castro, 2021), FGD plaster with cork and textile fibers (Camões et al., 2010), and geopolymers reinforced with quasicrystal particles (Barroso, 2009). Composites can offer advantages such as lightness, elasticity and resistance to fungi and termites (Castro, 2021). However, they also face challenges such as environmental degradation (Francisco Alisson de Queiroz et al., 2021) and compatibility between materials (V. Castro, 2021). Research into composites seeks to develop sustainable materials with improved mechanical properties for applications in construction and other industries (Camões et al., 2010; Barroso, 2009).

PIASSAVA FIBER

The *Leopoldinia piassaba* palm species, native to the Rio Negro Basin in the Amazon, is especially renowned for its fibres, which are used in broom making, rope production and as reinforcement in composite materials (Smith, 2022). Brazil has abundant resources of piassava fibers, especially in northeastern states such as Bahia, where *Attalea funifera* is endemic to the Atlantic Forest biome, shown in Figure 1 (Pimentel & Del Menezzi, 2020). This palm has traditionally been used by indigenous and quilombola communities, and currently involves large-scale cultivation practices and extractive activities (Pimentel, 2015). In addition, the western Amazon is home to *Aphandra natalia*, another source of piassava fibers (Kronborg et al., 2008). Figure 2 shows the extraction of the fiber, while Figure 3 indicates the locations of the piassava palm species.

Figure 02 - a) Piassava fiber; b) Sludge. Source: Guimarães (2012).

Figure 3. Map of the distribution of the three piassaba species in South America (Kronborg, 2008)

Despite Brazil's leadership in the production of natural fibers, the piassava industry remains underdeveloped. Improvements in processing techniques and market access could raise the income of agro-extractivists from R$360-600 per month to an estimated net gain of R$1,664.63 per month (Pimentel, 2015). However, unsustainable extraction methods in some regions threaten the availability of this resource (Kronborg et al., 2008). In order to maximize the economic and environmental benefits, it is essential to explore various applications for piassava and its by-products.

Recent studies have investigated the role of piassava fibers as reinforcements in polymer and cement matrix composites. Spectroscopic and morphological analyses have validated the rough surface and hydrophilic nature of these fibers (Fabio da Costa Garcia Filho et al., 2020). However, the incompatibility between fiber and matrix is a significant challenge, addressed through various surface treatments. For example, treatment with graphene oxide showed a significant improvement in the interfacial adhesion of piassava fibers with epoxy resin (Luz et al., 2021). In addition, treatment with sodium lignosulfonate proved effective in removing extractives and increasing fiber strength (Agrize et al., 2023).

Piassava fibers have attracted attention for their potential as reinforcements in polymer matrix composites. These fibers have a composite-like structure, with cellulose microfibrils embedded in lignin and hemicellulose, as well as silica deposits on the surface (Elzubair et al., 2007). Morphological analysis revealed rough surfaces with noticeable bumps, and Fourier transform infrared spectroscopy (FTIR) confirmed their hydrophilic nature (Fabio da Costa Garcia Filho et al., 2020).

Alkaline modification using sodium hydroxide (NaOH) has the potential to improve water retention and reduce air content in cementitious composites (Azevedo et al., 2022). These treatments seek to mitigate the hydrophilic properties and surface heterogeneity of piassava fibers, differentiating them from synthetic alternatives. Figure 4 shows the different types of treatments applied to natural fibers.

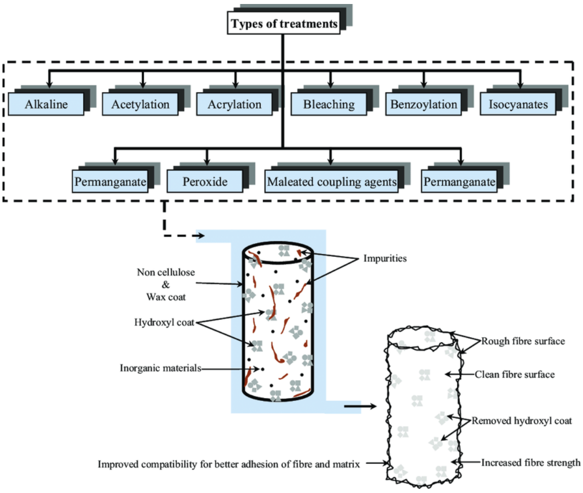


Figure 4. Different types of treatments on natural fibers and its result illustration (Nirmal, 2014).

In order to deepen our knowledge of these fibers, advanced characterization techniques such as X-ray diffraction and thermal analysis have provided valuable information on the structural properties of piassava fibers and their interactions with matrix materials, helping to optimize the performance of composites (d'Almeida et al., 2006). An example of X-ray diffraction for a piassava fiber is shown in Figure 5.

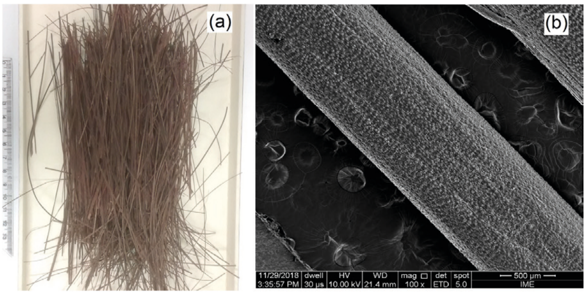


Figure 5. Piassava fiber: (a) bundle of as-received fibers and (b) SEM surface aspect of a fiber. (Garcia Filho et al. 2020).

In addition, studies on the incorporation of natural fibers into soil-cement mixtures have shown promising results, especially in improving mechanical properties and promoting environmental sustainability. For example, the addition of palm fibers to soil-cement mixtures has shown significant improvements in compressive strength (54.71%-68.38%) and California Bearing Ratio (CBR) values (1.91%-43.39%), with 5% fiber content in relation to the weight of cement identified as ideal (Suroso et al., 2013). Similarly, research into sisal fibers in self-compacting soil-cement composites has shown improvements in post-peak behavior, strength and deformation capacity, with increases in flexural and residual strengths, transforming the behavior of the composites from brittle to ductile (Martins et al., 2014).

The incorporation of natural and synthetic fibers into clay soils has also been shown to significantly improve their mechanical properties. Research indicates that fiber reinforcement can increase the unconfined compressive strength, stiffness and ductility of clay-fiber mixtures (Attom et al., 2009; Fatahi & Khabbaz, 2012). Natural fibers such as wheat straw, palm leaves and Imperata cylindrica have been shown to increase compressive strength by up to 126% and internal friction angle by up to 42% with optimal fiber content and length (Abood & Shakir, 2023). Furthermore, the addition of fibres to fly ash-stabilized soils improved geotechnical properties, with CBR values increasing by 40-50% and reductions in volume variation of up to 94.4% (Zafar et al., 2023). These improvements make fiber reinforcement a cost-effective and environmentally friendly technique for soil stabilization, especially beneficial for expansive clays and weak soils in geotechnical engineering. Given the benefits of natural fibres in soil stabilization, piassava fibres can be a valuable reinforcement material. Their unique properties can increase soil strength and stability, in line with sustainability objectives.

Therefore, this review examines the physical, mechanical and chemical properties of piassava fibers to evaluate their potential in a variety of industrial applications. Regarding the comparison between synthetic and natural fibers, we suggest that this be the subject of future research, as it is crucially important to obtain more information on the use of fibers and their differences, comparing them and presenting new possibilities for natural fibers that are already being used by synthetic fibers, such as reinforcing concrete, for example.

THE FIBER PRODUCTION CHAIN

ATTALEA FUNIFERA PRODUCTION

The raw vegetable fiber of Piassava *Attalea Funifera* is extracted from palm trees that are around ten years old, when the plants enter the stage known as "banana production". At this stage, exploitation can begin. By following good management practices, the palm trees continue to provide raw fibers, as illustrated in Figure 6, until they die, already in the "coconut tree" stage. This product is collected and sold in the south of Bahia, where agro-extractivists, producers and middlemen transport it to broom factories located in the states of Rio de Janeiro, São Paulo, Espírito Santo and Minas Gerais (Pimentel 2020).

Figure 6. a) Extraction of raw fiber; b) weighing; and c) storage ("mondongos") of raw fiber (Pimentel 2020).

Clean vegetable fiber results from the pre-processing of raw fiber and generates a by-product known as "ribbons", as well as waste that does not meet market standards. This process involves manually separating the fibers and ribbons, using tools such as a machete, brush and metal comb, as shown in Figure 7. Locally, this stage is called "cata" and is predominantly carried out by women known as "catadeiras". These workers work in "family pickers" (Pimentel 2020).

Figure 7. a) Comb for cleaning; and b) transportation of clean vegetable fiber (Pimentel 2020).

The amount of waste generated is directly related to the rigorous cleaning and selection required by the middlemen. On the other hand, less waste being generated at this stage could be a strategy by the extractivists to increase their profits from producing clean fiber.

When it comes to separating fibers and ribbons, it takes the pickers an average of 5.9 minutes to transform 1 kg of raw fibers into clean fibers and ribbons (Pimentel 2020). Thus, the average daily productivity of a "picker" is around 80 kg of raw vegetable fiber per day per person (Pimentel 2020).

Chopped vegetable fiber refers to piassava destined for export and is obtained after processing the clean fiber. This stage involves reopening the clean piassava bales to reselect the fibers based on their thickness and length, as well as discarding the waste and coarse fibers. The equipment used in this process includes combs for cleaning and adjusting the direction of the fibers, guillotines for cutting the fibers to the desired lengths, machetes, hatchets, scales and small tools for maintenance.

The cuts can vary between 13 cm and 37 cm. The fibers are classified as fine-medium and coarse-medium (marketable) and coarse (non-marketable). In Brazil, the first two thicknesses are used to make piassava brooms, while the coarse fibers are discarded due to their tendency to break when folded and attached to the broom stump. The selection and separation process is illustrated in Figure 8.

Figure 8. a) Selection and cleaning; b) stapling of clean vegetable fiber; c) "stump" brooms; and d) brooms sheet (Pimentel 2020).

The time needed to cut 1 kg of clean vegetable fiber is approximately 11.2 minutes. Thus, in a total period of 2 hours and 48 minutes, the extractivist manages to process 15 kg of clean fiber. Taking into account the additional time needed to prepare the cut (12 minutes for every 15 kg), the extractivist's productive capacity reaches around two and a half arrobas (37 kg per day per person) of piassava plant fiber during a working day (Pimentel 2020).

LEOPOLDINIA PIASSABA PRODUCTION

The production chain for *Leopoldinia piassaba* fiber involves several players, from the piassaveiros who collect the fiber in the forest to the traders who sell it in local markets and to industries in Manaus. The fiber is stored in warehouses before being transformed into products such as brooms and mops, with 90% of the production sold in Manaus and only 10% exported to other states. Piassava is harvested all year round, with sustainable practices that minimize environmental impacts, and handicraft production is an important source of income for local communities (Guimarães et al. 2021).

The collection of piassava in the state of Amazonas differs from that in the state of Bahia, where it is extracted from the genus *Attalea funifera*. The production chain is made up of the so-called piaçaveiros collectors (extractivists), who enter the forest and remain isolated for several days, especially at harvest time. This process takes place throughout the year, ensuring that there are no interruptions in the sale of the fiber. In the forest "retreats", the piaçaveiros carry out activities such as cutting, combing and tying the piassava, which require skill and endurance. A good piassaveiro can collect up to 50 kg of fiber a day, although the amount collected depends on their age and physical condition. To achieve this amount, it is necessary to cut down 30 to 40 plants a day, a job that requires intense physical effort and in-depth knowledge of the forest (Guimarães 2021). Photos from collection to transportation are illustrated in Figure 9.

Figure 9- Piassava collection and transportation. A) "Combed" piassava fiber; B) Piassava tied up in "logs"; C) Community members weighing the piraíbas; D) Piassava ready for Igarapé; E) Piassava embarked (Guimarães et al. 2021).

The relationship between piaçaveiros and patrons is based on the aviamento system, an exchange model in which, instead of cash, trade is carried out through goods supplied by patrons - who can be local or foreign agents. In this system, piaçaveiros receive supplies and inputs necessary for their subsistence and work, while handing over piassava production in exchange. In terms of environmental impact, piassava extraction causes minimal damage, but is not completely free of effects. However, a relevant aspect is the fact that harvesting takes place in specific forest fragments, which allows for the practice of sustainable and careful management of piassava, promoting the conservation of the plants and the local ecosystem. Figure 10 shows a schematic of the production chain.

FIBER TREATMENT

Treatments applied to the fibers are an alternative for reducing the lignin content of the fibers, such as hornification and applications of NaOH (sodium hydroxide) solutions. They increase the surface roughness of the fibers, leading to greater adhesion. They also reduce the absorption of the fibers, as they make them more hydrophobic (Juarez, 2007; Asasutjarit, 2009; Ozerkan, 2013).

The untreated piassava fiber shows deformations between 6 and 10 mm in length. This result is associated with the amount of lignin present in the piassava fiber (45.68%), since this component is a stiffener and a chemical adhesive acting inside and between the fibers, therefore, according to Razera (2006), Souza (2015) and Yan et al. (2014) this chemical element is responsible for the great rigidity conferred to Piassava.

In addition, chemical treatments remove dirt and part of the lignin impregnated in the fibrils, increasing water absorption by the fibers, as they expose OH (hydroxyl) groups belonging to the cellulose. Water absorption is increased by removing hydrophobic substances, exposing hydrophilic sites (Fonseca, 2021).

According to Fonseca (2021), the piassava fiber treated with hot water and hornification showed the highest crystalline peaks on the 002 (crystalline) planes, with intensities of 1973 and 2087 respectively, as well as more pronounced amorphous halos than the other treatments.

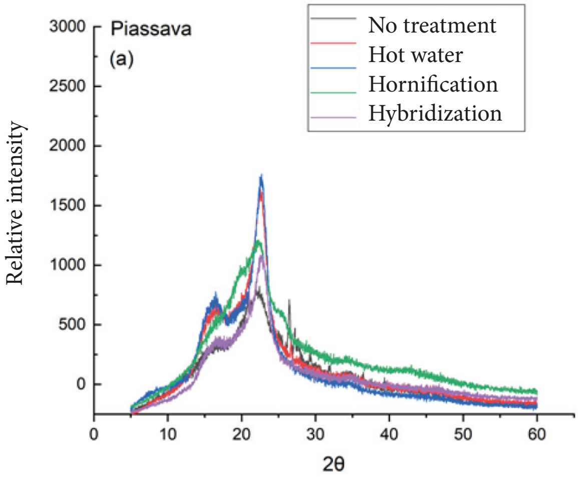


Figure 11. X-ray diffractograms of untreated and treated Piassava (adapted from Fonseca 2021).

The author also records how the crystallinity index of Piassava fiber varies according to the treatment adopted. Table 1 shows the results of the fiber's crystallinity index and proves the effectiveness of the hot water, NaOH and hornification treatments for Piassava fibers. The treatments increased the fiber's crystallinity index by 30%, 25.11% and 20.31% respectively. In addition, the treatments implemented removed part of the amorphous material from the fibers, providing greater packing of the cellulose chains. Thus, it can be said that the treated fibers will have a better interaction with the cementitious matrix (Fonseca 2021).

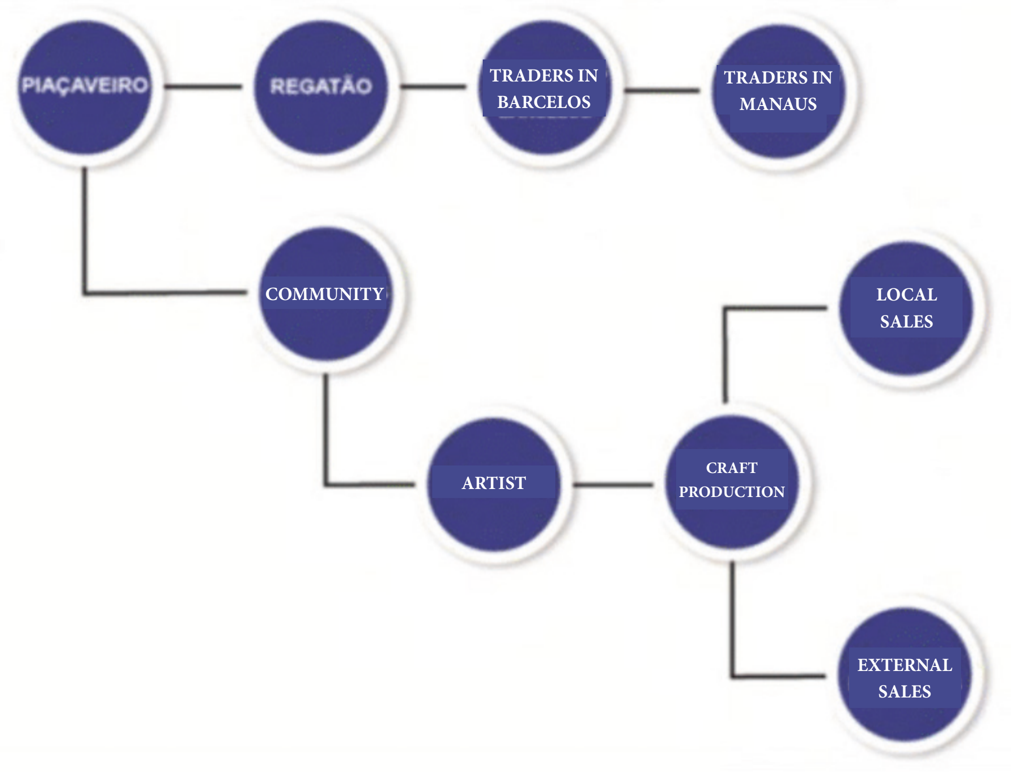


Figure 10 - Piassava production chain (Guimarães et al. 2021)

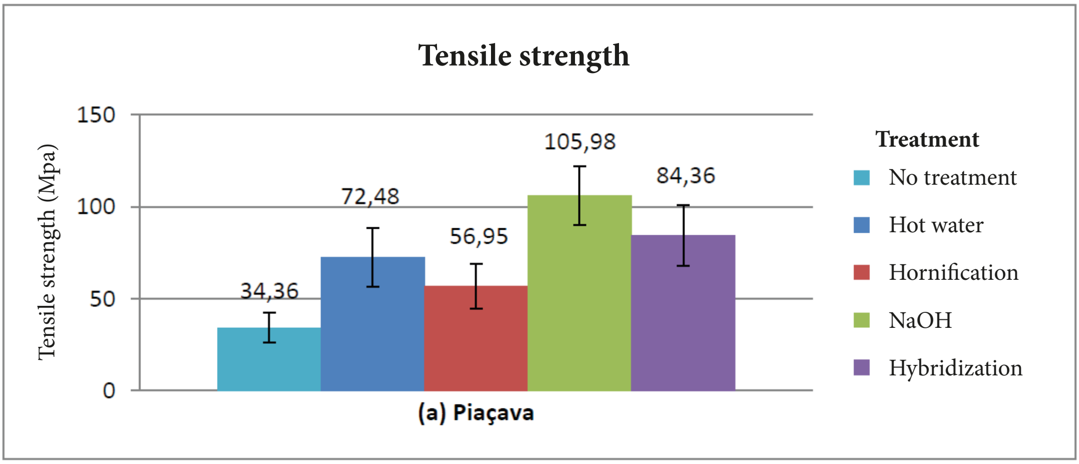


Figure 12. Tensile strength of untreated and treated Piassava fibers (adapted from Fonseca 2021)

Fiber	**Treatment**	**Crystallinity index C.I.(%)**
Piassava	No treatment	39,83
	Hot water	51,80
	Hornification	47,92
	Sodium hydroxide	49,83
	Hybridization	44,96

Table 1: Crystallinity index of treated and untreated Piassava fibers (adapted from Fonseca 2021).

According to the study carried out by Fonseca (2021) on natural fiber composites, for the tensile strength parameter, treatment with sodium hydroxide stands out, followed by hybridization, washing with hot water, hornification and untreated fibers, as can be seen in Figure 12 below.

Table 2 shows the specific mass measurements of the plant fibers before and after the treatments applied. It was observed that the hornification treatment on jute, tucum and razor grass fibers slightly reduces the specific mass, as properties linked to density tend to decrease with the modification of internal bonds. In contrast, treatments with NaOH and hybridization result in an increase in fibre density. Doshi and Dyer (2001) explain that alkaline treatments can increase fiber density by removing non-cellulosic components such as lignin, which, according to Ouarhim et al. (2019), has a relatively low density.

Fiber	Treatment	Liquid	Specific mass g/cm^3
Piassava	No treatment	Canola oil	1 ± 0,12
	Hot water		1,12
	Hornification		1,12
	Sodium hydroxide		1,14
	Hybridization		1,15

Table 2: Specific mass of piassava plant fibers (adapted from Fonseca 2021).

According to Kammoun and Trabelsi (2019), the decrease in compressive strength of plant fibers in a cementitious matrix may be related to the low mechanical strength of the inclusions, the increase in porosity in the matrix due to the entry of air or the lower fiber/matrix adhesion. In addition, for contents of less than 5%, Fonseca (2021) concludes that the higher the percentage of fiber, the lower the compressive strength of the composites, as can be seen in Figure 13. When it comes to flexural strength, the behavior is the opposite. Higher percentages of fibers have higher flexural strengths due to the tensile stresses exerted by the fibers, as reported by Rao and Ramakrishna (2020).

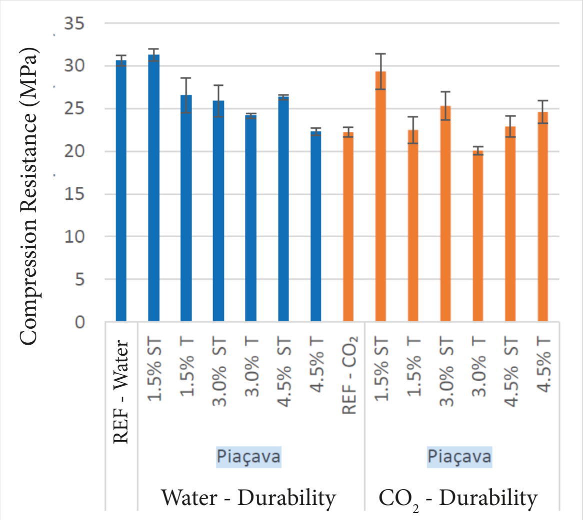


Figure 13 - Compressive strength of composites-after durability cycles. REF - no fibers, ST - untreated fibers and T - fibers treated in water curing and in a CO2 autoclave.

Although the compressive strength is reported to be lower for the composites studied by Fonseca and the treated fibers theoretically have a greater adhesion surface and more roughness for interlocking, the untreated fiber with a percentage of 1.5%, as shown in Fonseca's graph, shows an increase in compressive strength with the fiber.

The structure of the fibers after treatment, with surface protrusions, contributes to minimal fiber detachment and improves the performance of the composite during mechanical tests; after bending limits, the composites continue to withstand load without sudden rupture and with high deformation, especially for composites with piassava fibers (Fonseca, 2020). Thus, the treatment of piassava improves its mechanical properties, and the best treatment depends on the industrial application for which it is intended.

PHYSICAL, MECHANICAL AND CHEMICAL PROPERTIES OF PIASSAVA FIBERS

Natural fibers have gained prominence in the construction industry due to their sustainability, biodegradability and abundant availability. These fibers are known for their unique properties, such as low density, high flexibility and significant tensile strength, which makes them suitable for reinforcing materials in a variety of applications. From a chemical point of view, the composition of these fibers, including cellulose, hemicellulose and lignin, directly influences their mechanical behavior and durability. This diversity of characteristics makes natural fibers an attractive and environmentally responsible alternative to synthetic fibers, especially in areas such as paving and construction.

In addition to their sustainable advantages, natural fibers have shown great potential for increasing the strength and stability of soils and building materials. Mechanical properties such as tensile strength, modulus of elasticity and elongation are essential for assessing their effectiveness in reinforcing structures. Fibers such as piassava, for example, can be used to improve the performance of subgrade layers in paving, increasing durability and reducing soil deformation. These properties, combined with their low environmental impact and economic viability, make natural fibers an innovative solution for meeting sustainability demands in the construction sector. Table 3 presents a review of the properties presented by the most common natural fibers on the market, cited by Saheb (1999), Franco (2024), Gomez (2024), Elfaleh (2023), Dittenber (2012) and Monteiro (2009).

PROPERTIES OF *ATTALEA FUNIFERA*

The properties of piassava fiber from the genus *Attalea Funífera* were investigated and cited by Garcia et al. (2020), with its basic characteristics presented in Table 4 and its heat treatment shown in Figure 14.

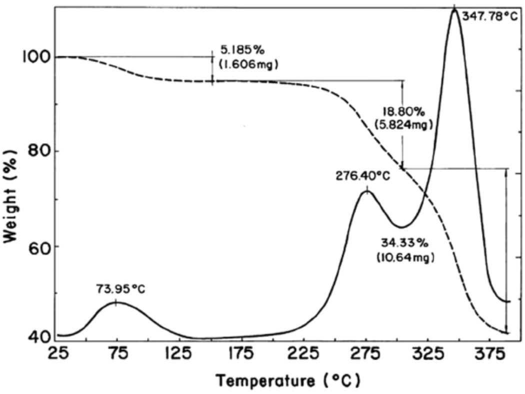


Fig. 14 - TGA and DTG curves of Piassava fibers.(D'Almeida 2006)

Figure 13 shows the distribution of the length and effective diameter of randomly selected fibers. From this distribution, an average length of 454.64 mm and an average effective diameter of 0.92 mm were obtained. In addition, the maximum relative frequency for the length distribution was 29%, while for the effective diameter distribution it was 25%. These results differ considerably from those reported by Elzubair et al. (2007) for effective diameter and by Aquino et al. (2003) for fiber length.

Fiber	Diameter (µm)	Density (g/cm3)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Moisture Absorption (%)	Cellulose (wt%)	Lignin (wt%)
Abaca	10-30	1.5	430-813	31.1-33.6	2.9-10	-	53-63	7-9
Bagasse	-	1.2-1.5	20-290	17-27.1	1.1	-	41-55	22-25
Bamboo	88-125	1.1	140-503	11-36	1.4	-	26-43	1-31
Banana	100-250	1.35	529-914	27-32	2.60-5.90	-	83	5
Basalt	17	2.8	4800	90	3.15	-	-	-
Coconut Coir	12-14	1.1-1.6	106-593	1.27-6	14.21-59.9	-	32-43	40-45
Cotton	-	1.5	287-597	5.50-12.60	0.3-10	8-25	82.7-92	0
Flax	25	1.5	344-1500	27-80	1.2-3.2	7	64.1-71.9	2-2.2
Hemp	25-600	1.48-1.5	550-900	70	1.6-4	8	70.2-74.4	3.7-5.7
Henequen	-	1.2-1.4	430-570	10-16.3	3.7-5.9	-	70-77.6	8-13.1
Jute	25-250	1.3-1.5	393-800	0.1-55	1.16-1.80	12	58-63	12-14
Kenaf	-	1.25-1.4	284-930	0.13-26.5	1.16-1.80	-	45-57	21.5
Pineapple (Leaf)	50	1.44-1.5	170-1672	60-80	14.50	-	70-82	5-12.7
Ramie	20-280	1.3-1.5	400-938	61.4-128	3.6-3.8	12-17	62-85	0.5-9
Rice Husk	-	0.5-0.7	-	-	-	-	35-45	20
Sisal	50-200	1.3-1.5	390-635	9.4-41	2-14	10-22	60-78	8-14
Softwood	-	1.50	1000	40	-	-	30-60	21-37
Sunhemp	-	1.07	389	35	-	-	70-78	4-5
Viscose Cord	-	-	-	-	-	-	-	-
Glass Fiber-E	-	2.5	3400	72	-	-	-	-
Kevlar	-	1.44	3000	-	2.5-3.7	-	-	-
Piassava	250-700	1.1-1.6	119-147	5.6-6.9			28.60	45

Table 3: Mechanical and organic properties of the most common natural fibers on the market

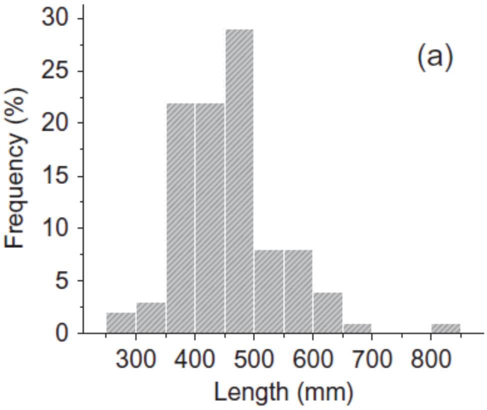
*Literature varies about some values, so we showed the interval of the range.

Physical		Morphological		Chemical		Mechanical	
Density (g/cm3)	Critical Length (mm)	Protrusion size (microm)	Average Diameter (mm)	Cellulose (%)	Lignin (%)	Tensile Strength (MPa)	Elastic Modulus (GPa)
1.10-1.45	15.3(in epoxy)	10-30	0.20-2.45	31.6	48.4	109-1750	5-6

Table 4 - Basic properties of the Piassava fiber (Garcia et al. 2020)

Like other natural fibers, piassava has non-uniform dimensions, attested to by the roughly bell-shaped distributions presented so far, which vary according to the type of extraction and selection used in the production chain. In particular, the average effective diameter, inferred from the histogram of Elzubair et al. (2007), of around 0.53 mm, is 58% smaller than that obtained in this study from Figure 15.

Another original finding from Monteiro's work (2009) related to the results in Figure 15 is the tendency for longer fibers to have a larger effective diameter. Although statistical proof is still needed, this trend is of practical importance for selecting fibers to be used as reinforcements in composites.



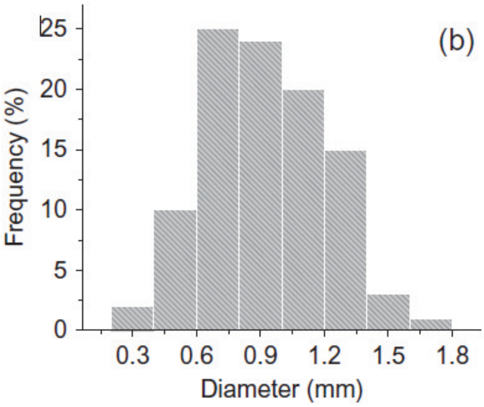


Figure 15: Statistical distribution of length (a) and diameter (b) of the lot of Piassava fibers (Monteiro 2009)

When it comes to the fiber surface, Figure 16 shows a typical Piassava fiber surface, which is partially covered by parenchyma cells and has protruding spiny spherical bodies that have been well described in many articles (Aquino et al. 2000a; Monteiro et al. 2001; Aquino 2003; Aquino et al. 2003b; Suarez et al. 2003; Aquino et al. 2004b, 2004c; Deus et al. 2004a; Bonelli et al. 2005; Elzubair et al. 2005; d'Almeida et al. 2006; Monteiro and Rangel 2006; Monteiro et al. 2006a; Elzubair et al. 2007; Monteiro et al. 2007). It has been suggested (d'Almeida et al. 2006) that these silicon-rich spiny protrusions could help in the mechanical interconnection of a fiber with the polymer resin matrix in a composite. In fact, computer simulations of the polymer matrix interface of Piassava fiber support this idea (Monteiro and Rangel 2006).

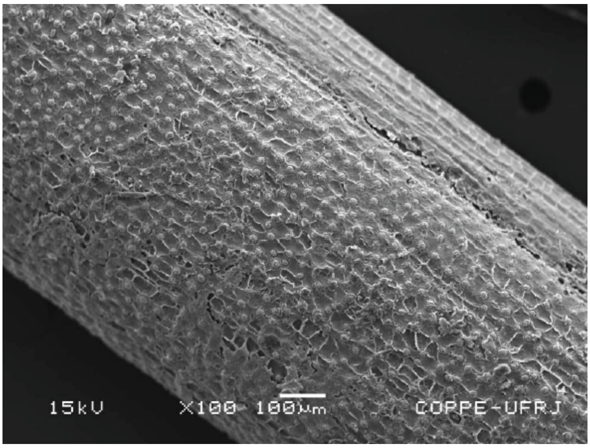


FIGURE 16 General aspect of an *Attalea funifera* Piassava fiber.

Despite all the information, there is one point highlighted by Monteiro (2009). The spiny protrusions are not perfectly fixed to the surface of the fiber. In other words, they can be torn off when subjected to abrasion, mechanical restriction or chemical attack. This is clearly indicated in the work of Elzubair et al. (2007) for desilted Piassava fiber. Figure 17 illustrates, at two different magnifications, some holes left in the surface of a Piassava fiber in the condition in which it was received from a broom industry. The detachment of the spiny protrusions responsible for the holes in Figure 17 was probably caused by the normal handling operations associated with extracting, transporting and storing the fibers. The reason for this relatively easy removal of a spiny protrusion is related to its silicon-rich nature, which confers a hard and brittle behavior typical of most ceramic materials. A hard and brittle bioceramic body embedded in a relatively soft and plastic lignocellulosic biomaterial tends to detach whenever the appropriate mechanical or chemical conditions occur. If, instead of a protruded body, the surface of the fiber has a hole, the reinforcing effect is impaired, due to the nucleation of cracks at the fiber-matrix interface by stress concentration in the geometric depression (Monteiro and Rangel 2006).

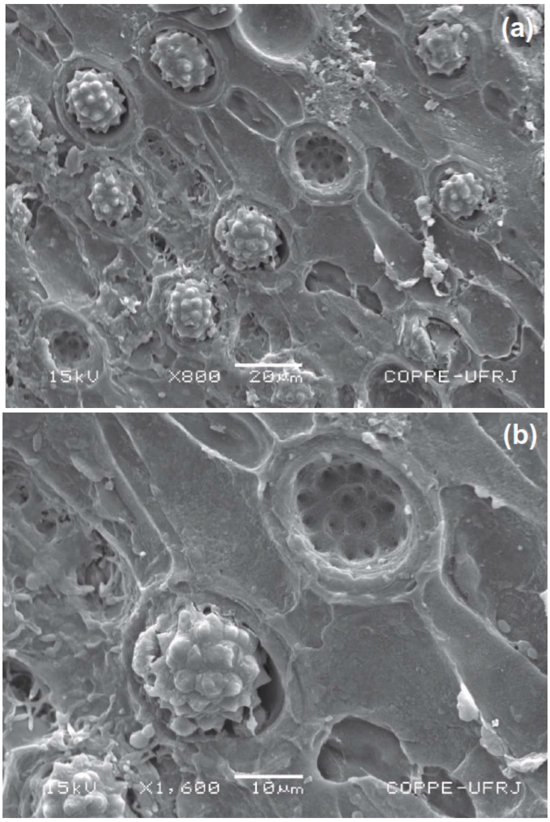


FIGURE 17 *Attalea funifera* Piassava fiber showing protrusions and holes at different magnifications.(a) 800x and (b) 1600x.

INDUSTRIAL APPLICATIONS OF PIASSAVA FIBERS

Fibers have many applications in technological fields today. Piassava fibers have some research in the area, which will be summarized in Table 5 along with other fiber applications. It is clear that although there are few applications for Piassava fibers compared to other fibers, the table can suggest new research topics and new applications considering fibers with similar properties, properties discussed in this review article. The main advantages of using Piassava fibers in polymer composites include their ability to improve mechanical properties, sustainability and low cost. Piassava fiber has a high tensile strength and good elasticity, which contributes to the durability of composites, making them comparable to traditional materials such as plywood and chipboard (Aquino, 2000). In addition, because it is a natural fiber, Piassava is biodegradable and comes from renewable sources, which makes it an environmentally friendly alternative to synthetic fibers (D'Almeida et al., 2006). The use of Piassava fibers can also reduce the weight of composites, improving their manageability and efficiency in industrial applications. Finally, the inclusion of compatibilizing additives can optimize adhesion between the fibre and the polymer matrix, resulting in superior mechanical performance (Passatore et al., 2014).

CONCLUSION

Piassava fibers present significant challenges and limitations in their application in polymer composites, which include incompatibility with polymer matrices, issues related to durability and degradation, and the need for further research to optimize properties. Incompatibility with polymeric matrices is one of the main obstacles, as Piassava fibers are naturally hydrophilic, which makes it difficult for them to adhere to most hydrophobic polymeric resins, resulting in weak interfaces that compromise the mechanical properties of the composite (Nóbrega, 2006).

In addition, durability and degradation issues are relevant concerns, since fibers can suffer degradation under adverse environmental conditions, affecting the structural integrity of the materials (D'Almeida et al., 2006). Finally, the need for more research is evident to optimize the properties of Piassava fibres through chemical or physical treatments, such as mercerization or the use of compatibilizers, which can improve fibre-matrix adhesion and, consequently, the performance of composites (Santos et al., 2008)a . These challenges need to be addressed in order to maximize the potential of Piassava fibres in industrial applications.

It is important to note that treatments such as mercerization, although they can improve water absorption and compatibility

Author	Fiber	Application	Results
Fonseca (2021)	Piassava	Cementitious composite	Treating the fiber can increase the degree of packing of the cellulose chains, giving the material better physical and mechanical properties.
Avelar (2008)	Piassava	Activated carbons	Piassava fibers have been used as a precursor material in the preparation of activated carbon, showing great potential for adsorbing organic contaminants and metal ions such as Cr+6, Cu+2 and Zn+2.
Aquino et al. (2000)	Piassava	Polymer composites	Microstructural analysis showed that piassava fiber has characteristics that make it suitable as a reinforcing phase in composites, with promising mechanical properties compared to other materials available on the market.
Miranda et al. (2014)	Piassava	Eco-friendly materials	Research into piassava fiber bagasse has shown that its chemical and mechanical properties are promising for use in eco-friendly composites, highlighting its potential as a sustainable material.
D'Almeida et al. (2006)	Piassava	Reinforcement in composites	The research highlighted that piassava fiber has mechanical properties comparable to synthetic fibers, suggesting its use as reinforcement in composites due to its high strength and low cost
Garcia Filho (2020)	Piassava	Polymer composites	Treatment with GO on Piassava and Piassava without this treatment showed different results. The right amount of fiber strengthens and increases the interlocking of the resin's polymer matrix.
Bonelli et al. (2005)	Piassava	Polymer composites	Piassava fibers, in particular, have shown promise when combined with recycled high-density polyethylene, with silane treatment improving the fiber-matrix interface and mechanical performance
Galvão Neto (2023)	Natural fibers	Polymer composites	The use of natural fibers faces significant challenges, such as moisture absorption, which compromises the mechanical properties of composites, and the variability in the properties of fibers from different geographical origins, making it difficult to achieve consistent performance. In addition, inadequate adhesion between the fibers and the polymer matrix can result in interface failures, reducing the effectiveness of the reinforcement. Research is being carried out to develop treatments that improve this adhesion.
Guimarães (2024)	Piassava	Sub-base reinforcement	The addition of piassava to the natural subgrade soil provides a significant re-reduction in permanent deformation, making it less plastically deformable. However, when a percentage of cement is added to the fiber, this deformation is practically zero, making it possible to use the soil in road subgrade layers

Table 5: Some applications of Piassava fiber and the results obtained from research.

with polymers, can cause microstructural degradation of the fibres, resulting in a loss of mechanical strength (Santos et al., 2009). The high moisture absorption of the fibers also represents a significant challenge, as it can cause swelling and initiate cracks in the matrix, further compromising the integrity of the composite (D'Almeida et al., 2006). These factors limit the performance of Piassava fibers in applications where strong adhesion and high strength are required.

Piassava (*Attalea funifera*) fibers have significant potential for sustainable product innovations, especially in polymer composites and building materials. Recent studies have explored surface treatments to improve fiber-matrix adhesion and mechanical properties. Treatment with sodium lignosulfonate demonstrates efficacy in removing extractives from piassava surfaces, preserving the cellulosic structure and increasing fiber strength (Agrize et al., 2023). Natural fibers, including piassava, offer advantages such as biodegradability, low weight and economic availability when used as reinforcement in polymer composites (Galvão Neto, 2023). Research has shown that piassava fibers can improve the mechanical strength of polymer matrix composites, with fiber percentages ranging from 30% to 50% by weight (Aquino et al., 2002). These innovations promote sustainability and open up new opportunities for the commercial use of piassava fibers in various industries, including construction and recycled products (Vianab & Bomfima, 2020).

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