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Production of Bio-Oil by Pyrolysis of açaí (Euterpe Oleracea, Mart.) Seeds Fibers and Slurry [Powder]

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ABSTRACT

The intensification of the search for renewable energy sources, combined with growing envi-ronmental concerns regarding the disposal of agro-industrial waste, has driven the development of sustainable technological routes, such as pyrolysis. In this context, the açaí seed, a lignocel-lulosic residue widely available in the Amazon region, stands out as a promising raw material to produce biofuels and value-added chemical inputs. This study aimed to evaluate the feasibility of pyrolysis of açaí seed fibers and sludge, carried out at 450°C, focusing on the production and characterization of bio-oil and aqueous phase. The preliminary physicochemical characterization of the biomass indicated low ash content and high volatile content, desirable attributes for thermochemical conversion. Pyrolysis tests revealed a bio-oil yield of 1.15% by mass for fibers and 2.13% for sludge, with observed acidity of 173.11 and 144.25 mg KOH/g, respectively. The aqueous phase showed high acidity (191.60 mg KOH/g for fibers and 181.07 mg KOH/g for sludge) and low viscosity (1.45 mm^2/s and 1.348 mm^2/s, respectively), suggesting a composition rich in volatile organic compounds. FTIR spectroscopic analysis revealed the presence of hy-drocarbons and oxygenated compounds in the bio-oils, and a predominance of organic acids in the aqueous phases. The results demonstrate the potential of pyrolysis in the valorization of agro-industrial waste from the Amazon, contributing to the development of sustainable energy alternatives and the strengthening of practices aligned with the circular economy.

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Introduction

The growing awareness of the importance of environmentally responsible practices has be-come a global imperative. Both individuals and organizations are increasingly called upon to adopt proactive approaches toward sustainability, aiming to preserve natural resources for future generations. In this context [1]. Emphasize that the pursuit of a sustainable develop-ment model, driven by environmental awareness, is a well-established topic in literature. Studies on human behavior regarding environmental issues indicate that individuals with a higher level of environmental awareness tend to make decisions that are more aligned with reducing negative environmental impacts [2].

The adaptation of companies to the new environmental paradigm has become an essential element in addressing contemporary sustainability challenges. The incorporation of practices aimed at environmental preservation and conservation, focusing on the mitigation of impacts resulting from productive activities, has increasingly become a requirement in both regulatory and market contexts [3]. In this scenario, the National Solid Waste Policy (PNRS), estab-lished by Law No. 12,305/2010, sets forth guidelines for the integrated management and en-vironmentally sound handling of solid waste in Brazil [4]. Among the guiding principles of the PNRS, the concept of eco-efficiency stands out, proposing a balance between economic performance and environmental responsibility by promoting sustainability through the opti-mization of natural resource use and the minimization of environmental impacts [5].

Iven the growing demand for sustainable energy solutions, plant biomass has emerged as a strategic component in the transition toward a new energy paradigm. This matrix encompasses a wide range of sources, from agricultural and forestry residues to energy crops specifically cultivated for fuel purposes and is characterized by its broad availability and versatility [6,7]. Biomass enables the production of various bioproducts, such as liquid and gaseous biofuels, biopolymers, and renewable-based chemical compounds, promoting the replacement of fos-sil-derived products and contributing significantly to the decarbonization of energy-intensive sectors such as transportation, industry, and electricity generation [8]. Furthermore, its use supports the principles of the circular economy by enabling the conversion of organic waste into value-added products, thereby reducing pressure on natural resources and fostering more sustainable production cycles.

Açaí (Euterpe oleracea Mart.), an emblematic fruit of the Amazon and the state of Pará, plays a significant socioeconomic and nutritional role for local populations and is widely consumed in various food preparations. However, its production chain generates a substantial volume of solid waste, as the seed accounts for approximately 85% of the fruit's total weight, while the edible pulp represents only 15%. This proportion highlights the urgent need to develop tech-nological solutions for the sustainable management of this waste, whose improper disposal can lead to significant environmental impacts, such as soil and water contamination, as well as the proliferation of disease vectors [9]. In this context, the residual biomass from açaí seeds, a widely available by-product of the fruit processing industry in the Amazon region, emerges as a promising alternative for energy production and value-added compounds [10]. Its lignocel-lulosic composition (rich in cellulose, hemicellulose, and lignin) makes this biomass suitable for application in thermochemical and biochemical conversion processes such as pyrolysis, gasification, and anaerobic digestion, aiming at the production of biochar, bio-oil, biogas, and other bioproducts with potential industrial and energy applications.

The search for eco-efficient strategies aimed at utilizing waste from the açaí production chain has gained prominence in the state of Pará, where the fruit represents an important component of both the local food culture and economy. According to the Association of Artisan Açaí Vendors of Belém and the Metropolitan Region each sales point in the metropolitan area of Belém generates, on average, around 280 kg of açaí seeds per day [11]. This significant vol-ume of waste highlights the importance of adopting sustainable practices throughout the en-tire production chain. AVABEL also emphasizes the growing awareness among producers regarding the importance of proper environmental management of this waste, which is often discarded without treatment or reuse.

Data from the Brazilian Institute of Geography and Statistics indicate that, on a national lev-el, açaí production reached approximately 1,699,588 tons in 2022, with the state of Pará ac-counting for 1,595,455 tons, representing over 93% of total production [12]. In the same year, 47,855 establishments dedicated to processing açaí pulp were registered across the country, highlighting the scale and relevance of the sector. Regarding the legal classification of the waste, NBR 10.004 characterizes açaí seeds as compostable waste, classifying them as Class II A – non-inert, biodegradable, and easily degradable, like organic waste such as food scraps, fruit peels, and leaves [13].

Given the growing demand for renewable energy and the need for sustainable solutions for the management of agro-industrial and urban solid waste, pyrolysis emerges as a promising technology for the conversion of biomass into biofuels. This thermochemical process, which consists of the thermal degradation of biomass in an environment without oxygen and at high temperatures, has been widely studied and applied in the degradation of various types of sol-id waste [14].

In the specific context of açaí seeds, an abundant waste in the Amazon region, pyrolysis has significant potential to produce bio-oil, biochar and combustible gases. The energy efficiency of the process, combined with the relatively low investment costs, makes pyrolysis a viable alternative for the reuse of this waste, contributing to the reduction of environmental impact and the generation of clean energy. To optimize energy production from the pyrolysis of açaí seeds, it is essential to carry out in-depth studies on the reaction kinetics and process parame-ters, considering the specific characteristics of this biomass.

This article investigates the utilization of residual açaí seed biomass, in the forms of raw fiber and raw powder (borra), as a feedstock for biofuel production. The study addresses the need for a sustainable solution for managing the waste generated by the açaí production chain in the Metropolitan Region of Belém, Pará, Brazil. The objective is to propose a thermochemical conversion methodology for lignocellulosic biomass at 450 °C, evaluating the yield, quality of the resulting biofuels, and the potential for technological application.

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Materials and Methods

This study presents the methodology adopted to achieve the research objectives, including the study area, methodological design, data collection procedures, and the analyses used. The process of utilizing açaí seeds, outlined in the flowchart in Figure 1, began with the collection and drying of the raw material, resulting in dried seeds. A portion of these seeds (fiber and in natura pulp) was subjected to physical characterization, evaluating parameters such as moisture content, ash con-tent, volatile matter, and fixed carbon. Subsequently, the fiber and pulp were processed through pyrolysis, decomposing them into three phases: liquid, solid, and gaseous. The liquid phase yielded bio-oil and water, both of which were physicochemical analyzed. The bio-oil was characterized in terms of acidity, viscosity, and density, while the water was analyzed to determine its composition and potential for reuse. Additionally, both liquid phases were subjected to Fourier Transform Infrared Spectroscopy (FT-IR) to identify the functional groups present.

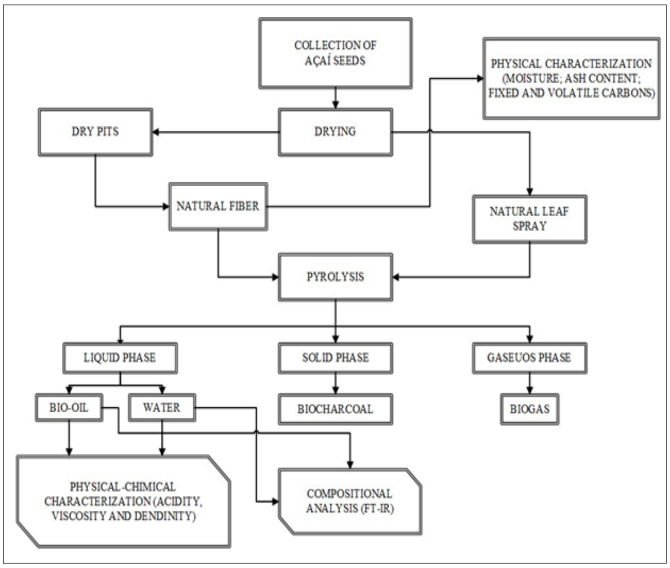

Figure 1: Flowchart of the Steps Developed in the Research

Collection and Pre-treatment of Açaí Seeds

The choice of location was motivated by the high concentration of açaí processors, ensuring a continuous supply of raw material. The seeds, initially moist due to the pulp removal process with water, underwent a drying process to remove excess moisture. The initial moisture, resulting from both the pulping process and environmental exposure, could promote the decomposition of the seeds.

Drying was an essential step to standardize the samples and prepare them for the subsequent stages of the research. The drying treatment of the moist seeds was conducted in a LABNANO forced air circulation oven (De Leo Ltda, 127 V, analog control N 1030), at a constant temper-ature of 105 °C for 24 hours. The goal was to remove the water from the seeds, preventing the degradation of organic compounds. The forced air circulation ensured temperature homogeni-zation, promoting uniform drying. The temperature of 105 °C, commonly used for lignocellulosic materials, was chosen to ensure the process's efficiency until the sample reached constant weight, indicating the complete removal of free water.

The drying pre-treatment was carried out with an initial mass of 10.0 kg of moist açaí seeds, in compliance with ASTM D 3173-87. The choice of a larger mass aimed to increase the sample representativeness, allowing for the acquisition of more robust and reliable results. The goal of the drying was to reduce the moisture content of the seeds, preparing them for subsequent stages, such as the separation of fibers, pomace, and pyrolysis. The determination of the moisture content of the açaí seeds, both before and after drying, was based on the calculation of mass loss through evaporation, expressed as a percentage of the initial moist mass. To ensure the accuracy of the results, the final mass (Mf) was measured using the same precision scale employed for the measurement of the initial mass (Mi). The determination of Mf was carried out at regular intervals until the variation between successive weighings was less than 0.01 g, indicating the complete removal of free water and the attainment of constant mass. This procedure ensured the reliability of the data for the calculation of moisture content, a key parameter for the characterization of the raw material, evaluation of the drying process efficiency, and for the subsequent stages, such as pyrolysis. The moisture content of the açaí seeds was quantified according to the application of Equation 1.

$$U\ (\%) = \frac{Mf - Mi}{Mi}\ x\ 100 \qquad (1)$$

Where
U (%): relative moisture of the sample;
M_i: initial mass of the wet sample (g);
M_f: Final mass of the dry sample (g).

After the drying process was completed, the acai seeds were manually separated into two frac-tions: fibers and press cake. This step was essential for the proper handling of the biomass, con-sidering the differences in composition and properties between the components. The segregation allowed each fraction to be processed individually by pyrolysis, aiming to optimize the utilization of the residues.

Physical Characterization of Acai Seeds

After the drying process, immediate analyses (moisture content, ash content, volatile matter, and fixed carbon) were performed on the previously dried acai seed samples. The volatile matter content was determined according to ASTM D3175-07, "Standard Method for Volatile Matter in the Analysis Sample of Coal and Coke," adapted for analysis in a muffle furnace (Muffle Furnace SOLIDSTEEL model SSFM). The samples were placed in the muffle furnace at 900 ± 10 °C for 10 minutes. The ash content was determined using a procedure similar to the ASTM E1755-01 method. The fixed carbon content will be determined according to the ASTM D3172-89 methodology.

Thermochemical Process

Experimental Apparatus

The laboratory-scale Pyrolysis unit consists of a 304 stainless steel reactor with cylindrical ge-ometry, a diameter of 4.5 inches (11.4 cm) and a height of 35 cm, with a volume of 1200 cm³, featuring a flange-type seal in 304 stainless steel. The unit includes a 1100-watt heating system around the pyrolysis reactor with digital temperature control and heating rate. The reactor is connected to a 304 stainless steel (straight) condenser, 300 mm long, with a cooling system comprising a thermostatic bath with digital temperature control (Figure 2). The liquid reaction products are collected in a 2000 mL borosilicate glass separation funnel, and the non-condensable gaseous products are directed through an opening in the distillation adapter, which is attached between the condenser and the separation funnel, to the exhaust system (Figure 3).

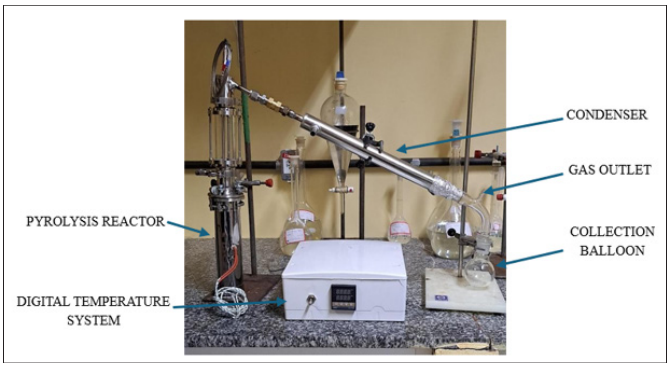

Figure 2: Experimental Setup of the Laboratory-Scale Pyrolysis Unit.

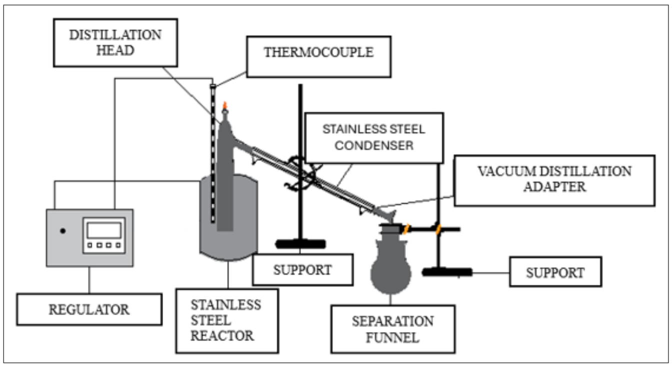

Figure 3: Layout of the Experimental Apparatus of the Laboratory Unit.

Laboratory-Scale Pyrolysis Experiments

To evaluate the influence of the nature of the starting material (fibers and raw pomace) on the yield and physicochemical properties of the liquid product (bio-oil) obtained, the experiments were conducted in semi-continuous mode, at temperatures of 450°C and a pressure of 1.0 atm. The masses of the acai seeds were pre-weighed on a semi-analytical balance (QUIMIS, model Q – 500L210C), approximately 250 g. The seeds were then placed in a 200 mL borosilicate glass reactor. The reactor was subsequently inserted into a cylindrical jacketed furnace, and with the help of a temperature controller, the reaction time, heating rate, and final temperature of the process (set-point) were programmed according to Equation 2. With the parameters established, a reaction time of 88 and 80 minutes was set to maintain each final operating temperature constant. The experimental setup was assembled by connecting the cooling condenser to the reactor, with the coolant fluid maintained at 10°C. Starting from room temperature (25°C), the slow pyrolysis process began with a heating rate of 10°C/

min, while monitoring and recording the operational parameters of the process, such as heating ramp, time, and temperature for product formation. The reaction time was calculated according to Equation 2.

$$t = \frac{(T_f - T_i)}{r} \quad (3)$$

Where
t = reaction time (min);
Tf = final temperature (°C);
Ti = initial temperature (25 °C);
r = heating rate (10 °C/min).

After each pyrolysis experiment, the products were quantified to determine their yields. The liquids (bio-oil and aqueous phase) were collected in 125 mL Erlenmeyer flasks, while the bi-ochar was weighed on a precision balance. The yield of non-condensable gases was obtained by mass difference, disregarding losses. To separate the bio-oil from the aqueous phase, the liquid was filtered in a glass funnel with J. PROLAB filter paper (24 mm, 14 µm porosity). The masses of the bio-oil and aqueous phase were then measured separately to calculate the yields, according to Equation 3.

$$\eta(\%) = \frac{m_p}{m_{csa}} \quad (3)$$

η= yield of reaction products (%);
m_p = mass of product obtained (g);
m_{csa}= mass of impregnated açaí seeds (g);

Physicochemical and Compositional Characterization of Bio-Oil and Aqueous Phase Acid Value, Density and Kinematic Viscosity

The bio-oil and aqueous phase were characterized in terms of Acidity Index, determined based on an adaptation of the official AOCS Cd 3d-63 method (AOCS, 2001), which is applicable to vegetable and animal oils (natural or refined), marine fats, and various de-rived products. Dynamic viscosity was measured according to ASTM D 445-06 (2006). The analysis of the absolute density of both the bio-oil and aqueous phase followed the official methodology outlined in ABNT NBR 7148 (2014).

Fourier Transform Infrared Spectroscopy (FT-IR)

Fourier transform infrared spectroscopy analyses were performed at the Laboratory of Vibra-tional Spectroscopy and High Pressures (LEVAP/UFPA). The measurements were performed in an environment using ATR, on Bruker equipment, model Vertex 70v. The scanning range was 400 to 4000 cm^{-1}.

Results

Physical characterization of açaí Seeds

Table 1 presents the physical characterization of the açaí seeds, fibers and grounds, providing essential information about the structure and properties of these materials, which are fundamental for optimizing the pyrolysis process and the quality of the products generated.

Table 1: Physical Characterization of açaí Seed Fiber and Sediment

Material	Humidity [%]	Ashes (%)	Volatiles (%)	Fixed Carbon (%)
Seeds	18	-	-	-
Fiber	-	3,10	75,77	21,13
Sludge	-	1,31	77,42	21,27

Legend: Physical characterization of açaí seed fiber and sediment, including moisture content, ash content, volatile matter, and fixed carbon. These parameters are essential for evaluating the thermal behavior and suitability of the biomass for pyrolysis processes.

The açaí seed had a moisture content of 18%, which is within a range considered acceptable for biomass intended for pyrolysis. However, lower moisture values are generally desirable, as they reduce the energy consumption required for water evaporation and increase the thermal efficiency of the process. The fibers had an ash content of 3.10%, while the same value was recorded for the seeds. The sludge, on the other hand, had a significantly lower content, of only 1.31%. The low ash content of the sludge indicates a lower presence of inorganic materials, which is advantageous for pyrolysis, as it reduces problems such as scale and corrosion in the equipment, in addition to improving the quality of the bio-oil produced.

All materials analyzed presented high volatile content, with emphasis on sludge (77.42%), followed by fibers and seeds (both with 75.77%). This high volatile fraction is a desirable characteristic in pyrolysis processes, as it is directly associated with the formation of liquid products, such as bio-oil. The higher the volatile content, the greater the tendency for light organic compounds to be released during thermal degradation.

Fixed carbon was slightly higher in sludge (21.27%), followed by fibers (21.13%). Fixed carbon content is related to the fraction of the material that remains as solid residue (biochar) after the release of volatiles. Although biochar formation is desirable in certain applications, such as soil improvement or carbon sequestration, for the purpose of maximizing bio-oil production, ideally fixed carbon should be balanced with volatiles.

Results of the Pyrolysis Process of Acai Seed Fibers

The results of fiber pyrolysis, including yields of bio-oil, biochar and gases, as well as time and temperature of phase formation, are illustrated in Table 2.

Table2: Pyrolysis Parameters of in Natura Fibers from Açaí Seeds

Process parameters	Fibers (in nature)
Process temperature [°C]	450
Acai seed fiber mass [g]	313.69
Cracking time [min]	88
Initial cracking temperature [°C]	204
Mass of solid (biochar) [g]	99.73
Mass of liquid (bio-oil) [g]	3.609
Aqueous phase mass (H2O) [g]	124.246
Mass of gas [g]	86.105
Bio-oil yield [wt.%]	1.15

Aqueous phase yield [wt.%]	39.60
Solid yield (biochar) [wt.%]	31.79
Gas yield [wt.%]	27.44
Acidity value of the aqueous phase [mg KOH/g]	191.60
Acidity value of bio-oil [mg KOH/g]	173.11

Legend: The operating conditions, steady-state mass balances of the pyrolysis of açaí seeds (Euterpe oleracea Mart.) and the yields of the reaction products are presented.

Pyrolysis of açaí seed fibers, conducted at 450°C, resulted in the predominance of the aqueous phase (39.60%) over the other products, followed by biochar (31.79%), non-condensable gases (27.44%) and a low production of bio-oil (1.15%). The low conversion to bio-oil may be asso-ciated with the lignocellulosic composition of the fibers, possibly with a low content of oily extractives and a high proportion of oxygenated groups, which favor the formation of polar and water-soluble compounds in the aqueous phase. The high generation of aqueous phase indicates intense thermal degradation of the cellulosic and hemicellulosic constituents, resulting in the formation of water-soluble organic acids, aldehydes and ketones. This behavior is confirmed by the high acidity levels observed in both the bio-oil (173.11 mg KOH/g) and the aqueous phase (191.60 mg KOH/g), revealing a significant presence of acidic and phenolic compounds, which compromises the stability and direct application of these liquids as fuels or industrial inputs without prior treatment or refining. The significant biochar yield (31.79%) suggests that the biomass has a thermally resistant solid fraction, such as lignin, which may be advantageous for applications in carbon sequestration, adsorbents or soil improvement. Gas production (27.44%) is within the expected range for moderate temperatures and contributes to the energy balance of the process.

Results of the Pyrolysis Process of the in Natura açaí Seed Sludge
The results of the pyrolysis process of açaí seed sludge, the yields of bio-oil, biochar and gases, as well as the time and temperature parameters of phase formation, are presented in detail in Table 3.

Table 3: Pyrolysis Parameters of in Natura açaí Seed Sludge
Pyrolysis of açaí seed sludge at 450°C resulted in a high yield of biochar (40.50%), followed by the aqueous phase (38.18%), non-condensable gases (19.17%) and a reduced fraction of bio-oil (2.13%). These results reflect the composition of the sludge, characterized by a higher fixed carbon content and lower volatile content compared to other fractions of the residue, favoring the formation of biochar and limiting the generation of condensable organic compounds. The high biochar yield highlights the potential of sludge as a precursor of carbonaceous materials, with possible applications in adsorption, soil improvement, or as a carbon source for industrial use. In addition, its greater thermal stability suggests a lignocellulosic structure that is more resistant to degradation, which contributes to carbon retention in the solid matrix. Bio-oil production was modest but presented an acidity index of 144.25 mg KOH/g — a value that is still high, although lower than that recorded for fibers. This data indicates the presence of organic and phenolic acids, which affect the stability and viability of the direct use of bio-oil as fuel, requiring additional refining or stabilization steps. The aqueous phase, with an acidity of 181.07 mg KOH/g, confirms the significant release of water-soluble compounds and light acids, typical of the decomposition of hemicellulose and cellulose.

Physicochemical Characterization of Liquid Pyrolysis Products Obtained from açaí Seed Fiber and Dregs
According to the data presented in Table 4, the bio-oil obtained from the fibers and sludge of the açaí seeds presented high viscosity (11.27 mm^2/s and 11.57 mm^2/s, respectively) and density close to 1 g/cm^3, characteristics that indicate the presence of high molecular weight organic com-pounds, typical of heavy fractions originating from the thermal degradation of biomass. The acidity of the bio-oil, although significant (173.11 mgNaOH/g for the fibers and 144.25 mgNaOH/g for the sludge), is lower than that observed in the aqueous phase generated. In con-trast, the aqueous phase presented low viscosity (1.45 mm^2/s for fibers and 1.348 mm^2/s for sludge) and high acidity (191.60 mgNaOH/g and 181.07 mgNaOH/g), respectively), evidencing its highly polar and acidic profile, resulting from the formation of water-soluble compounds such as light organic acids and phenols during the pyrolysis process.

Table 4: Physicochemical Characterization of Liquid Pyrolysis Products
These results demonstrate that the pyrolysis of açaí seeds allows the production of two liquids with distinct physical and chemical properties and potential applications. Due to its high viscosity and density, bio-oil is viable as a biofuel or input for the synthesis of value-added chemical products. However, its high acidity can compromise stability and require treatment processes to adapt it to energy use. The aqueous liquid, with low viscosity and high acidity, shows potential for application in the food, agricultural and pharmaceutical industries, provided it is adequately purified and characterized. The valorization of açaí agro-industrial waste through pyrolysis not only contributes to the mitigation of environmental impacts but also strengthens the principles of sustainability and the circular economy in the Amazon region, promoting the full use of biomass.

Compositional characterization of liquid pyrolysis products (FT-IR)
Fourier transform infrared spectroscopy (FTIR) is an analytical technique widely used in the characterization of organic materials, allowing the identification of functional groups and providing detailed structural information on the chemical composition of samples. In the present study, the FTIR technique was applied to the analysis of the liquid phases resulting from the pyrolysis (bio-oil and aqueous fraction) of fibers and sludge from açaí seeds, with the aim of identifying the main organic compounds formed during the thermochemical process. The spectral analyses, presented in Figures 4, 5, 6 and 7, were interpreted considering the specific character-istics of each sample, allowing relevant inferences about the predominant molecular constituents in each liquid fraction.

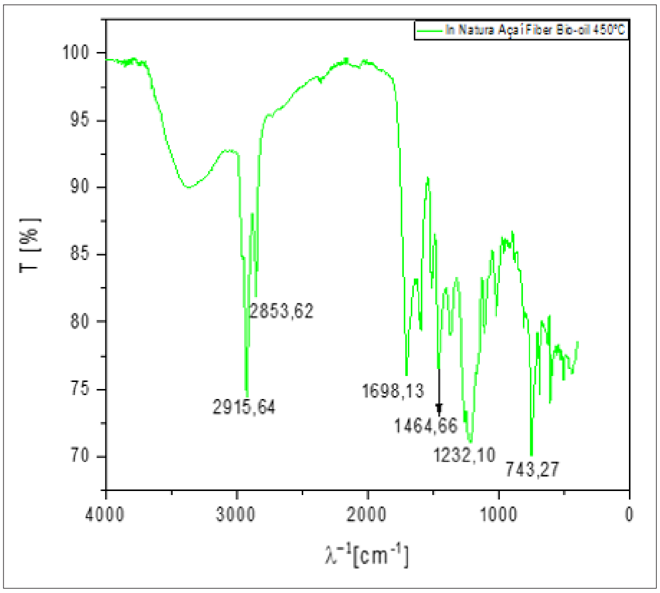

Figure 4: FTIR Spectrum of the Bio-oil of the in Natura Açaí Fiber

The FTIR spectrum of the bio-oil obtained from the pyrolysis of fresh açaí fiber at 450°C, shown in Figure 4, shows a complex chemical matrix, characterized by multiple absorption bands as-sociated with different functional groups. The bands located at 2915.64 cm⁻¹ and 2853.62 cm⁻¹ are attributed to the presence of C–H stretches of aliphatic hydrocarbons, indicating the occur-rence of alkanes and possibly alkenes. The band at 1698.13 cm⁻¹ corresponds to C=O stretches, typical of carbonyl compounds, such as carboxylic acids, aldehydes and ketones, which confer a polar character and high acidity to the bio-oil. The absorptions at 1464.663cm⁻¹ and 1232.10cm⁻¹ indicate the presence of alcoholic groups (C–O) and ethers, respectively, while the band observed at 743.27cm⁻¹ is related to out-of-plane deformations of the C–H bonds of alkenes. These results confirm that bio-oil is a heterogeneous mixture of organic compounds, with a predominance of hydrocarbons and oxygenated compounds, which directly influence its physicochemical prop-erties and expand its application possibilities in different sectors, such as energy and chemi-cal-industry.

The analysis of the FTIR spectrum of the aqueous phase resulting from the pyrolysis of the açaí fiber in natura at 450°C, presented in Figure 5, shows a predominantly aqueous composition rich in oxygenated compounds. The broad and intense band observed at 3350.66 cm⁻¹ is attributed to the stretching vibration of the O–H groups, indicating the presence of water, alcohols, phenols or carboxylic acids. The band at 1636.11 cm⁻¹ is associated with the C=O stretching, characteristic of carbonyl groups, such as carboxylic acids, aldehydes and ketones, which contribute signifi-cantly to the acidity of the liquid phase. The absorption recorded at 1278.61 cm⁻¹ may be related to the presence of C–O bonds, common in alcohols, ethers or carboxylic acids, possibly derived from the thermal degradation of the biomass constituents during the pyrolytic process. These results confirm that the aqueous fraction has a hydrophilic character, being composed mainly of low molecular weight oxygenated compounds, which influence its physicochemical properties and expand its potential for application in the food, agricultural or pharmaceutical industries.

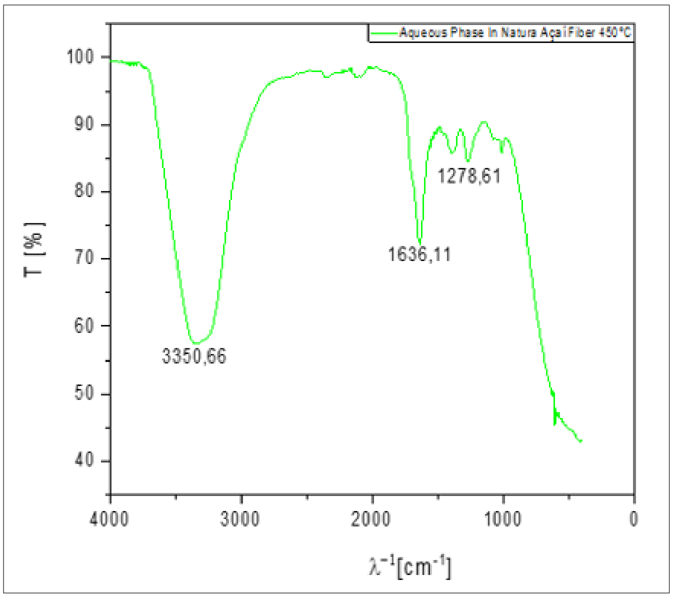

Figure 5: FTIR Spectrum of the Aqueous Phase of the in Natura Açaí Fiber.

The FTIR spectral analysis of the bio-oil obtained from the pyrolysis of in natura açaí sludge at 450°C (Figure 6) reveals the presence of several functional groups, indicating a complex and heterogeneous chemical composition. The bands located at 2931.14 cm⁻¹ and 2861.83 cm⁻¹ correspond to the stretching of the C–H bonds of aliphatic hydrocarbons, suggesting the for-mation of alkanes and alkenes. The band at 1713.63 cm⁻¹ is attributed to the stretching of carbonyl groups (C=O), present in compounds such as carboxylic acids, aldehydes or ketones, which confer polarity and acidity to the bio-oil. The absorption at 1232.10 cm⁻¹ is related to the presence of C–O bonds, typical of alcohols, ethers or also carboxylic acids. In addition, the band at 751.48 cm⁻¹ may be associated with out-of-plane deformations of C–H bonds in alkenes or substituted aromatic rings.

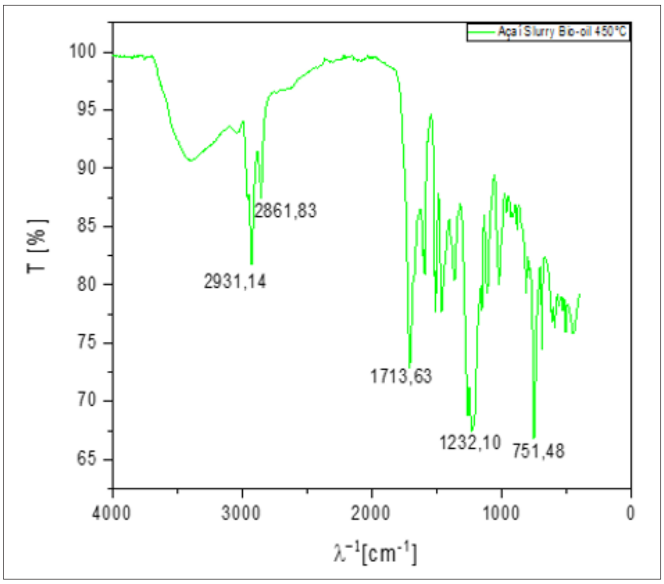

Figure 6: Ftir Spectrum of the Bio-Oil of the in Natura Açaí Seed Sludge

The analysis of the FTIR spectrum of the aqueous phase obtained from the pyrolysis of fresh açaí sludge at 450°C (Figure 7) shows the presence of several organic functional groups, indicating a complex chemical composition. The broad and intense band at 3366.16cm⁻¹ is associated with the O–H stretching, characteristic of hydroxyl groups present in molecules such as water, alcohols and carboxylic acids. The presence of water is expected, given the nature of the sample, although the contribution of other oxygenated compounds cannot be ruled out. The band at 1643.41cm⁻¹ suggests the presence of carbonyl groups (C=O), as in carboxylic acids and aldehydes, while the absorption at 1387.14cm⁻¹ is related to deformation of C–H bonds. The band at 1271.31 cm⁻¹ can be attributed to C–O stretching, indicative of alcohols or esters, and the absorption at 1006.83 cm⁻¹ suggests the presence of C–O–C bonds, typical of ethers or polysaccharide structures.

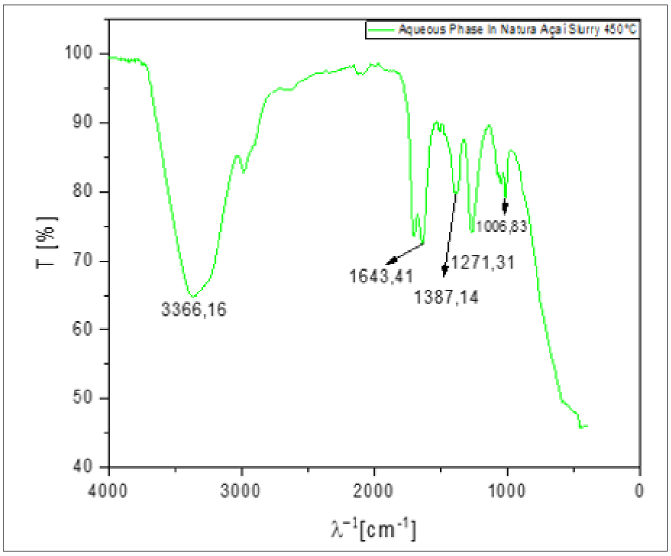

Figure 7: FTIR Spectrum of the Aqueous Phase of the in Natura Açaí Seed Sludge

Discussion

In general, açaí seed sludge demonstrated more promising characteristics to produce bio-oil via pyrolysis, due to its lower ash content and higher volatile content. The fibers and seeds, although presenting slightly higher ash content, are still materials with good energy potential. These data reinforce the feasibility of the full use of açaí residues in thermal conversion processes, contrib-uting to the valorization of agro-industrial waste and sustainability in the Amazon region. The results of the pyrolysis of açaí seed fibers indicated that, although the bio-oil yield was limited, the fibers have potential to produce biochar with added value, while the liquids generated require additional treatment steps due to their high acidity and compositional complexity. In summary, the sludge demonstrated greater thermal stability and potential for the generation of high-quality biochar, with liquids rich in acidic compounds that require additional treatment for energy or chemical applications.

Conclusions

The physical characterization of the fiber and açaí seed sludge confirmed their potential as bio-mass to produce bio-oil via pyrolysis, highlighting their low ash content and high volatile content. Pre-drying proved to be essential for the efficiency of the process, and the solid residue (biochar) has additional energy potential.

The pyrolysis of the fiber resulted in a low yield of bio-oil (1.15% by mass) and high acidity, highlighting the need to optimize the operational parameters and pre-treatment of the biomass. In contrast, the sludge presented a higher yield and lower acidity, proving to be more promising as a raw material for biofuels. In both cases, the composition of the products is sensitive to the tem-perature conditions and cracking time.

The physical-chemical characterization of the liquids obtained revealed two distinct fractions: the bio-oil, with high viscosity and density, composed of hydrocarbons and oxygenated compounds, suitable for energy or chemical applications; and the aqueous phase, with high acidity and po-tential for use in the food, agricultural and pharmaceutical industries. FTIR spectroscopic analysis confirmed the presence of various functional groups, such as carbonyls, hydroxyls, alcohols, ethers and carboxylic acids, in both the bio-oils and the aqueous phases, attesting to the compo-sitional complexity and added value of the products. Thus, the pyrolysis of açaí seed fiber and sludge is a viable strategy for the valorization of agro-industrial waste, contributing to the sus-tainability of the açaí production chain and to the advancement of bioenergy solutions and re-newable products.

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