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Alternatives of reusing an Amazonian vegetal fiber through a Material-Driven Design Methodology

Alternativas para a reutilização de uma fibra vegetal amazônica por meio de uma metodologia de design orientada pelo material

Alternativas de reutilización de una fibra vegetal amazónica mediante una metodología de diseño orientado a materiales

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Abstract

A native species of the Amazon, açaí (*Euterpe oleracea* Mart.) is one of the most consumed fruits in the northern region of Brazil. Its production chain is important due to its cultural and economic identity, as well as the health benefits that the consumption of the pulp provides. However, processing waste is responsible for environmental, social, and economic problems. Among the byproducts, the fiber from the açaí seed stands out. The article presents two scenarios and possibilities (cellulose sheets and nonwoven) for reusing the fiber through an experimental methodology, called Material Driven Design (MDD), in a context of research and experimentation with waste. As a result, this work provides the possibility of relating two distinct production processes but with common backgrounds, highlighting rich teaching and learning narratives. Fourier Transform Infrared Spectroscopy (FTIR) on the fibers identified the presence of absorption bands commonly found in alternative materials used in paper production. Scanning Electron Microscopy (SEM) allowed visualizing the microstructure of the developed materials, revealing how changes in the processes directly impact their structure and properties. Visual and tangible analysis is crucial to provide insights into the changes that occurred and why they occurred, linking the theory of scientific bibliography to laboratory practice.

Keywords: Agro-industrial waste. Alternative materials. Practice-oriented design. Biodiversity.

Resumo

Nativo da Amazônia, o açaí (Euterpe oleracea Mart.) é uma das frutas mais consumidas na região Norte do Brasil. Sua cadeia produtiva é importante devido à sua identidade cultural e econômica, bem como aos benefícios à saúde proporcionados pelo consumo da polpa. No entanto, os resíduos do processamento são responsáveis por problemas ambientais, sociais e econômicos. Dentre os subprodutos, destaca-se a fibra do caroço do açaí. Este artigo apresenta dois cenários e possibilidades (folhas de celulose e nãotecidos) para o reaproveitamento da fibra por meio de uma metodologia experimental denominada Material Driven Design (MDD), em um contexto de pesquisa e experimentação com resíduos. Como resultado, este trabalho oferece a possibilidade de relacionar dois processos produtivos distintos, mas com origens comuns, destacando narrativas ricas de ensino e aprendizagem. Espectroscopia de Infravermelho com Transformada de Fourier (FTIR) nas fibras identificou a presença de bandas de absorção comumente encontradas em materiais alternativos utilizados na produção de papel. A Microscopia Eletrônica de Varredura (MEV) nos permitiu visualizar a microestrutura dos materiais desenvolvidos, revelando como as mudanças no processo impactam diretamente sua estrutura e propriedades. A análise visual e tangível é crucial para fornecer insights sobre as mudanças que ocorreram e por que ocorreram, conectando a teoria da literatura científica à prática laboratorial.

Keywords: *Resíduos agroindustriais. Materiais alternativos. Design orientado à pràtica. Biodiversidade.*

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Resumen

Originario de la Amazonia, el açaí (Euterpe oleracea Mart.) es una de las frutas más consumidas en el norte de Brasil. Su cadena productiva es importante debido a su identidad cultural y económica, así como a los beneficios para la salud que brinda el consumo de su pulpa. Sin embargo, los residuos de su procesamiento son responsables de problemas ambientales, sociales y económicos. Entre los subproductos, destaca la fibra de la semilla de açaí. Este artículo presenta dos escenarios y posibilidades (láminas de celulosa y telas no tejidas) para la reutilización de fibras mediante una metodología experimental denominada Diseño Impulsado por Materiales (MDD), en un contexto de investigación y experimentación con residuos. Como resultado, este trabajo ofrece la posibilidad de relacionar dos procesos de producción distintos, pero con orígenes comunes, destacando narrativas enriquecedoras de enseñanza y aprendizaje. La espectroscopia infrarroja por transformada de Fourier (FTIR) en las fibras identificó la presencia de bandas de absorción comunes en materiales alternativos utilizados en la producción de papel. La microscopía electrónica de barrido (MEB) permitió visualizar la microestructura de los materiales desarrollados, revelando cómo los cambios en el proceso impactan directamente en su estructura y propiedades. El análisis visual y tangible es crucial para obtener información sobre los cambios que ocurrieron y por qué ocurrieron, conectando la teoría de la literatura científica con la práctica de laboratorio.

Keywords: *Residuos agroindustriales. Materiales alternativos. Diseño orientado a la práctica. Biodiversidad.*

1 Introduction

The depletion of resources through human exploitation of the environment, due to the extraction of raw materials and the generation of waste, supports the need to think of new alternatives to current production models. Thus, the circularity of materials emerges as a solution to make the best use of resources (Velenturf; Purnell, 2021).

Brazil is one of the largest agricultural and extractive producers in the world. In recent years, the processing industry has generated large amounts of waste, which can be reused efficiently (Silva et al., 2020). Residual biomass can be converted into biofuels, bioenergy, and biofertilizers, addressing energy deficiencies in industries and throughout the Brazilian region. Other possibilities include developing potential applications for bio-based agrofibers, packaging, interior design, and industrial products (Siqueira et al., 2022; Santos, 2025).

Among the most promising species is Açaí (Euterpe oleracea Mart.). After the fruit's popularity, the production chain became one of the most important for Brazil, representing 13.32% of the national plant extraction (IBGE, 2024). On the other hand, the interest and demand to serve an external market are responsible for the high production of waste, which in many situations is discarded irregularly in the urban areas of the region. Waste disposal is largely done through dumping in sewage channels, in peripheral areas or directly into rivers and streams (Miranda et al., 2022).

Design activity is understood as crucial to this alternative, as it refers to the field of creativity, in which ideas are generated and a parallel is made between technical possibilities and creative opportunities. Furthermore, the area is understood as an important vector for identifying and adding value to production chains in the country.

This study aims to report the process of developing possibilities for reusing fiber, such as cellulose sheets and nonwovens. The methodological approach follows an exploratory and experimental character, with the aim of testing combinations through experiments. This work offers the possibility of relating two distinct production processes but with common origins, highlighting rich teaching and learning narratives.

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1.1 Sustainability and new alternatives

Although the food system has achieved productivity gains in recent centuries, it is currently inadequate to meet long-term needs. The industry has made progress in increasing global production and meeting the demands of the world's growing population. However, the scenario also has negative consequences, such as environmental pollution, irregular disposal, and the degradation of natural or urban environments (Ellen MacArthur Foundation, 2019).

The Amazon region is a space with a great biodiversity and traditional knowledge deeply linked to the management of natural resources. However, spaces in this territory are becoming increasingly urban, with the growing demand for basic services, including waste management. It is important to highlight that there is no single solution to guarantee a sustainable future for the Amazon, however, the decisive factor is to reconcile biodiversity conservation, urbanization, and local development (Paes; Campos-Silva; Oliveira, 2021).

In this case, the principles of the circular economy are essential to change the scenario described. The need to eliminate waste and pollution to reduce threats to biodiversity and to circulate products and materials stands out.

The textile sector can be defined as the sector that transforms fibers and threads into raw materials for a wide range of products, such as clothing, bed linen, table linen, and bath linen. Since the industrial revolution, textile goods have gained volume and importance never before seen. There is an emerging awareness of the different impacts of the textile industry, with emphasis on the need to develop and apply sustainable approaches. Due to the increase in the consumption of textile fibers, new raw materials and circular processes are the focus of Research & Development in different sectors of the chain (Felgueiras et al., 2021).

One example of the use of agro-industrial waste is bags made from waste from the melon agro-industry, in which the peels undergo enzymatic treatment and result in a malleable/resistant material (Shibata et al., 2023). In the textile area, the Indian startup Aamati Green stands out, producing cases with a material similar to leather, obtained from the fibers of the mango peel (Gomes, 2023).

In addition to research, testing and alternatives, it is considered that financial investment in the development of sustainable materials has increased considerably on

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the global stage. Between 2015 and 2024, $2.3 billion was invested in design and fashion products made from waste, fungi, plant fibers, and other alternative sources. It is estimated that by 2026 the sector will represent 3% of a market valued at $70 billion (Material Innovation Initiative, 2024).

Throughout history, paper, a common material today, was once rare and costly. Its scarcity hindered the shift from oral to literary culture, with early forms of knowledge transfer relying on stone, clay, wood, or wall paintings (Lefteri, 2017). Historically, paper was made from plant biomass like flax, cotton, bamboo, and straw. However, by the mid-19th century, increased demand led to the use of woody materials. Today, there's renewed interest in alternative raw materials, given their diverse characteristics, fiber dimensions, and chemical compositions, offering great potential for varied paper production (Eugenio et al., 2019).

Brazil is the world's second-largest producer of cellulose pulp, yet its forestry relies mainly on Eucalyptus and Pine. Eucalyptus is predominantly planted due to its resilience, rapid growth, adaptability, economic potential, and versatile wood use (Cunico et al., 2021).

Although eucalyptus is the predominant raw material in the Brazilian pulp industry, its monoculture causes environmental problems such as the simplification of ecosystems and the depletion of soil nutrients. However, the growing research into alternative fiber sources is quite promising. These new sources offer the opportunity to diversify the characteristics of paper, in addition to reducing dependence on a single species, contributing to more sustainable production and a greater variety of products, exploring the particularities of each fiber to meet specific market demands (Sanquettta et al., 2020).

1.2 Design for the development of materials

Historically, the development and advancement of society were directly linked to the skills of producing and manipulating materials to meet human needs. In some cases, it is common to associate certain civilizations with their relationship with materials (Callister; Rethwisch, 2020). The world and perceptions of materials are undergoing changes, driven by the need to find sustainable solutions. As a result, knowledge of materials is becoming very important for designers, not only to develop

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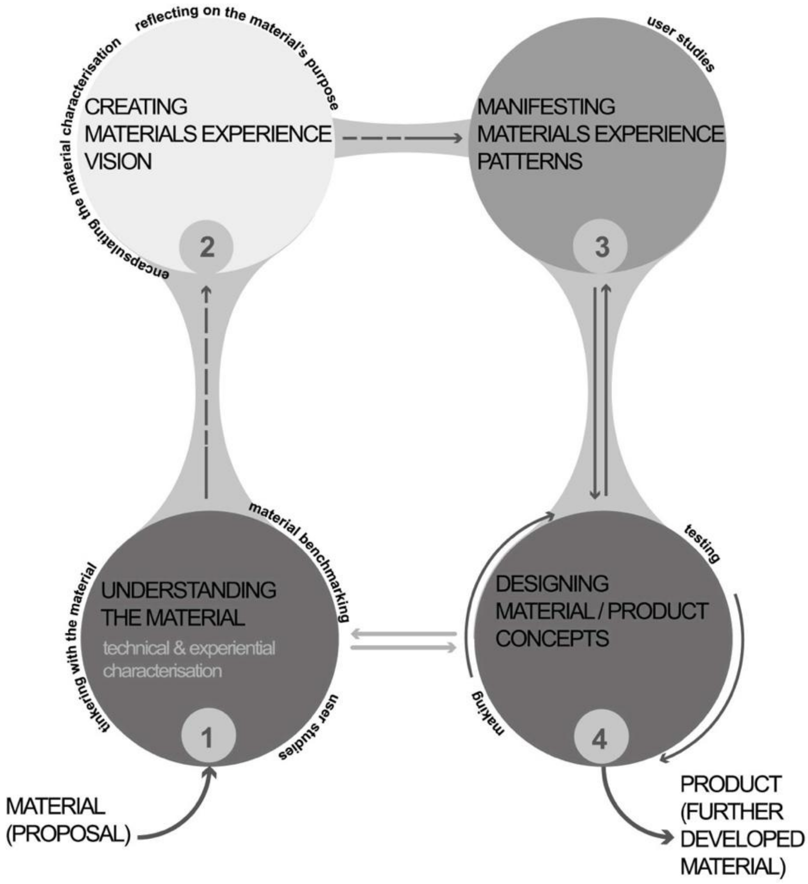
new products, but also to have a better understanding of their properties and values (Lefteri, 2017).

Design professionals tasked with developing new materials must adeptly navigate the multifaceted nuances inherent in a material project. Practical handling and laboratory experience are paramount, providing essential technical and experimental information for product design that can be translated into various aspects.

Within a teaching and learning context, these experiences contribute significantly to the training of designers and engineers, enabling them to develop a profound understanding of material properties, manufacturing processes, and their practical applications, thereby fostering innovation and the ability to solve complex problems in product development.

One of the Design approaches to material development is exemplified in the Material Driven Design (MDD) method, Figure 01. It is a tool that aims to design based on the experiences and perceptions of materials, one of its objectives is to bring the material to the center of the project, so that the design practice is guided by the development of the material (Karana et al., 2015). From the development of a new material or product in the MDD process, the designer will be able to know how the material behaves in different circumstances and how it reacts when subjected to different manufacturing techniques or processes. This method is indicated for product designs with materials from waste (Ferreira et al., 2024).

Figure 01: Method Material-Driven Design (MDD)



Source: Karana et. al, 2015

From this context, a variety of possibilities can be understood within the experimentation with raw materials. Proximity to the knowledge and manipulation of materials allows designers to control the manufacturing of their own projects, with the ability to design based on sustainability criteria and break a barrier in the exploration of new resources, capable of representing valuable and sustainable alternatives (Bak-Andersen, 2021).

1.3 Açaí (*Euterpe oleracea* Mart.)

The açaí palm tree, Figure 02, is a palm tree typical of the Amazon region, from which the açaí fruit is obtained. It occurs spontaneously in the states of Pará, Amazonas, Maranhão and Amapá. Dense and nearly homogeneous, native açaí groves are common in floodplains, *igapós* (constantly flooded lands), and dry land, forming part of the daily lives of people who inhabit the regions of the islands or are bathed by the

REAMD, *Florianópolis, v. 9, n. 3, p. 01-30, out.-jan., 2025-2026.*
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river. Açaí is a term of indigenous origin (yassa"y) that means "water palm tree" (Nogueira et al., 1995).

Figure 02: Açaí palm tree and Açaí fruit

Source: Authors, 2025.

Until the end of the 1990s, the fruit was not considered, in financial terms, a relevant activity for market logic. The scenario has changed due to national and international interest, linked to the natural benefits and marketing of the pulp. Currently, the açaí industry is one of the most important economic sources for the northern region. A survey shows that in 2023 year, 232.892 tons of the fruit were produced, with the state of Pará being the largest producer (167.625 tons), followed by Amazonas (43.877 tons). In terms of production value, the production generated R$ 1.854.764.00 thousand in the year (IBGE, 2024).

The main disadvantage of the production chain is the amount of biomass waste, composed of the stone, fibers (which revert to the stone), and sludge from the pulp processing. The amount of waste generated varies from 71% to 95% of the processed mass of the fruit (Bufalino et al., 2018). The waste, as shown in Figure 03, is accumulated in deposits, placed in front of commercial açaí establishments or in peripheral areas, which increases urban pollution and reinforces a scenario of predatory development in the region.

REAMD, Florianópolis, v. 9, n. 3, p. 01-30, out.-jan., 2025-2026.
Universidade do Estado de Santa Catarina. ISSN:2594-4630.
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Figure 03: Açaí waste in an urban context in the city of Belem (Para- Brazil)

Source: Authors, 2025.

From a material perspective, açaí residue is an attractive research target, as it is an abundant industrial byproduct. Various alternatives have been found, such as the development of composites with a polyurethane matrix and castor bean resin, with applications in product and interior design (Cavalcanti et al., 2021; Mesquita et al., 2018), poly(lactic acid) composite for use in 3D printing filaments (Cohen; Ayres, 2025), and the use of particles for construction (Barbosa et al., 2019).

In a previous study, the importance of the production chain was reinforced by the viability and use of its by-products for other activities. However, a notable gap in Design studies and experiments often directs investigations to focus predominantly on the technical parameters of materials. Within a teaching and learning context, this highlights a critical area for curriculum development and practical exploration, encouraging students to not only understand material properties but also to investigate the broader implications of production chains, circular economy principles, and the potential for design innovation through the valorization of by-products. This approach fosters a more holistic understanding of design's role in sustainable practices and resource optimization.

2 Methodology

As for methodological procedures, the one used in the development of materials is experimental, with the purpose of testing new combinations through

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laboratory experiments and evaluating the results obtained. For Design research, the experimental method is used as a tool for visualizing perceptions and potential applications (Bak-Andersen, 2021). The experimental process was based on the MDD method, according to the Board 1. This research applies the first step, called "Understanding the materials", to evaluate the results of the processing and technical characterization of açaí cellulose sheets and nonwovens.

Board 1: Description of the MDD phases and their application in research

Phase	Description Techniques	Application scenario Karana (et al., 2015)	Tools and strategies Karana (et al., 2015)	Application in the proposed research
Initial phase	Knowledge of the technical and subjective properties of the material.	- Unknown Material; - Sample under development; - Designer seeks to define properties and study application areas.	- Bibliographic Review; - Manual and laboratory experiments.	- Material collect from waste context; - Manual experiments with the fiber; - Laboratory experiences for the development and characterization of samples; - Understanding results based on theoretical assumptions and practical learning.

Source: Authors, 2025.

The materials were collected by researchers in bags of waste material found on the streets of Belém (Pará – Brazil), generated by commercial pulping establishments (popularly known as “Açaí Houses”). It was necessary to use safety equipment and sort the collected material using a strainer, to separate the açaí residues from other residues found in the bags (such as food scraps and household waste). The following activities were developed in scientific laboratories.

2.1 Cellulose sheet

The processing of açaí fibers for the production of cellulose sheets began with the bleaching of the material (removal of lignin). For this process, sodium chlorite supplied by Petra Química Indústria e Comércio de Produtos Químicos (Apucarana – PR), sodium hydroxide and glacial acetic acid supplied by Dinâmica Química Contemporânea (Indaiatuba – SP) were used.

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Two solutions were prepared: (I) sodium chlorite solution, in which 17 g of sodium chlorite were weighed and the volume was made up to 1000 mL with deionized water; (II) acetate buffer solution, in which 27 g of sodium hydroxide were dissolved in 700 mL of deionized water and 75 mL of glacial acetic acid were added. The volume was then made up to 1000 mL with deionized water. Bleaching was performed in a 3-way flask with both solutions in a 1:1 ratio for 1 hour at reflux temperature.

To produce the pulp sheet, a 1:10 solution was prepared, the ratio between the mass of bleached fiber/volume of solution. Two methods for producing the pulp sheet were evaluated: (i) vacuum filtration system with a 0.22 μm Millipore membrane and drying at room temperature; (ii) rectangular nylon screen and drying at room temperature.

To observe changes in the surface morphology of the samples, SEM images of the in natura and bleached fiber were taken, in addition to images of the produced pulp sheets. Another characterization was the FTIR of the pulp sheet, with the purpose of investigating the presence of absorption bands commonly found in alternative materials used in paper production.

SEM images were obtained using a Hitachi 4000 Plus benchtop electron beam scanner operating at 15 kV. Samples were coated and fixed to a sample holder with conductive carbon tape and imaged with a backscattered electron detector. FTIR was performed using a Perkin Elmer Frontier FT-IR spectrometer in attenuated total reflection mode, and spectra were recorded at wavenumbers from 500 to 4000 cm^{-1} with a 4 cm^{-1} resolution.

2.2 Non-woven

The nonwoven fabric development process began with the formation of a blanket with açaí fibers. For this, two polymeric molds were used, one rectangular (11.5 x 20 cm) and the other square (8 x 8 cm). The fibers were dispersed in the containers with the aid of a strainer. The thickness was controlled by the amount of material poured. For the rectangular mold, 5 grams of fiber were used, and for the square mold 2 grams were used.

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Universidade do Estado de Santa Catarina. ISSN:2594-4630.
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To consolidate the blanket, a solution with cassava starch was prepared. Cassava starch is one of the most available and economically viable biopolymers, used as a natural binder in the development of polymer composites and different green technologies (Matheus et al., 2023). Furthermore, this is a raw material found abundantly in the Amazon region. During the development of the project for the new material, this parameter was taken into consideration so that the raw material could be replicated in different Amazonian scenarios with ease. After all, the samples were subjected to the lamination process in a set of rotating cylinders.

To observe the formation of the nonwoven fabric under a microscope, SEM images of the processed material were taken. The SEM images were taken with the aid of a Hitachi 4000 Plus benchtop equipment with an electron beam operating at 15 kV. The samples were fixed in a sample holder with the aid of a conductive carbon tape and captured using the backscattered electron detector.

3 Results and discussions

The process of experimenting with the materials began with obtaining the açaí residues and the initial cleaning treatments to separate the components of the raw material, as shown in Figure 4. Part of the method was intuitive due to the lack of a specific protocol for maintaining the byproducts of the açaí production chain. Based on the MDD method, this is an opportunity for the designer to evaluate criteria for process sustainability and conduct the processing and generate insights according to questions relevant to the research (Karana et al., 2015)

Figure 04: Mixed waste; pits; fibers and açaí grounds - respectively

Source: Authors, 2025.

In this process, running water and a nylon sieve were used for the initial separation of the açaí grounds. After drying at room temperature, the fibers were manually separated from the seeds.

During this process, the friction caused by the sieve facilitated the removal of the fibers, which began to detach from the seed without direct interference from the researcher. One alternative, to avoid manual work, would be to insert the seeds with the fibers into a batch mill. However, during the experiments, manual separation was chosen to avoid consuming electrical energy and mixing the fibers with the seed into smaller particles.

In these environments, knowledge of design and materials is fundamentally built through practical immersion. Laboratory experience provides an in-depth understanding of the nuances of materials and their applications, generating critical insights that emerge directly from experimentation and manipulation. Unlike the traditional classroom teaching model, where theory precedes practice, here learning is intrinsic to the doing, allowing designers and researchers to explore limitations and potential in an organic way based on the reality of materials (Bak-Andersen, 2021).

The manual experience was crucial for the designer to understand the limitations of açaí fiber extraction and the project. This practical experience demonstrated that the current method is not viable on an industrial scale, requiring adaptations for faster processes and strict quality control, revealing the real barriers to optimizing the project.

In contrast to the experimental method adopted in the present study, the research by Mesquita et al. (2018) focuses on the mechanical extraction of açaí fibers using a benchtop circular sander. A fundamental divergence is observed in terms of scale, purpose, and technique. This approach aimed to obtain a larger volume of reference fibers, standardized to meet specific technical requirements for panel manufacturing, moving away from the experimental scope and smaller scale of cellulose sheet and nonwoven samples.

On the other hand, the empirical technique employed bore a remarkable resemblance to the method traditionally used by artisans in the Maracanã community in

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the city of São Luís (Brazil). Açaí seeds are a valuable raw material for artisans, and their high point is their sale during the community's festive periods. If they are disposed of for a specific purpose, the remaining waste (fiber and grounds) are used in experiments to produce panels, vases, and other ornaments which are not always marketed (Saraiva et al., 2021). This finding reveals a valuable convergence between scientific knowledge and ancestral practices, highlighting the wisdom contained in manual techniques and the potential for dialogue and mutual enrichment between design research and popular knowledge.

3.1 Cellulose sheet

After bleaching, the natural fibers, which are brown in color, undergo a significant change in their visual appearance, as shown in Figure 5. In addition to the change to a light color, the chemical treatment favors the formation of thinner and lighter fibers (Gavrilas et al., 2024).

Figure 05: Samples of raw açaí fiber and samples of bleached fiber

Source: Authors, 2025.

According to Figure 6a, the FTIR spectrum of açaí fibers presents the main bands attributed to lignocellulosic materials. Thus, the functional groups detected are those due to hemicellulose, cellulose, and lignin. The band at 3304 cm^{-1} corresponds to the O-H bond, while the band at 2928 cm^{-1} is attributed to the asymmetric stretching of CH and CH2 (Oliveira et al., 2019; Sena Neto et al., 2013).

REAMD, *Florianópolis, v. 9, n. 3, p. 01-30, out.-jan., 2025-2026.*
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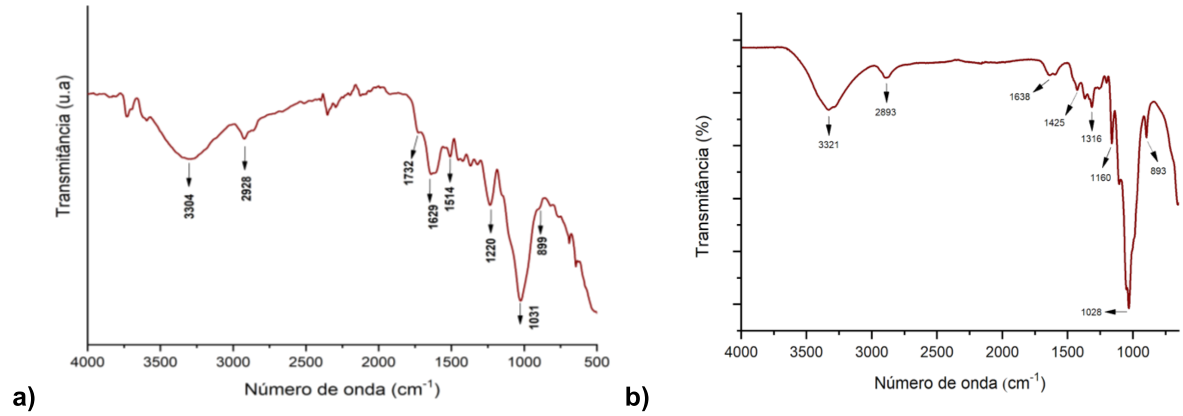
Figure 06: FTIR spectrum: **a)** raw açaí fiber; **b)** bleached açaí fiber



Source: Authors, 2025.

The bands at 1732 and 1629 cm^{-1} are related to acetyl groups and C=O bonds, characteristics of hemicellulose. A lignin peak is located in the 1514 cm^{-1} band due to aromatic vibrations in the C=C plane. The band at 1220 cm^{-1} and 1240 cm^{-1} was found in the literature as elongation of hemicellulose acetyl groups (-COR) (Oliveira et al., 2019; Sena Neto et al., 2013).

At 1220 cm^{-1} as aromatic ring breathing with C-O and C=O stretching of lignin. The band at 1031 cm-1 is associated with the elongation of the C-O-C groups present in hemicellulose, lignin, and cellulose. In addition, small bands at shorter wavelengths would be interpreted as the elongation of the Si-O bond, indicating the presence of silica crystals (Aridi et al., 2020).

As shown in Figure 6b, the FTIR spectrum of the bleached fiber pulp presents the main bands attributed to lignocellulosic materials after bleaching. Thus, the main functional groups detected are those derived from cellulose. The 1732 cm^{-1} band attributed to hemicellulose in the raw açaí fiber disappeared after the alkaline treatment. The 1220 cm^{-1} and 1514 cm^{-1} bands associated, respectively, with the aromatic ring and the lignin peak also disappeared (Oliveira et al., 2019).

FTIR analysis in design and materials research is crucial to understanding changes in the chemical composition of natural and bleached açaí fiber, directly impacting the product design process. Understanding these chemical changes allows designers to select the most suitable fiber type for a specific application.

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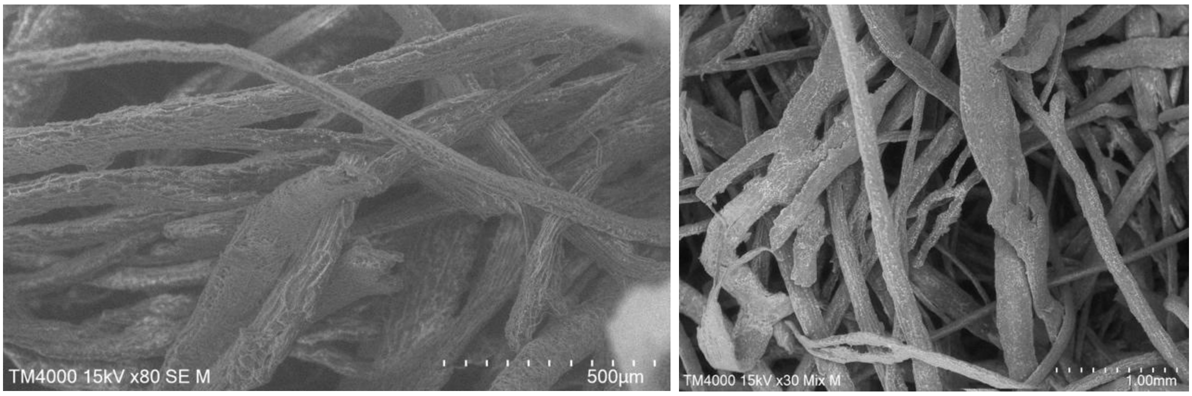
In addition to FTIR, bleaching efficiency can be monitored by measuring the reduction in colored bodies (Anisuzzaman, 2025), as shown in Figure 5 of this research. The studies corroborate the importance of controlling the processing and bleaching processes for pulping efficiency, highlighting that the use of alkaline solutions, such as NaOH, promotes the selective manipulation of lignin and hemicellulose, favoring the purification of cellulosic fibers and color changes (Martins et al., 2025).

By identifying changes in functional groups, FTIR reveals the implications of bleaching treatments on fiber properties, such as thermal stability and compatibility with different matrices (Aridi et al., 2020). A bleached fiber with lower lignin content may offer better adhesion in certain composites or greater visual clarity, while the natural fiber may retain greater mechanical strength and sustainability (Oliveira et al., 2019; Sena Neto et al., 2013).

The SEM images, Figure 07, show that the raw fiber does not have a smooth and homogeneous surface. Bright points are found and suggest the presence of the element silicon, with an atomic number higher than carbon and hydrogen, which justifies the reflection in the image (Gavrilas et al., 2024).

Figure 07: SEM images of the raw fiber



Source: Authors, 2025.

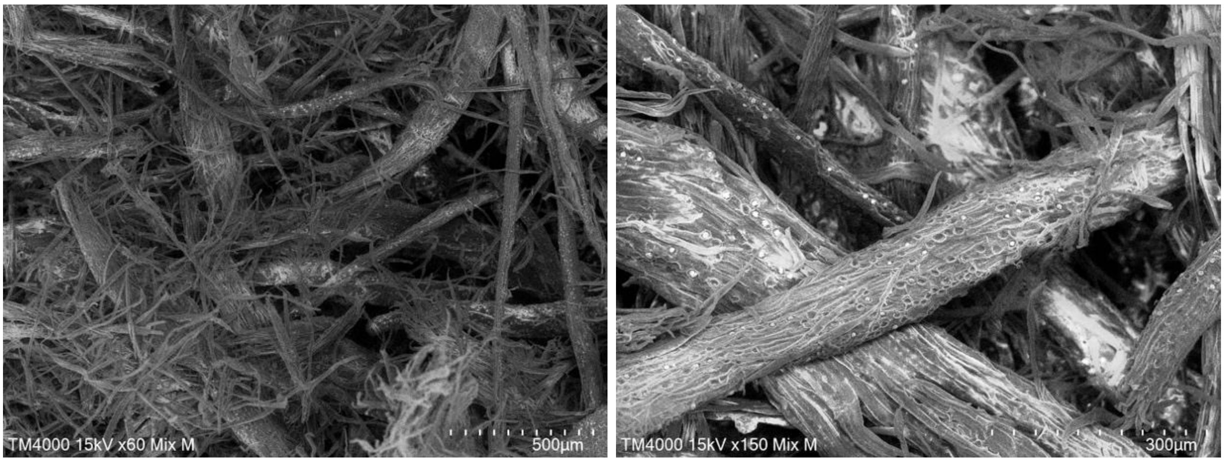
This suggestion is in line with the FTIR results, which showed small bands at wavelengths corresponding to the Si-O bonds found in silica. When the plant fiber undergoes chemical treatment to remove lignin, its roughness increases (Vinod et al., 2020). Studies reveal that these obstructed structures are trench channels. After the reported process, the channels are unobstructed. This structure, which is porous and

REAMD, *Florianópolis, v. 9, n. 3, p. 01-30, out.-jan., 2025-2026.*
***Universidade do Estado de Santa Catarina**. ISSN:2594-4630.*
***DOI**: 10.5965.25944630932025e7514*

has large cavities, has adsorption and filtration potential (Oliveira et al., 2019; Pessoa et al., 2010).

The SEM images of the bleached fiber, Figure 08, illustrate that the chemical treatment was responsible for altering the surface structure of the material. As a consequence, there was defibrillation of the fiber and the individualization of its bundles. After bleaching, the surface became rough and some channels were unobstructed, although silica was still found, as indicated by the presence of white dots. In addition, the images prove the decrease in the diameter of the material.

Figure 08: SEM images of the fiber after bleaching



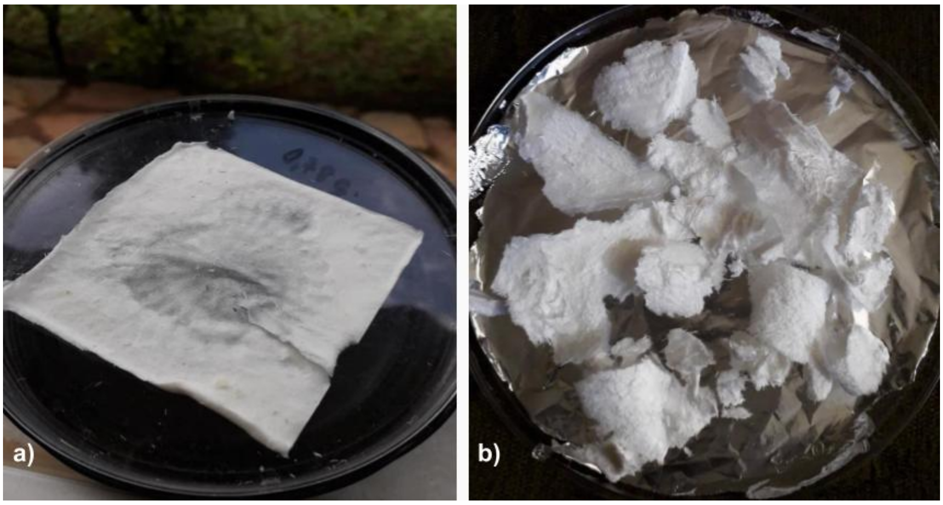
Source: Authors, 2025.

According to the literature, shorter plant fibers are suitable for the formation of cellulose sheets with satisfactory physical properties (El-Sayed; El-Sakhawy; El-Sakhawy, 2020). With the chemical action, the cell wall of the fiber is damaged and this phenomenon is very important, as it increases the specific area and the ability of the fibers to join together, so that the pulps for paper production tend to be less flocculated. The formability of the fiber also has its performance enhanced, which means that the amount of contact between the fibers increases in the cellulose sheet (Passas, 2012).

The sample formed by means of vacuum filtration, Figure 09a, presents malleability and resistance (qualitative analysis). After the drying process, one of the surfaces of the material showed the topography of the filter surface. It is recommended that the samples be removed after the material is completely dry, since when in contact with moisture, it presents a fragile structure prone to tearing, as shown in Figure 09b.

REAMD, Florianópolis, v. 9, n. 3, p. 01-30, out.-jan., 2025-2026.
***Universidade do Estado de Santa Catarina**. ISSN:2594-4630.*
***DOI**: 10.5965.25944630932025e7514*

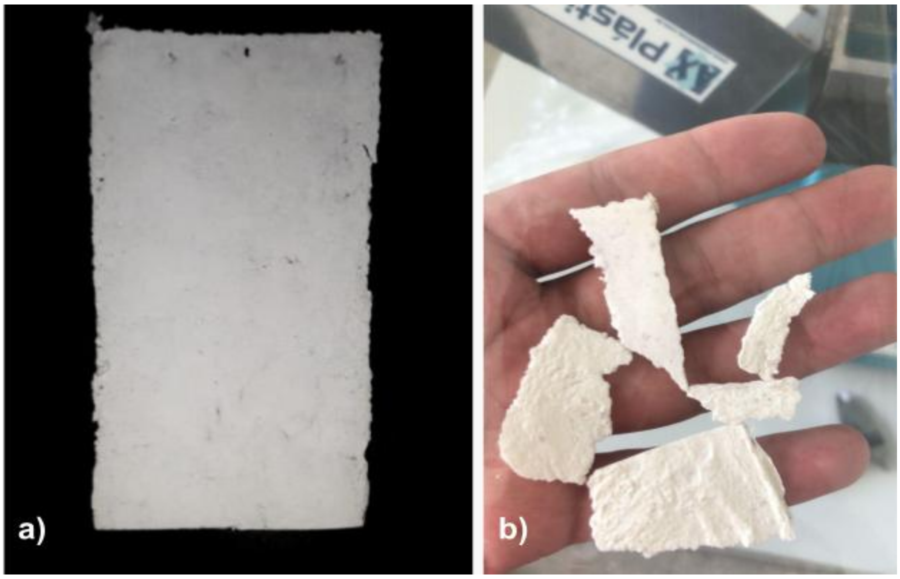
Figure 09: a) Sample of vacuum filtered cellulose sheet; b) Samples deformed during removal from filter



Source: Authors, 2025.

During the drying process, the samples formed using nylon screens, Figure 10a, presented a material with a uniform, smooth and touch-sensitive surface. A consistent material was obtained, but rigid, brittle and less malleable, Figure 10b, when compared to the samples from the first processing, which does not allow bending without damaging the structure.

Figure 10: Cellulose sheet samples formed through nylon screens



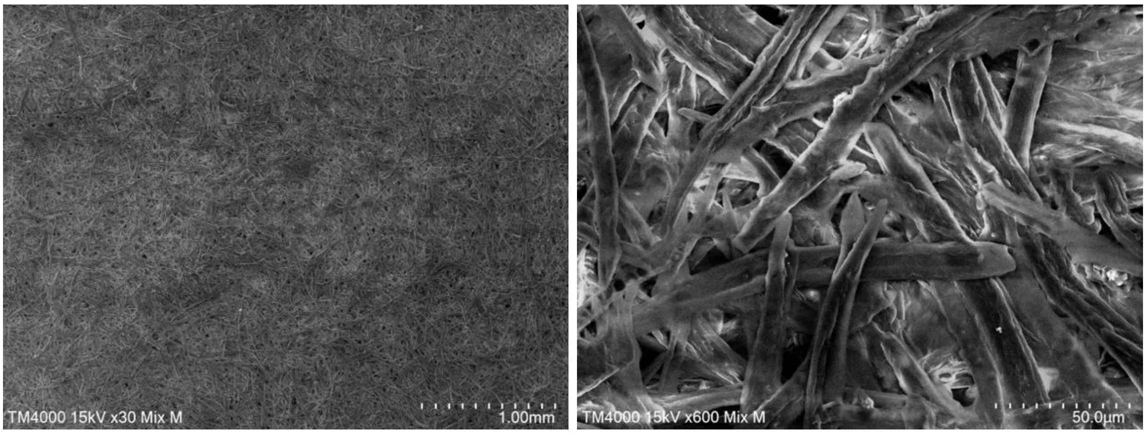
Source: Authors, 2025.

The difference in characteristics between the materials developed by two different processes can be understood by comparing SEM images of the two samples.

REAMD, Florianópolis, v. 9, n. 3, p. 01-30, out.-jan., 2025-2026.
***Universidade do Estado de Santa Catarina**. ISSN:2594-4630.*
***DOI**: 10.5965.25944630932025e7514*

The material obtained by vacuum filtration, Figure 11, presents a low presence of empty spaces on its surface, in addition to the proximity between the açaí fibers through interlacing.

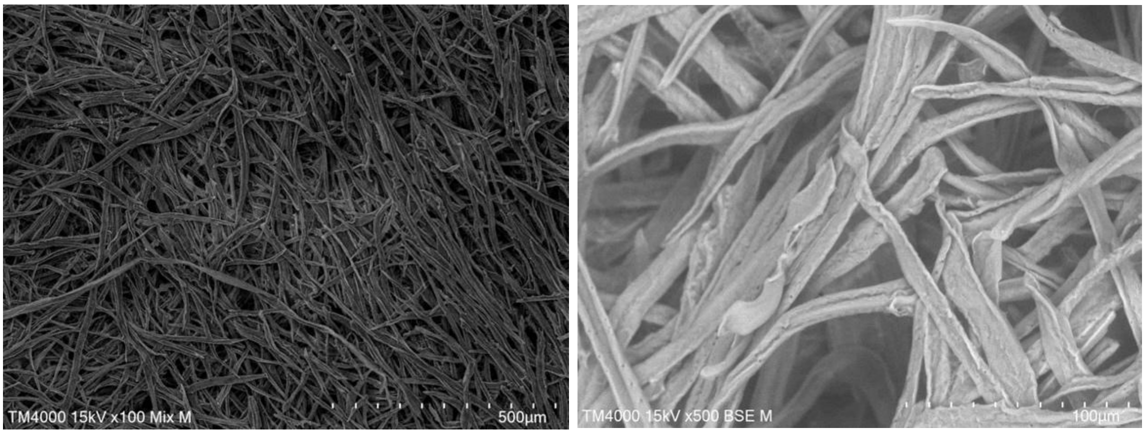
Figure 11: SEM images of cellulose sheet formed through vacuum filtration



Source: Authors, 2025.

Despite the similar dispersion and surface formation, the SEM images of the cellulose sheet formed using the nylon mesh, Figure 12. It is indicated that the fibers are intertwined with a greater number of empty surfaces.

Figure 12: SEM images of the cellulose sheet formed using the nylon mesh



Source: Authors, 2025.

It is understood that during the artisanal process, there is a certain difficulty in maintaining control over the conditions in which the material is formed, and, according to the results obtained, there is a need to improve the process of forming the sheet with the nylon mesh. In these cases, the addition of additives, such as CMC (carboxymethyl

REAMD, Florianópolis, v. 9, n. 3, p. 01-30, out.-jan., 2025-2026.
***Universidade do Estado de Santa Catarina**. ISSN:2594-4630.*
***DOI**: 10.5965.25944630932025e7514*

cellulose) or PVA (polyvinyl acetate) glue, is recommended to provide strength, occupy the empty surfaces and structure (El-Sayed; El-Sakhawy; El-Sakhawy, 2020).

SEM characterization plays an extremely important role in materials design research and in deepening knowledge about raw materials. As a visual and tangible tool, SEM allows for a deep understanding of the material's microstructure, revealing details that are crucial for the designer's learning.

In addition to providing valuable insights into transformation processes (visually evidencing what changed, how and why it changed in the different stages of manipulation or treatment) SEM analysis acts as an essential bridge between the theory present in the scientific literature and the practice carried out in the laboratory, solidifying knowledge and enabling the development of more informed and effective design solutions (Bak-Andersen, 2021).

In the literature, there are studies on the use of plant fibers, derived from waste from production processes, in the production of recycled paper. One of them is the artisanal production of paper with fibers from the pseudostem of the banana tree, a raw material that is discarded after the fruit is harvested, as is the case with açaí. Two possibilities were investigated: the first was paper made only with banana fibers, which proved to be a flexible but brittle material. The second was material made with fibers mixed with post-consumer paper, which proved to be more flexible and malleable (Balda et al., 2021).

Another initiative is the paper produced with the residual sheaths from the processing of pupunha palm hearts. To indicate the possibility of application, the surface closure of the raw material was evaluated through SEM, with the low presence of empty spaces and the proximity between the cellular elements of the residue. Among the characteristics obtained, malleability, the great variability of applications, and the possibility of artisanal reproduction stand out. Cutlery wrappers were made and possible applications included packaging for paper trays and stationery items (Gottardi, 2019).

The MDD method, as outlined by Karana et al. (2015), represents an innovative approach that moves away from traditional materials research methodologies by placing the material at the heart of the design process. MDD aims to empower

REAMD, Florianópolis, v. 9, n. 3, p. 01-30, out.-jan., 2025-2026.
***Universidade do Estado de Santa Catarina**. ISSN:2594-4630.*
***DOI**: 10.5965.25944630932025e7514*

designers to deepen their understanding of the distinct properties and experiential qualities of materials, enabling them to explore, define, and apply these characteristics effectively in product development (Ferreira et al., 2024).

In-depth practice and understanding of materials, especially in relation to chemical transformations, is crucial to the development of more sustainable processes. Through MDD, it is clear that the action of manipulating and experimenting with materials reveals hidden complexities. In the context of bleaching, for example, recognizing the chemical reactions involved and their by-products is essential for a complete sustainability assessment (Cohen; Ayres, 2025). Without such detailed study, it is impossible to determine the true environmental impact of the process, reinforcing the need for a more investigative approach to ensure truly sustainable practices. The visual and tactile manipulation of the developed materials complements these perceptions, offering practical insights into the perceived changes, uniting the theory of the scientific literature with laboratory practice and providing designers with the information necessary to make informed decisions about the use of bleached açaí fiber.

3.2 Non-woven

The fibers were dispersed in a way that controlled the thickness that the blanket could take. It was observed that even without the addition of any binder, the fibers formed a good bond between themselves, Figure 13. It is estimated that the ruptures observed in the microscopic image, and the irregularity in the surface, may allow the fibers to bond together.

Figure 13: Fiber blanket after dispersion

Source: Authors, 2025.

REAMD, Florianópolis, v. 9, n. 3, p. 01-30, out.-jan., 2025-2026.
Universidade do Estado de Santa Catarina. *ISSN:2594-4630.*
DOI: *10.5965.25944630932025e7514*

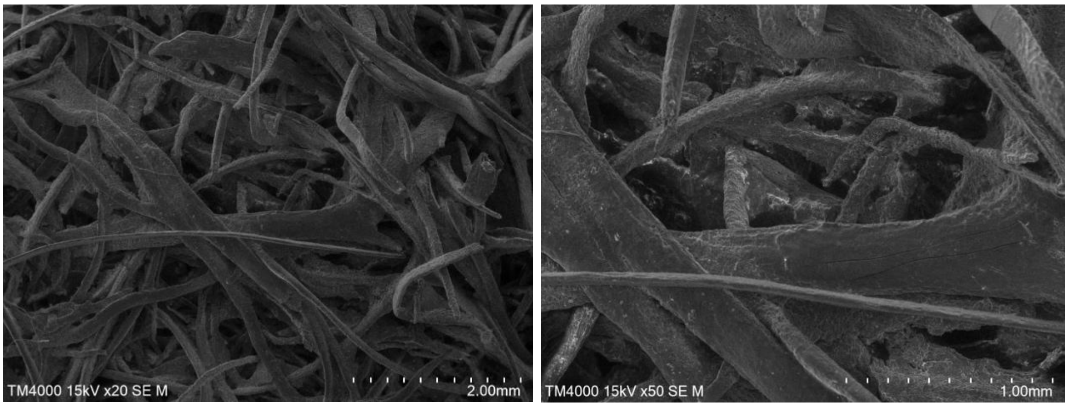
It was observed that, with handling, part of the fiber blanket disintegrated until the veil completely disintegrated, Figure 14. This action signaled the need for a binder to consolidate the union of the fibers. As opportunities, the natural predisposition of açaí fibers to form a blanket, through induction or manipulation, stands out.

Figure 14: Blanket disintegrated after handling

Source: Authors, 2025.

The SEM of the nonwoven, Figure 15, provides crucial insights into the materials learning approach by revealing the complex structure of fibers and their relationship to tactile perception. The SEM images indicate that the fiber has a naturally rough surface and an innate tendency to intertwine, forming a cohesive structure.

Figure 15: SEM images of cellulose sheet



Source: Authors, 2025.

REAMD, Florianópolis, v. 9, n. 3, p. 01-30, out.-jan., 2025-2026.
***Universidade do Estado de Santa Catarina**. ISSN:2594-4630.*
***DOI**: 10.5965.25944630932025e7514*

The SEM of the raw açaí fiber reveals that its surface is not smooth and homogeneous, presenting bright spots that suggest the presence of elements such as silicon, as indicated by the FTIR. This roughness and heterogeneity of the surface are characteristics that directly contribute to the intertwining capacity and tactile perception of the fiber in the nonwoven, as mentioned above.

The benefit of using short fibers, such as açaí, in these processes is the ease of structuring through random arrangement. Studies leds to the manufacture of a dispersible nonwoven fabric with short cotton fibers and shows that the nonwoven fabric can be dispersed and structured because the fiber ends form webs, which can be bonded with biodegradable binders (Santos; Ferreira; Maloney, 2021).

The starch solution was successful as a binder for the blanket, which helped maintain the structure of the material and prevented it from disintegrating during handling. Widely used in studies with coconut, piassava, and jute fibers, the starch solution acts as a plasticizer/binder, and the dispersion of plant fibers facilitates their assembly with the solution to form nonwoven structures (Ávila-Orta et al., 2023). The chemical and structural-property relationships of starch demonstrate its potential as an attractive raw material source, which can be exploited for conversion into various high-value bio-based products. Starch processing for the development of bio-based fibers can result in the sustainable replacement of high-value petroleum-based materials with economical, environmentally friendly, and abundant products (Temesgen et al., 2021).

For this research, this raw material was chosen because it was locally available, among the sensory characteristics, it is noted that the solution gave the material a surface shine. The açaí nonwoven fabric has a flat, flexible, malleable, and porous surface. Unlike woven fabrics, its structural form is composed of randomly arranged fibers with a low thickness in relation to the other dimensions of the material (width and length).

A variety of finishing processes capable of improving the appearance, and aesthetics of nonwoven after production are being explored in different researches. The role of these technologies in modifying fabric properties late after sizing and customizing performance is crucial to the final form of the raw material, resulting in products with durability, strength, improved texture, and more vibrant colors, significantly expanding their applications (Tipper; Ward, 2022).

The lamination process was performed on the sample, which resulted in a reduction in the thickness of the material, Figure 16. The control consisted of a purely mechanical process, without changing the temperature or applying another component to the nonwoven fabric. After this process, the material continued to have good agglutination between the fibers, without generating residue or deformation in the external structure of the nonwoven fabric.

Figure 16: Non-woven fabric with consolidated açaí fibers

Source: Authors, 2025.

Understanding these inherent compositions allows designers to not only predict the behavior of the material during processing but also to consciously integrate them into the product concept, transforming what could be seen as a limitation into a distinctive and desirable characteristic, shaping aesthetics and functionality. When comparing the SEM images, it is observed that the vacuum-filtered cellulose sheet sample exhibits fewer voids in its structure when contrasted with the nonwoven and the cellulose sheet made with nylon mesh (which underwent a manual structural formation process).

This suggests that the way in which the structure is formed can, in certain cases, have a similar visual and tactile impact on the final microstructure, regardless of

REAMD, Florianópolis, v. 9, n. 3, p. 01-30, out.-jan., 2025-2026.
Universidade do Estado de Santa Catarina. ISSN:2594-4630.
DOI: 10.5965.25944630932025e7514

some prior treatments. These finding guide designers to consider not only the chemical composition but also the processing techniques as determining factors in achieving the desired material properties and product experience, allowing the choice of methods that optimize both performance and sustainability.

4 Conclusions

Through experimentation, samples of cellulose sheets and nonwovens were obtained, and a bleaching process was carried out on açaí fibers, which demonstrates the viability of processing waste from the production chain into new materials. The SEM allowed us to understand the structural formation of the materials, in addition to understanding the changes with the production processes. The MDD method allowed for experimentation with materials oriented towards technique and learning. In the field of scientific knowledge, the topics presented are situated in ways of discussing problems and presenting solutions focused on the Amazonian reality, through the innovative character of design, supported by experimentation with materials. It is expected that the opportunities and challenges exposed and discussed in the study can be considered in future investigations or ongoing research.

As suggestions for future work, we indicate the development of product prototypes with the materials developed, biodegradation tests, and the analysis of the perception of potential users regarding the results obtained, with the objective of understanding possible experiences and acceptance of the solution.

Although there is a range of agro-industrial waste in the country, in addition to the potential for biodiversity, the sustainable use of these resources is still restricted, or with little access to the rest of the country. The raw material developed contributes as a democratic alternative, which seeks to promote a scenario that preserves the biodiversity of the forest, which can contribute to strengthening a consolidated production chain, presents new opportunities to locals, and guarantees decent living conditions in urban centers and peripheral areas of cities in the Amazon.[2]

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REAMD, Florianópolis, v. 9, n. 3, p. 01-30, out.-jan., 2025-2026.
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Contributions (CRediT - Contributor Roles Taxonomy)

Nubia Santos supervision the study and methodology for the development of non-woven, Eliane Ayres supervision the study and methodology for the development of cellulose sheet, Lauro Cohen organized and conducted the visualization, writing – review & editing the article critically.

REAMD, Florianópolis, v. 9, n. 3, p. 01-30, out.-jan., 2025-2026.
Universidade do Estado de Santa Catarina. ISSN:2594-4630.
DOI: 10.5965.25944630932025e7514

Supplemental material

All data necessary to reproduce the results are contained in the article itself.

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