

Thinking about Alternatives to Açai Waste in Amazonia Communities

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In the Amazon, *Euterpe oleracea* Mart. (açai), is part of the identity of traditional communities, and the fruit is integrated into their everyday sociocultural dynamics. Hydrolysis and pyrolysis of residual biomass can be alternatives to yield sugars, ethanol, biochar and bio-oil. The açai seeds subjected to oxidative pretreatment followed by acid hydrolysis increased cellulose to fermentable sugars (reaching 23.5%) and second-generation ethanol production (17.441 L t⁻¹). Açai oil (ca. 30%) was extracted using a Soxhlet apparatus (using hexane as solvent) and detected through gas chromatography coupled to mass spectrometry (GC-MS), where acids accounted for 82.43% of the total composition, while alcohols comprised only 13.15%. For pyrolysis, temperatures (500 and 550 °C), time (20 and 30 min), and activation temperature (750 and 800 °C) were evaluated, resulting in yields of ca. 22% for biochar and 30% for bio-oil. For the bio-oil, the main compounds detected by GC-MS were acids (16.3%), aldehydes (13.08%), amides (12.19%), alcohols (6.72%), and phenols (4.64%). The obtained biochar displayed surface area values of 553.7 m² g⁻¹ and 10% crystallinity, indicating its more amorphous nature.

Keywords: *Euterpe oleracea* Mart. (açai), pyrolysis, thermal conversion, ethanol, second generation biofuels

Introduction

Açai is a palm tree native to the Amazon (*Euterpe oleracea* Mart), and can produce up to 45 stems *per* cluster at different stages of growth. It can reach heights of up to 30 meters with a diameter of 12 to 18 centimeters. Reproduction occurs between 5 to 10 years, and the lifespan typically ranges from 10 to 25 years. The infructescence varies from 3 to 8 *per* stem at different stages

of development. It consists of hundreds of fruits, weighing from 0.5 to 2.8 grams and measuring 1 to 2 centimeters in diameter. The fruit contains a thin mesocarp, 1 to 2 millimeters thick, with variable coloration, and the edible part (epicarp and mesocarp), represents an average of 15% of the fruit, with the epicarp being indistinct. The majority of the fruit is composed by the endocarp, which is spherical and fibrous on the outer surface. It contains a seed with an embryonic axis and a reserve tissue composed of silica and rich in lipids.¹

According to data from Instituto Brasileiro de Geografia e Estatística (IBGE),² in 2021 the production of açai pulp

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reached 227.3 thousand tons, which was 3.1% higher than the previous year. In terms of value, however, it increased 11.1%, totaling 771.2 million.² The extraction of açai is concentrated in the states of the Northern Region of Brazil, with emphasis on the State of Pará, which contributes to 95% of the national production. Brazil is the largest global producer,³ with more than 1485 million tons of açai in 2021.²

In the Amazon region, açai holds significant social and economic importance. It is not only a vital food source for the local population, but also plays a crucial role in generating income, employment, and local production. Açai cultivation contributes to the consolidation of family farming and helps sustain people's livelihoods in rural areas.⁴ Currently, the demand for açai is driving the market and has expanded beyond the Amazon region due to its high social, cultural, and nutritional value.⁵

The açai seed, corresponding to the endocarp and kernel of the fruit, is a byproduct of the açai production chain.⁶ It is a rich organic material that has attracted the interest of many scientists due to its physicochemical composition (cellulose > 65%, lignin > 22%).⁷ These seeds are typically discarded after the pulp is removed and represent an average of 85% of the weight of the fruits (Figure 1). For every kilogram of açai produced, 2 to 4 kilograms of waste are generated.⁸

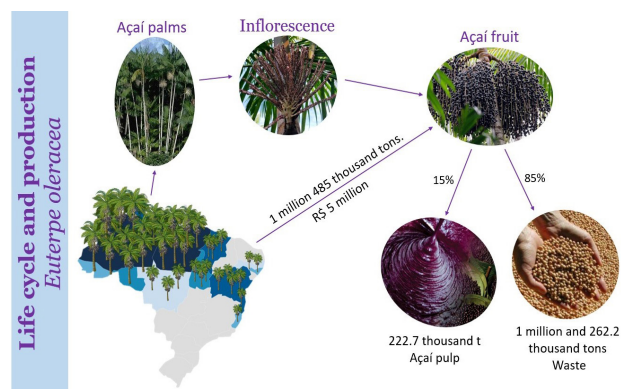


Figure 1. Life cycle and production of *Euterpe oleracea*.

In this context, studies indicate a growing interest in obtaining added value from food waste, hydrolysis and pyrolysis are among the viable options for obtaining energy, bioproducts, oil, biochar, and other valuable products from açai waste.⁹ Several studies have shown the potential of açai waste for energy production. de Castro *et al.*¹⁰ obtained relevant bio-oil yields in pyrolysis, gas, and coke with yields of 4.38, 30.56, and 35.67% (wt.), respectively. Gas chromatography coupled to mass spectrometry (GC-MS) identified 21.52% (wt.) of hydrocarbons and 78.48% (wt.) of oxygenates in the bio-oil, making it possible for

application of fractional distillation to obtain fossil fuels. Sato *et al.*¹¹ evaluated the production of biochar considering favorable agronomic characteristics, such as the high temperature (> 600 °C) and residence time of 60 min. They investigated physicochemical properties, such as pH, porosity, density, and water-holding capacity for possible benefits of biochar.

Pyrolysis can be described as a thermochemical process of decomposing organic compounds and hydrocarbons in an atmosphere with reduced oxygen to form charcoal, oil, and gas.¹¹ In addition to the biomass source, pyrolysis conditions such as temperature, residence time, and heating rate are crucial factors that determine the characteristics of biochar, with temperature being the key factor in defining its properties.¹²

This way, the objective of this study was to use agro-industrial açai residues as raw material for the production of higher-value-added materials, biochar and bio-oil, since these residues are easily acquired and disposed of in inappropriate areas. For this, these residues were pyrolyzed and the products obtained were characterized.

Experimental

Samples

The residual biomass of açai was collected outdoors in the municipality of Dom Eliseu in the State of Pará, located at a latitude of 4°25'57.72" South and longitude of 47°31'32.28" West.

Methodology

The collected material was processed at the Laboratório de Química da Universidade Federal do Tocantins, where the fractions (seeds) were separated manually. The material was separated and dried in an oven at 60 °C for 24 h.

The açai seeds were analyzed according to standardized procedures (NBR 8292,¹³ ASTM D 2013-86)¹⁴ for moisture, ash, fixed carbon and volatiles. The oil extractions were performed using the Soxhlet system with ethanol and hexane (Êxodo Científica, Sumaré, Brazil), separately as a solvent following NREL guidelines.¹⁵

The ethanol extractions were only dried and weighed for quantification. After hexane extraction, the sample was rotary evaporated to eliminate the solvent, then anhydrous sodium sulfate (Êxodo Científica, Sumaré, Brazil) was added and the oil was filtered and analyzed by GC-MS (7890B, Agilent, Santa Clara, USA), with selective mass detection systems (MSD). The employed capillary column was an HP-5MS (Agilent, Santa Clara, USA) stationary

phase, measuring $30\text{ m} \times 250\text{ }\mu\text{m} \times 0.25\text{ }\mu\text{m}$ with helium carrier gas. The sample injection into the equipment occurred directly by introducing $1\text{ }\mu\text{L}$ of sample in 1:50 split sample mode with the dissolution of the oil sample in a 1/100 percentage by volume (v/v) in hexane. The system temperatures were as follows: injector, $155\text{ }^\circ\text{C}$; oven temperature programming starting at $45\text{ }^\circ\text{C}$ for 3 min with subsequent increase to $150\text{ }^\circ\text{C}$, remaining for 5 min at a rate of $20\text{ }^\circ\text{C min}^{-1}$, ending at $250\text{ }^\circ\text{C}$ with a run time of 48 min, ionization source at $230\text{ }^\circ\text{C}$ and the quadrupole analyzer at $150\text{ }^\circ\text{C}$.

The major constituents (holocellulose) were determined using the determination of fiber in neutral detergent (NDF) and acid detergent (FDA) methods proposed by Van Soest, as cited by Khudyakova and Kosolapova.¹⁶ Lignin was determined through hydrolysis.¹⁷

For the oxidative pretreatment used to facilitate access to cellulose, 2 g of samples were subjected to a 1% hydrogen peroxide (H_2O_2 , Quimex, Uberaba, Brazil), solution (40 mL) with a pH of 11.5 for a period of 24 h. Afterward, they were filtered and dried in an oven for an equal period.

The hydrolysis performed was of an acidic nature, using 72% sulfuric acid (Quimex, Uberaba, Brazil), followed by autoclaving for 15 min at $121\text{ }^\circ\text{C}$. After hydrolysis, the samples (*in natura* and pre-treated) were subjected to high-performance liquid chromatography (HPLC) to quantify the production of glucose from cellulose hydrolysis.

The theoretical ethanol production was estimated from the hydrolyzed fraction of the fiber (soluble sugars) using the Gay-Lussac stoichiometric equation for alcoholic fermentation.¹⁸

Pyrolysis consists of a stainless-steel fixed bed reactor (FLYEVEER, model FE50RPN and line 05/50, São Paulo, Brazil) heated by a reclining split furnace using heated water steam as a carrier gas.¹⁹ The pyrolysis process was carried out according to the optimized conditions, evaluating three factors: pyrolysis temperature (500 and $550\text{ }^\circ\text{C}$), pyrolysis time (20 and 30 min), and activation temperature (750 and $800\text{ }^\circ\text{C}$). The mass of the açai seeds was measured before and after pyrolysis, and the yield of the obtained activated biochar was calculated. Finally, analysis of variance (ANOVA: single-factor with 95% confidence) was conducted to determine whether the evaluated factors had an influence on productivity.¹¹

The biochar and bio-oil samples were submitted to pH measurements, using a QUIMIS model Q400-AS pH meter (Diadema, Brazil). The biomass density was established by one pycnometer method in a thermostatic bath at $20\text{ }^\circ\text{C}$, and for the bio-oil a portable digital densimeter was used (Anton Paar, São Paulo, Brazil), both following

the American Society for Testing and Materials (ASTM) D-4052 procedures.²⁰

For the analysis of the bio-oil constituents, a GC-MS QP2010 Ultra Shimadzu (Shimadzu company, Kyoto, Japan), equipped with a capillary column Rtx-5MS WCOT ($30\text{ m} \times 0.25\text{ mm} \times 0.25\text{ }\mu\text{m}$) was used. The temperature conditions used in GC-MS injector temperature, $250\text{ }^\circ\text{C}$; split mode, 1:50; detector temperature, $230\text{ }^\circ\text{C}$; injection volume, $1.0\text{ }\mu\text{L}$; and oven program, $60\text{ }^\circ\text{C}$ for 1 min, $3\text{ }^\circ\text{C min}^{-1}$, $200\text{ }^\circ\text{C}$ for 2 min, $20\text{ }^\circ\text{C min}^{-1}$ and $230\text{ }^\circ\text{C}$ for 10 min. The intensity, retention time and identification of the compounds were recorded for each analyzed peak according to the NIST mass spectral library (Standard Reference Database 1A, V14). The bio-oil was not derivatized before analysis.

The biochar samples were analyzed on a Fourier transform infrared (FTIR) spectrometer (Agilent Cary 630 FTIR spectrometer, Santa Clara, California, USA) with a range from 4000 to 650 cm^{-1} , with an increase of 4 cm^{-1} . Crystallinity was measured through X-ray diffraction (XRD) analysis (Bruker D8 Advance, Karlsruhe, Germany) with Cu K α radiation at 20 mV, diffraction angle 2θ from 5 to 35° in steps of 0.05° and the crystallinity index (IC) calculated according to Rambo *et al.*²¹

The scanning electron microscopy analysis (SEM) was performed (Shimadzu SSX-550, Kyoto, Japan), with dried samples and coated with Au/Pd film. The images were amplified to magnitudes ranging from 300 to 3,000 \times , and observed at 10 kV.

Results and Discussion

Characterization and hydrolysis

The results presented in Table 1 demonstrate the possibility of açai seeds being used as a source for obtaining bioproducts. The high hemicellulose content, (35.4%) is useful for the production of xylitol, the essential oils for cosmetics production, and lignin (40.3%) for charcoal production.²²⁻²⁴

The low levels of ash and moisture (after oven drying) allow easier transportation and handling, without affecting the pyrolysis and hydrolysis processes.²⁵ Similar results of hemicellulose content were found by Rambo *et al.*,²¹ in açai seeds, in which the hemicellulose amount was significantly higher than cellulose with mannose being the main sugar identified. Moreover, Tavares *et al.*²⁶ found similar results for moisture, extractives, and ash content, but in contrast, cellulose (45.1%) had higher levels than hemicellulose (6.6%). Santos *et al.*,²⁷ in their study of the composition of fresh açai seed biomass, found the following values:

Table 1. Biomass characterization results (percentage of dry mass)

Component	Concentration untreated biomass / %	Concentration pretreated biomass / %
Moisture	8.9 ± 0.1	–
Ash	2.2 ± 1.9	–
Extractives ethanolic	14.1 ± 0.2	–
Extractives hexane	27.5 ± 3.5	–
Cellulose	8.0 ± 1.0	23.5 ± 0.8
Hemicellulose	35.4 ± 0.9	13.3 ± 0.8
Lignin total	40.3 ± 0.01	21.7 ± 0.1
Volatile material	73.8 ± 0.3	–
Fixed carbon	24.0 ± 0.8	–

lignin 25.1%, hemicellulose 58.1%, and cellulose 18.6%, which differ significantly from the values obtained in the present study.

In terms of chemical composition, a higher lignin (40.3%) and extractives (14.1%) and a lower cellulose content (8.0%) were observed compared to other vegetable fibers. However, the chemical composition of the açai fiber can vary depending on the species and collection location.⁸

In order to increase the low cellulose percentages (8.0%), the biomass was subjected to an oxidative pretreatment. The pretreatment facilitated enzyme access for cellulose conversion (increasing to 23.5%) into fermentable sugars and subsequent conversion into second-generation ethanol. When analyzing the effect exerted by the pretreatment on açai seed biomass, a positive effect is observed, resulting in the removal of lignin (21.7%) present in the biomass after pretreatment. Regarding hemicellulose approximately 38.0% of this fraction was removed. Santos *et al.*,²⁷ when analyzing the lignocellulosic composition of açai seeds after treatment with hydrogen peroxide, found cellulose, hemicellulose, and lignin values of 40.3, 16.2, and 18.3%, respectively.

With the aim of estimating ethanol production, both untreated and hydrogen peroxide pretreated açai seeds were subjected to acid hydrolysis, and hydrolysate products were quantified (Table 2). In a study conducted by Cordeiro *et al.*,²⁸ when analyzing the glucose fraction present in açai seeds hydrolysate, found values ranging from 4.93 to 13.68 g L⁻¹, which were higher than the results in the present study.

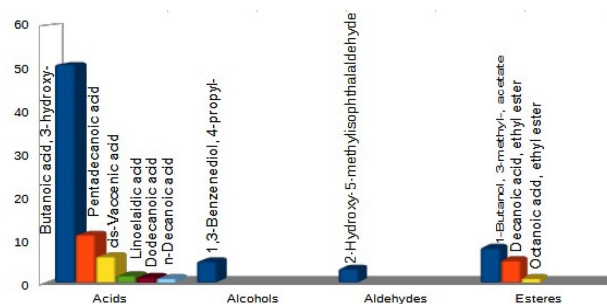
Table 2. Carbohydrates and alcohol production estimation from açai wastes

Biomass	Glucose / (g L ⁻¹)	Ethanol yield / (L t ⁻¹)
<i>In natura</i>	1.099	12.951
Pretreated	1.480	17.441

dos Santos²⁹ evaluated the fresh sorghum biomass, which showed 30.72% cellulose. From the cellulose hydrolysis, they found glucose values between 0.186-0.685 g L⁻¹. When compared to the results obtained in the present study, it can be observed that the açai seed biomass presents higher post-hydrolysis glucose values, making it a viable alternative for second-generation ethanol production. The difference in values for both cellulose and the amount of glucose is justified by the different types of biomasses used, in which açai seed biomass performed better in the conversion of cellulose into glucose even at a lower concentration when compared to sorghum.²⁹

When comparing the estimated alcohol production of the *in natura* biomass with the pretreated biomass, it can be observed that the biomass subjected to hydrogen peroxide treatment had an increase of 34.7%. This makes the pretreatment stage essential for increasing glucose concentrations and, consequently, higher bioethanol production. The pretreatment employed in this study (with a yield of 70.6%) with the central objective of facilitating access to the cellulose fraction and subsequently hydrolyzing it into glucose, has proven to be effective in significantly reducing hemicellulose and lignin fractions, thereby making cellulose accessible.

Continuing with the utilization of açai waste, the oil extracts were analyzed and quantified for further economic evaluation. Acids were the most abundant, representing 82.4% of the total composition, while alcohols accounted for 13.1% of the organic groups present in açai oil. These alcohols include compounds such as glycerol and fatty alcohols, which can have emulsifying and moisturizing functions that benefit the skin and hair when used in cosmetic products.³⁰ Aldehydes and esters are present in smaller quantities, representing 3.3 and 0.6% of the organic groups, respectively (Figure 2).

**Figure 2.** Chemical compounds obtained from açai hexane extracts (relative abundance).

Pyrolysis products

Table 3 contains the results of the average percentage yields obtained from the initial mass of açai seeds with

respect to the activated biochar after pyrolysis. The average percentage yield was $22.7 \pm 1.5\%$, with the pyrolysis temperature condition of $550\text{ }^{\circ}\text{C}$, residence time of 30 min, and activation at $750\text{ }^{\circ}\text{C}$ yielding the highest percentage, at 24.9% . The average yield in this study is in line with the yield found by other authors, such as 22.2% using a temperature of $700\text{ }^{\circ}\text{C}$, $23.4 \pm 0.13\%$ of non-volatile matter,³¹ and 26.4% in laboratory tests at a temperature of $450\text{ }^{\circ}\text{C}$.⁷ This yield is due to the amount of lignin present in the açai seeds, as lignin requires higher temperatures (up to $900\text{ }^{\circ}\text{C}$) to completely degrade.³²

Table 3. Pyrolysis conditions (temperature, residence time and activation temperature) for evaluated activated biochar yield

Pyrolysis temperature / $^{\circ}\text{C}$	Residence time / min	Activation temperature / $^{\circ}\text{C}$	Yield / %
550	20	800	20.1
550	20	750	21.7
550	30	800	21.7
550	30	750	24.9
500	20	800	22.8
500	20	750	23.7
500	30	800	22.7
500	30	750	23.8

Table 4 contains the data from the single-factor ANOVA tests for the three parameters evaluated. From the *F*-value and the *p*-value, it can be observed that among the three factors evaluated in pyrolysis, the difference in activation temperature has the greatest influence on the yield of activated biochar. This is likely because activation temperatures are higher than pyrolysis temperatures and are closer to the temperature of lignin degradation. However, the ANOVA test rejected the hypothesis that variations in the parameters influence the yield of activated biochar. For this reason, the characterizations of activated biochar were performed on the composite sample from the eight pyrolysis conditions.

The pH values measured for the biochar and bio-oil were 9.61 and 5.22, respectively, and the densities were 0.47 and

Table 4. Analysis of variance (ANOVA) statistical tests-checking whether the factors evaluated in pyrolysis (pyrolysis temperature, residence time and activation temperature) influenced the yield of activated carbon

Group	Critical <i>F</i>	<i>F</i>	<i>P</i> -value
Pyrolysis temperature (500 and $550\text{ }^{\circ}\text{C}$)		1.301509	0.297418
Residence time (20 and 30 min)	5.987378	1.330484	0.292589
Activation temperature (750 and $800\text{ }^{\circ}\text{C}$)		3.302517	0.119068

1.46, respectively. The basic nature of the biochar's pH indicates good stability, and therefore, suitability for use in soil.³³ The agronomic potential from elephant grass biomass biochar obtained through slow pyrolysis was evaluated.³⁴ The biochar was incubated in the soil for 60 days to determine the soil fertility. The biochar produced had a high content of micro and macronutrients and the agronomic tests showed that the biochar presented great potential to be used as an auxiliary liming agent, and as a fertilizer.

The microscopies of *in natura* açai seeds samples showed a scaly surface (Figure 3a). In contrast, for the activated charcoal, a heterogeneous surface with well-defined pores can be observed after the physical activation process, featuring cavities of different sizes distributed on its surface.

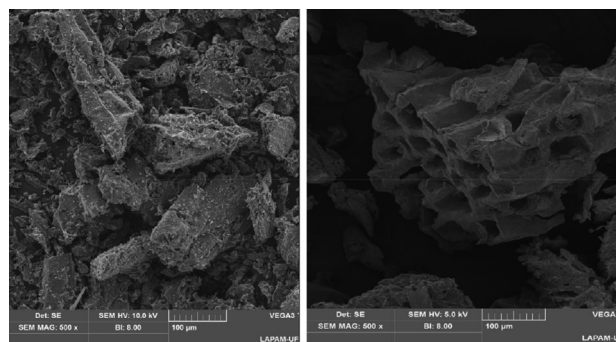


Figure 3. Scanning electron microscopy images of (a) *in natura* biomass; (b) activated açai biochar.

Regarding the porosity of the biochar (Figure 4a), the N_2 adsorption/desorption isotherm on the activated açai biochar (AAB) is classified as type I, characteristic of microporous solids with a relatively small external surface area.³⁵ This characteristic of AAB is confirmed by Figure 4b, which shows the pore size distribution, indicating that most of the pores are in the range of smaller micropores and mesopores (below 5 nm).

The Brunauer-Emmett-Teller (BET) surface area in this study (Table 5) was lower than that of the studies by Ramirez *et al.*,³⁶ with $920.59\text{ m}^2\text{ g}^{-1}$ and Feitoza *et al.*,³⁷ with $1315\text{ m}^2\text{ g}^{-1}$, both of which also produced biochar from açai seeds. However, both of those studies used chemical activation, while this study used physical activation. But, when compared to commercial activated carbon (CAC), there was no significant difference in the surface area value. The total pore volume is $0.23\text{ cm}^3\text{ g}^{-1}$, with $0.19\text{ cm}^3\text{ g}^{-1}$ attributed to micropores. Thus, AAB is predominantly microporous, which is consistent with Figure 4b and, also with the BET surface area ($553.7\text{ m}^2\text{ g}^{-1}$). Higher specific surface area may contribute to significant changes in the physical properties of the soil by changing its texture, structure, consistency, porosity, pore size, size distribution, and density.³⁴

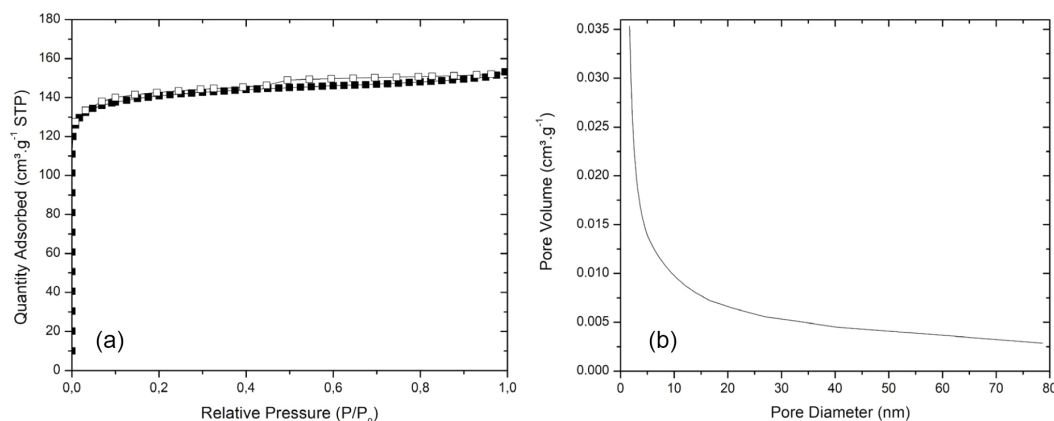


Figure 4. (a) Isotherm of adsorption/desorption on N₂ of activated açai biochar (AAB); (b) pore size distribution of activated açai biochar (AAB).

Table 5. Surface area of the activated açai biochar and commercial activated carbon

Component	Biochar	
	AAB	CAC
Surface area BET / (m ² g ⁻¹)	553.7	926
Micropores volume / (cm ³ g ⁻¹)	0.19	0.29
Total pore volume / (cm ³ g ⁻¹)	0.23	0.22
Micropores area / (m ² g ⁻¹)	490	642

AAB: activated açai biochar; CAC: commercial activated carbon;³¹
BET: Brunauer-Emmett-Teller.

The presence of micropores supports the use of this material as a potential soil fertilizer, since they are responsible for the sorption capacity (retention of water, gases, heavy metals, organics, and nutrients).

It is noticeable from the FTIR analysis (Figure 5) that the structure of açai seeds was modified after pyrolysis and activation. Pyrolysis and activation reduced the stretching of C–H (2980–2820 cm⁻¹) groups and methylene methyl.^{12,38} The bands at 2430 and 2370 cm⁻¹ underwent modifications after the thermal treatment, causing a shift to 2530 cm⁻¹.

The bands from 1578 to 1620 cm⁻¹ demonstrate that the C=C bond of alkene and aromatics are present in the biochar, respectively. Thermal destruction of cellulose and lignin in the feedstock may result in the exposure of aliphatic alkyl –CH₂, hydroxyl –OH, ester, carbonyl, and aromatic C=O functional groups in the biochars. The presence of oxygen containing functions in the raw açai is confirmed by the C–O stretching (carboxyl group) at approximately 1072 cm⁻¹.³⁴

Aromatic structures are evidenced by the presence of a strong band peaking at 1424 cm⁻¹ attributed to C6 ring modes. Carboxyl and carbonyl groups in the biochar act as chelating agents, may enhance the ion exchange capacity of the material, helping to chelate and to release cations.³⁹

The diffraction patterns of the charcoal did not exhibit characteristic diffraction peaks of crystalline materials, but

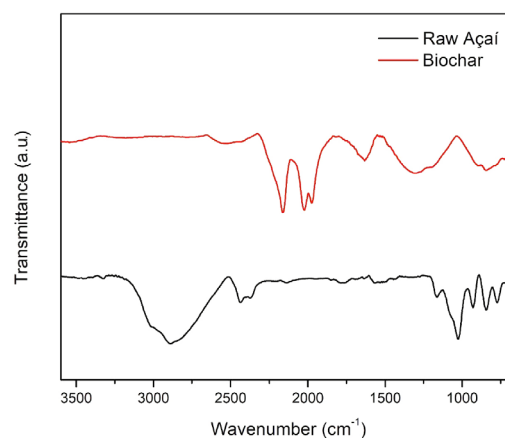


Figure 5. FTIR spectra of raw açai biomass (açai seeds) and activated açai biochar.

showed a typical pattern of an amorphous solid (amorphous carbon), different from the açai biomass in its natural state (40% carbon index). Normally, biochar has a structure composed of crystalline graphene sheets and amorphous aromatic structures, with low reactivity, making it a much more difficult product to degrade than many other forms of organic matter in the soil. Oxidation of biochar generally occurs slowly in the soil, leading to the production of negative functional groups on their surface, with a high cation exchange capacity (CEC), meaning the ability of the soil to retain nutrients in the form of available cations for plants.⁴⁰

The aromatic structure of biochar with amorphous carbon is the main reason for the high stability of biochar. This means that microorganisms will not be able to easily use the carbon as an energy source and possibly other nutrients contained in the carbon structure. This demonstrates that the biochar obtained in this study has high potential to act as a soil conditioner. Similar XRD biochar diffractograms with the same characteristic peaks from other lignocellulosic residues were found.⁴⁰

The thermal decomposition of lignocellulosic biomass components during pyrolysis leads to the formation of

thousands of different compounds (cited only in this work with > 1%), mostly oxygen-containing, compounds.⁴¹ These compounds are of different chemical origin, they have a wide distribution of physical and chemical properties including density, viscosity, polarity, solubility, boiling, etc. Oxygen is present in these compounds in a variety of different chemical classes (functional groups) including acids (16.3%), alcohols (6.7%), phenols (4.64%), aldehydes (13.08%), amides (12.2%), esters, ethers, furans, ketones, etc. (Table 6). The bio-oil compounds with yield of 30% for the liquid phase (aqueous + organic phase) can be monofunctional or multifunctional, that is, they can contain one functional group or several different functional groups.

Table 6. Quantitative determination by GC-MS of the most commonly found compounds in the liquid phase

Compound	Height / %
	Bio-oil
Furfural	13.77
Piperidine-4-carbonitrile	12.06
2-Furanmethanol	8.48
2-Butanone, 1-(acetyloxy)-	5.57
Phenol	5.22
N-Hexadecanoic acid	3.84
Pentadecanoic acid	2.75
Phenol, 2-methyl-	2.52
Tridecane	2.42
Phenol, 3-methyl-	2.24
3-Methylcyclopentane-1,2-dione	2.18
Phenol, 2-methoxy-	2.03
<i>cis</i> -Vaccenic acid	1.93
Undecane	1.89
1-Ethynyl-1-cycloheptanol	1.65
Ethanone, 1-cyclopentyl-	1.65
Dodecanoic acid	1.42
Heptadecane, 2,6-dimethyl-	1.30
Phenol, 2,5-dimethyl-	1.29
3,6-Dimethyl-4-octyn-3,6-diol	1.21
Phenol, 4-ethyl-2-methoxy-	1.20
Maltol	1.17

These concentrations are similar to reported values for bio-oil production from other studies. The analysis of de Pires *et al.*²⁵ revealed a bio-oil yield of 31%, devoid of water content. Biochar yield is a similar result to than found for other lignocellulosic biomasses subjected to pyrolysis in the temperature range 400-700 °C, even under different residence times.

Social and economic analysis

The hydroxyl group is the most abundant functional group

in bio-oils and quantifying the total content of the hydroxyl compounds is very important for optimizing pyrolysis processes and/or the potential bio-oil upgrading processes. On the one hand, bio-oil carbohydrates (found in low concentrations) are very interesting from the point of view of biorefining, since oligomeric or polymeric carbohydrates can be transformed into fermentable monomers and subsequently into biofuels. Another application of bio-oil is its use for heat and energy supply, as it has a similar calorific value to conventional fuels (17.00 MJ kg⁻¹). In addition to this applicability, bio-oil is associated with the production of high-value chemicals, which can be used directly, taking advantage of the functional groups with higher concentration, and those that require compound separation. In the former, there are pesticides and phenolic resins, while in the latter, there are substances that can be used as intermediates in reactions and as final products in the fragrance, cosmetics, and pharmaceutical industries.⁴²

Açaí in the Amazon region holds significance and contributes to income generation, playing a crucial socioeconomic role by supporting the livelihoods of riverine populations, creating jobs, and generating income. Açaí production has been gaining momentum in the local market, opening up opportunities that stimulate income growth in communities through extractivism. According to da Silveira *et al.*,⁴³ there is a notable research trend focusing on the use of fruit seeds, a byproduct of açai processing, which is still considered a significant technological challenge.

The use of 10% of the total açai biomass generated in the Amazonia was simulated, to give an idea of the total profit that could be obtained if they were used through the pyrolytic process (Figure 6). These 10% correspond to 126,234,605 kg of fruit *per year* if they are allocated for pyrolysis.

The estimated revenues were considered based on the fractions obtained through pyrolysis and the average prices practiced in the market, according to IBGE.² In 2021, the açai production in Brazil was 1,485,133,000 kg, and the pulp extracted from this production corresponds to only 15% of this total value, generating revenue of over 1 billion dollars. Considering that 85% of the entire production is waste, if 10% of these residues are used for the production of bio-oil and biochar through the pyrolysis process, it could generate over 20 million dollars. If all the residues were utilized, this revenue could exceed 160 million dollars. The yield rates obtained for biochar (31%) and bio-oil (30%) were considered satisfactory, with a high associated energy content, considering the calorific value of 18.60 MJ.²¹

The processing of açai seeds through pyrolysis can benefit the families involved in açai harvesting, generating employment and income, as demonstrated by the values of bio-oil and biochar achieved in this study.

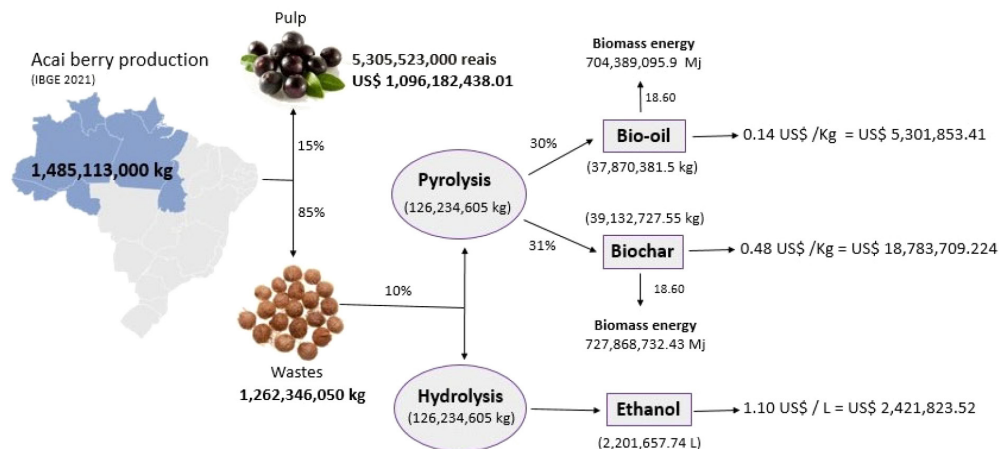


Figure 6. Product yield and theoretical energy potential obtained from açai cycle.

Conclusions

The açai production chain has high economic representative in the Brazilian Amazon. The low cost and wide availability of residues, if used as a potential substrate, can provide significant savings in various sectors of the economy, such as the chemical sector and agriculture.

The results of the post-treatment biomass achieved a higher yield of 70.6%, with concentration of 1.48 g L⁻¹ of glucose and consequently a possible production of 17.4 liters of ethanol. This makes açai seed a viable alternative for the production of second-generation ethanol, due to the high levels of cellulose (23.5%).

Thus, this paper provides positive evidence that the production of biochar (22%) and bio-oil (30%), through pyrolysis can result in the production of several bioproducts (biochar, acids, aldehydes, amides, alcohols, phenols) and also sustainable conservation practices. In addition to promoting social benefits for Amazonian communities, açai is part of the identity of traditional communities and fosters sociability, and the management of the fruit is integrated into everyday sociocultural dynamics.

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Author Contributions

José E. C. Leal was responsible for conceptualization, investigation, project administration, resources, visualization and writing of the original draft; Michele C. D. Rambo for data curation, investigation, validation and visualization; Marcelo M. Pedroza

for data curation, research, resources and validation; Radames A. Q. Cardoso for conceptualization, data curation, investigation, validation and writing of the original draft; Helida M. C. Fagnani for data curation, investigation, visualization, writing original draft, review and editing; Vânia F. de Sousa and Andreia S. Coêlho for conceptualization, research and visualization; Magale K. D. Rambo for conceptualization, data curation, acquisition of funding for formal analysis, investigation, project administration, resources, software, validation, visualization, original draft writing, review and editing.

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