

UTILIZAÇÃO DE BIOMASSA PARA GERAÇÃO SUSTENTÁVEL DE ENERGIA EM COMUNIDADES ISOLADAS DA AMAZÔNIA

BIOMASS UTILIZATION FOR SUSTAINABLE ENERGY GENERATION IN ISOLATED AMAZONIAN COMMUNITIES

Fábio Cordeiro de Lisboa^{1*}, Carlos Alberto Gurgel Veras¹, Augusto César de Mendonça
Brasil¹

¹ Universidade de Brasília – UnB, FCTE, Brasília DF, * E-mail: fabiolisboa@unb.br

Resumo

Este artigo investiga o potencial de três fontes de biomassa amazônica - *Theobroma grandiflorum*, *Astrocaryum aculeatum* e *Acrocomia aculeata* - como soluções para a produção de eletricidade em comunidades isoladas na floresta amazônica brasileira. Essas comunidades enfrentam desafios devido aos altos preços do diesel e à disponibilidade limitada de combustível. O estudo propõe um processo de conversão de energia em duas etapas adaptado para aplicações de calor e energia combinados (CHP). Envolve a carbonização da biomassa seguida pela gasificação do carvão para produzir gás de baixo teor de alcatrão, que é utilizado em um motor bicomcombustível com óleo vegetal puro para ignição piloto. A pesquisa enfatiza a caracterização metódica da matéria-prima, examinando as propriedades físicas e químicas da biomassa e seus derivados adquiridos por métodos de conversão térmica. Protocolos padronizados garantem precisão e confiabilidade, incluindo preparação de amostras seguindo diretrizes ASTM, análise imediata de amostras e modelagem de gasificação. Modelos de equilíbrio preveem concentrações de produtos de gasificação, facilitando o projeto do sistema. O sistema integrado proposto demonstra uma eficiência geral de 40,3%, potencialmente gerando 1.220 MWh de eletricidade limpa anualmente e mitigando aproximadamente 680 toneladas métricas de emissões de CO₂ por ano. Essa abordagem de resíduos para energia promete melhorar a qualidade de vida das comunidades locais ao impulsionar a produção de eletricidade e reduzir a dependência de combustíveis fósseis. A caracterização da matéria-prima e a análise do processo desempenham um papel crucial na utilização de biomassa para geração de energia, oferecendo insights vitais para o desenvolvimento sustentável.

Palavras-Chave: Comunidades isoladas. fontes de biomassa. produção de eletricidade.

Abstract

This paper investigates the potential of three Amazonian biomass sources - *Theobroma grandiflorum*, *Astrocaryum aculeatum*, and *Acrocomia aculeata* - as solutions for electricity production in isolated communities within the Brazilian rainforest. These communities face challenges due to high diesel prices and limited fuel availability. The study proposes a two-step energy conversion process tailored for combined heat and power (CHP) applications. It involves biomass carbonization followed by charcoal gasification to produce low-tar producer gas, which is used in a dual-fuel engine with straight vegetable oil for pilot ignition. The research emphasizes meticulous feedstock characterization, examining the physical and

chemical properties of biomass and its derivatives through thermal conversion methods. Standardized protocols ensure accuracy and reliability, including sample preparation following ASTM guidelines, proximate analysis according to NBR standards, and elemental analysis for comprehensive insights. Specialized equipment aids immediate feedstock analysis, while gas chromatography-mass spectrometry offers chemical composition insights of bio-oil. Gasification modeling evaluates biomass conversion performance, aiding in optimization. Equilibrium models predict gasification product concentrations, facilitating system design. The proposed integrated system demonstrates a 40.3% overall efficiency, potentially generating 1,220 MWh of clean electricity annually and mitigating approximately 680 metric tons of CO₂ emissions yearly. This waste-to-energy approach holds promise in enhancing local community quality of life by boosting electricity production and reducing fossil fuel reliance. Feedstock characterization and process analysis play a crucial role in biomass utilization for energy generation, offering vital insights for sustainable development.

Keywords: Isolated communities. biomass sources. electricity production.

1. Introduction

The national electric power distribution network reveals an insufficient supply of electricity to Brazil's northwest region, primarily dominated by the Brazilian rainforest, accounting for about half of the nation's territory (ONS, 2017). In the Amazon region, thermoelectric generators burning diesel oil realize most of the off-grid electrification of the municipalities, referred to as the isolated distribution network system (Van Els; De Souza Vianna; Brasil Jr, 2012). In remote communities, diesel generators work for a short period of the night, producing limited power, mostly for lighting and television sets because of the high oil price and the shortage of nearby fuel retailers. Besides electricity generation, diesel engines also propel ships and small boats that comprise the large part of the region's primary transportation system. For these communities, increased electrification should help implement productive activities, which would improve income generation and their quality of living (Narula; Bhattacharyya, 2017).

In a report for the Brazilian Ministry of Mines and Energy, Di Lascio e Fagundes Barreto, (2009) presented an economic and technological assessment on renewable energy sources for off-grid electrification of remote communities in the Amazon region. The authors recommended actions towards more intensive use of biomass in combination with solar and hydro, in standalone or combined systems. The rainforest has large biomass resources that can be converted into heat, biofuels, and electricity. In supplying the latter, it is fundamental to consider the widespread diesel generator set across the region. Apart from pure hydrocarbons, diesel engines can also operate in dual mode (Aklouche et al., 2018). The power plant could run with fuel gas from bio-based feedstock gasification and straight vegetable oil (Corsini et al., 2015).

For remote areas, electrification can be materialized through hybrid energy systems. In hybrid mini-grid systems, diesel engine generator sets play an important role either for backup or peak load applications. In dual-fuel operation, diesel engine cycles can also provide baseload power when integrated into a small biomass gasification plant. Through partial or total substitution of fossil fuel, remote communities could increase the share of local renewable resources for power generation. The Energy and Environment Laboratory at the University of Brasilia has considerable experience in the dual-fuel operation mode of compression ignition engines burning straight vegetable oils and producer gas from downdraft gasification of biomass (Rodrigues *et al.*, 2009). In this configuration, gas cleaning has always been challenging to manage. The plant has also been a concerning source of secondary waste, mostly condensed tar.

In biomass gasification, low-tar producer gas can be obtained when pyrolysis and char reduction occur in specific locations inside the reactor separated by a high-temperature pyrolysis gas combustion zone. Such configuration is referred to as staged gasification. Instances are the two-stage downdraft Viking, and the three-stage fluidized bed FLETGAS gasification system. The technologies, however, are not affordable and mature to work in remote areas of the Amazon. Besides, the gasifiers require skilled operators, and the overall cost prevents broad-scale implementation (Brandt; Larsen; Henriksen, 2000; Gómez-Barea; Leckner, 2010; Henriksen *et al.*, 2006).

We propose a different strategy for staged gasification and power generation (Miranda; Veras; Ghesti, 2020). Conceptually, pyrolysis and gasification would occur in different specialized reactors rather than in one piece of standalone equipment. Charcoal from biomass should be produced in a carbonization reactor, optimized for high char yields (Idris *et al.*, 2015). Then, the charcoal from the carbonization plant would feed a gasifier integrated into an internal combustion engine for power generation. By such means, the producer gas would have inexpressive tar content, virtually eliminating the complex process of gas cleaning and the generation of secondary waste. The diesel generator would operate in dual-fuel technology, burning producer gas from charcoal gasification combined with a small amount of diesel or diesel-like fuel to provide the pilot ignition of the air-gas mixture. The proposed technology can be straightforwardly materialized by cost-effective off-the-shelf hardware.

The aim of this study was then to investigate the potential of three biomasses from the western Amazon region of Brazil for CHP (Combined Heat and Power) application: endocarp of the "macaúba" palm fruit (*Acrocomia aculeata*), the endocarp of the "tucumã" palm fruit

(*Astrocaryum aculeatum*), and the epicarp of the fruit of the "cupuaçu" tree (*Theobroma grandiflorum*). A survey in the literature indicated an absence of previous research on the utilization of these biomasses for heat and power generation, particularly their charcoals. The proposed system configuration also circumvents the seasonality of the fruits by storing only energy-densified charcoals. Biological decay of the biomasses is also prevented through carbonization.

Throughout the text, the biomasses *Astrocaryum aculeatum* (Costa et al., 2016; Lira et al., 2013b), *Acrocomia aculeata* (Ciconini et al., 2013; Motta et al., 2002), and *Theobroma grandiflorum* (Cerón; Higuira; Cardona, 2015; Müller et al., 1995) are referred to by their local names, i.e., tucumã, macaúba, and cupuaçu, respectively. The parent feedstocks were characterized by calorific value and by proximate and ultimate analysis. Thermogravimetric analysis was conducted to infer the feedstocks' thermal conversion dynamics. The results help in planning the carbonization experiments in an externally heated batch reactor. The biomasses were subjected to slow thermal degradation for charcoal, bio-oil, and non-condensable gases yield determination. The charcoal and bio-oil produced were also characterized as value-added by-products for energy applications. Additionally, a preliminary energy analysis was performed for the proposed thermal conversion pathway. In a broader sense, the research was conducted in two phases: characterization and fundamental performance analysis of the biomasses and their charcoal for energy application (this work), and performance analysis of the derived charcoal gasification in a small fluidized-bed reactor to be presented in a forthcoming paper (Lira et al., 2013a).

2. Material and Methods

2.1 Feedstock Characterization

The physical and chemical properties of the parent biomass and its thermal conversion by-products were characterized using specific analyses in dedicated devices, adhering to rigorous testing methods. For sample preparation, 20 g of biomass per sample were prepared according to ASTM E 1757-01 "Method A". Initially, the samples were spread on a metal tray to dry at room temperature, then placed in a Marconi MA035 oven for at least 12 hours. The dried samples were cooled in a desiccator and weighed to determine water content. The biomass and charcoal characterization, referred to as feedstock, followed the same drying and preparation procedures. After cooling, samples were crushed in an Ika Werke model M20 crusher and classified by particle size using ASTM 60 (250 mm opening) and ASTM 100 (0.150 mm opening) sieves, which were sieved for 15 ± 1 minutes in a Bectel shaker. The material

from the sieving was then used for proximate analysis (volatile and fixed carbon), while fine particles collected at the bottom were reserved for ash analysis. The proximate chemical analysis of feedstock, standardized by NBR 8112/1986, included moisture, ash, volatile, and fixed carbon contents, relevant to biofuel classification for energy conversion. All analyses were conducted in triplicate, with results averaged. For immediate feedstock analysis, two Quimis Q318A24 furnaces, a precision scale BEL AS200, and desiccants were used. Carbon moisture analysis, performed according to NBR 8112 and E871 standards in triplicate, involved drying approximately one gram of crushed samples (ASTM 60 sieve) at 105°C for five hours. After cooling, the samples were stored in a desiccator for further analysis. Water content was estimated according to Eq.1

$$w = \left(\frac{m_i - m_f}{m_i} \right) \times 100 \quad (1)$$

where m_i and m_f are the initial and final mass of the sample, respectively.

The volatile content estimate was performed according to NBR 8112 and E872 on a triplicate and dry basis. For this analysis, we used three crucibles with lid. The furnace was heated to 900 °C, and biomass samples of $1.0 \text{ g} \pm 0.0003 \text{ g}$ were used for the characterization. When the furnace temperature reached 900 °C, the samples were moved to the vessel opening, kept there for three minutes, followed by seven minutes inside the closed vessel. Then, the crucibles were placed in a desiccator to complete the cooling process. Volatile matter content of the sample (biomass or charcoal), expressed on a dry basis (%_{db}), was determined according to the equation

$$VMC = \left(\frac{m_{i,s} - m_{f,s}}{m_{i,s}} \right) \times 100 \quad (2)$$

where $m_{i,s}$ (g) is the initial mass of the sample taken for test and crucible and $m_{f,s}$ (g) is the mass of charcoal and crucible.

The ash content was performed according to NBR 8112 and D1102 norms, in triplicate and dry basis. For this analysis, we used crucibles previously calcined. The furnace was heated to 700 °C maintained at that temperature for five hours, with $1.0 \pm 0.003 \text{ g}$ of the sample under analysis. After that, the crucibles were placed in a desiccator for cooling. The ash content in the sample (biomass or charcoal) expressed on a dry basis (%_{db}) was determined from the equation

$$AC = \frac{m_{ash} + m_c}{m_{i,s} + m_c} \times 100 \quad (3)$$

where m_{ash} (g) is the mass of the sample, m_c (g) is the mass of the crucible, and $m_{i,s}$ (g) is the initial mass of the sample under analysis.

Fixed carbon (%_{db}), on a dry basis, was calculated by difference following

$$FC = 100 - (VMC + AC) \quad (4)$$

Elemental analysis was carried out to infer carbon (C), oxygen (O), nitrogen (N), and hydrogen (H) content in the biomass and charcoal. These elements were determined by a Perkin Elmer 2400 Series II CHN Elemental Analysis equipment. The NBR / NM 52: 2009 norm was used for the determination of the bulk density, using a cube-shaped container with a volume of 1.0 cm³. Each sample was crushed and classified using ASTM 60 sieves and kiln-dried for 24 hours at 103±2 °C. A desiccator was used for the cooling of the samples after the drying. The samples were loosely placed in a container and then weighed in triplicate. The density was calculated with the following equation

$$\rho = m_s/V_c \quad (5)$$

where m_s (g) is the mass of the sample and V_c (cm³) is the volume of the container.

The specific surface area (BET) and pore size were measured using an accelerated surface area and a porosimeter system ASAP 2020, Micromeritics (Norcross, GA). Charcoal samples were classified and 0.5 g placed in each container for further analysis. Degasification was performed for four hours, allowing the determination of the micropore and mesopore distribution in the sample.

Feedstocks higher heating values (HHV) were determined according to the NBR 8633/1984 standard test norm. Samples of biomass or charcoal were placed in aluminum dishes and dried inside a furnace at 103 ± 2°C until a constant mass was achieved. After drying, the hot samples were placed in a desiccator for cooling. Three compressed samples, weighing approximately 0.45 g were used in a Parr 6400 calorimeter for analysis. The following equation was used to infer the low heating value from the measured higher heating value and the hydrogen (HC) and moisture (MC) contents in feedstock

$$LHV = HHV - 0.0245MC - 0.212HC \quad (6)$$

The carbonization of biomass, a complex process generating charcoal, pyrolygneous liquor (bio-oil), and light gases, typically results in approximately 35% charcoal, 35% liquid, and 30% non-condensable gases under an external heat source in the absence of oxygen (Bridgewater, 2004). To evaluate the potential of parent biomasses for energy applications, a basic characterization of the slow pyrolysis bio-oils was conducted using thermal analysis and

gas chromatography-mass spectrometry (GC/MS). This analysis was performed on a Thermo Scientific Dionex UltiMate 3000 analyzer, following the methodology described by Fortes & Baugh, (2004). Preliminary thermal decomposition experiments were conducted in a TG-FTIR system before the main carbonization experiments in a small batch reactor. The TG-FTIR system, comprising a SCIENTIFIC TGA reactor coupled with an FTIR unit via the THERMO interface, enabled monitoring of pyrolytic gas evolution. The gas passed through a heated transfer line to the TGA interface flow cell IR for IR spectrum analysis, with results stored for further access. The gas line, measuring 100 mm in length with a 23 ml internal volume and KBr windows, was connected to the TG furnace tube, facilitating the passage of inert gases into the gas cell. Approximately 10 mg of finely crushed and screened biomass samples were placed in a platinum crucible and heated at a rate of $2\text{ }^{\circ}\text{C min}^{-1}$ up to $400\text{ }^{\circ}\text{C}$ under a nitrogen flow of 100 ml min^{-1} , with a holding time of 120 minutes at the maximum temperature. The gas cells and transfer line were maintained at $200\text{ }^{\circ}\text{C}$ and $190\text{ }^{\circ}\text{C}$, respectively. Based on the differential thermogravimetric (DTG) curves, parameters for the carbonization experiments in the batch reactor were defined, including heating rate, temperature range, and holding time. The carbonization strategy for the biomasses, ensuring that over 90% of char formation occurs between 200 and $450\text{ }^{\circ}\text{C}$, is summarized in Table 1.

Table 1. Basic parameters for pyrolysis experiments

Biomass	Cellulose peak in DTG ($^{\circ}\text{C}$)	Heating rate ($^{\circ}\text{C min}^{-1}$)	Temperature range (ΔT) ($^{\circ}\text{C}$)	Time in ΔT (min)
Tucumã	328	2.0	330-430	420
Macaúba	325	2.0	330-430	420
Cupuaçu	288	2.0	290-360	420

Source: the author (2020)

The temperature range in Table 1 was defined as the minimum and maximum temperatures for the sample's thermal degradation in a prescribed time. The minimum pyrolysis temperature refers to the end of cellulose degradation. Higher temperatures and process time would enhance lignin degradation, thus reducing charcoal yields. Then, a reaction time at the prescribed temperature range was established for each sample.

2.2 Sample preparation and carbonization

An electric kiln manufactured by SLFI was used for carbonization experiments in a controlled temperature environment (Fig. 1). The kiln had an internal cylindrical container measuring 19 cm in diameter and 35 cm in length with thermocouples inserted at the reactor's center and wall. A minimum of 360 g of each biomass was thermally degraded. The

thermocouple inserted at the vessel's external wall was used to control the maximum temperature the samples would be subjected to. In the reactor, heat propagates from the outer layers to the center (cylindrical coordinates) of the samples. Consequently, the pyrolysis front travels radially from the wall to the center of the reactor, making the thermal degradation slightly non-isothermal. During the entire process, a software named Pyrolysis 10L was responsible for monitoring and controlling the heat input and retrieving data for further investigation. Volatile gases were condensed, and the pyroligneous liquor was collected and measured for subsequent yield and chemical analysis.

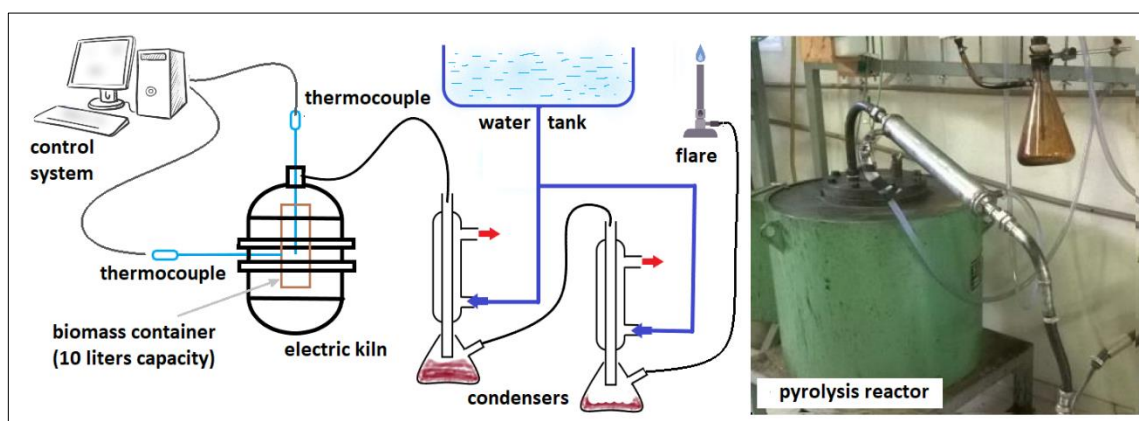


Figure 1. Layout of the carbonization plant and a picture of the pyrolysis batch reactor.

Source: the authors (2024)

For carbonization performance analysis, solid material (charcoal) and condensed liquid (tar) were weighed on a Mars A5000 scale. Solid and bio-oil yields were calculated by the ratio between the respective mass of solid and liquid, and the mass of dry biomass placed into the reactor. Through mass difference, it was possible to infer the yield of non-condensable gases.

2.3 Gasification model

Energy analysis of the integrated gasification dual-fuel engine cycle was performed using models developed by our research group, which rely on a non-stoichiometric thermochemical equilibrium model to evaluate gasification performance. The combined heat and power (CHP) plant analysis was based on energy conservation principles, with process efficiencies determined experimentally by our research team. These models serve as low-cost tools for preliminary performance analysis of CHP systems, allowing the comparison of various gasification parameters, such as feedstock composition and reaction temperature, regardless of gasifier type. While equilibrium models typically predict H₂, CO, and CO₂ concentrations with deviations within 5% (vol.) from experimental values (Safarian; Unnpórsson; Richter, 2019), methane formation in syngas often requires constraints, as simple equilibrium models tend to

underestimate it (Mendiburu; Carvalho; Coronado, 2014). Gasification performance estimates were conducted for parent biomasses and their charcoals, using a reference mass flow rate of 10 kg/h per feedstock (daf). The thermal equilibrium model minimizes the Gibbs free energy of the gasification products, constrained by an element mass balance using Lagrange multipliers. Figure 2 illustrates the code's solution diagram window, developed on the Engineering Equation Solver platform. The code allows pre-setting of carbon conversion efficiency and tar concentration in syngas based on gasifier type, including provisions for regenerative heat transfer for gasification agent preheating and reactor insulation performance. It can also be applied to a lab-scale reactor by setting external heating power, with predictions made by solving the First Law of Thermodynamics or by specifying process temperature at a given pressure. Key input data include feedstock immediate and elemental analysis, system equivalence ratio, and pressure, with the gasification agent comprising a mixture of oxygen, nitrogen, steam, and carbon dioxide at specified concentrations. The feedstock's high heating value can be prescribed or estimated from its elemental composition, and methane concentration in syngas is prescribed using a correlation from (Mendiburu; Carvalho; Coronado, 2014). The code optimizes gasification performance parameters by varying two independent variables using either a conjugate directions method or a variable metric method, with variable thermodynamic properties calculated using NASA polynomials.

3. Results and Discussion

In biomass thermal degradation, several factors influence product yield and properties, including the type of feedstock, reaction atmosphere, temperature, pressure, presence of minerals, particle size, and heating rate (Kan; Strezov; Evans, 2016). Table 2 presents the main characteristics of the parent feedstock and by-products after slow thermal degradation in a batch reactor. The uncertainties in Table 2 are derived from the standard deviation of the mean from three experiments. Generally, the biomasses exhibited similar characteristics in terms of composition and elemental constitution, with fixed carbon and volatile matter ranging from 18-23% and 66-70%, respectively. Ash and moisture contents ranged from 1.5-2.8% and 9-10.2%. The elemental composition of the biomass included 46-56% carbon, 5.9-7.9% hydrogen, and 4.3-9.5% oxygen, with higher heating values (daf) between 19 and 25 MJ/kg. Temperature profiles at the reactor's center and wall indicated the duration the samples were maintained within the specified temperature ranges listed in Table 1. The overall heating rate of the samples was 1.7 °C/min, increasing from 25 to 340 °C, over approximately 190 minutes. Following this steady temperature rise, the samples experienced a prolonged heating phase at an average rate

of 0.25 °C/min, reaching maximum temperatures of about 360 °C for cupuaçu and 420 °C for macaúba and tucumã. Specifically, tucumã samples were thermally degraded within the 330-415 °C range for approximately 290 minutes, followed by a 110-minute conversion period at 420 °C.

Table 2. Main characteristics of the parent feedstocks and the derived charcoals

Analysis	Tucumã	Macaúba	Cupuaçu
Proximate analysis of biomass (dry wt%)			
Fixed carbon	20.56±0.15	22.45±0.13	18.06±0.11
Volatile	66.54±0.12	66.69±0.09	70.01±0.10
Ash	2.78±0.01	1.54±0.01	2.80±0.02
Moisture	10.12±0.19	9.32±0.22	9.13±0.18
Ultimate analysis (dry wt%) - biomass as received			
Carbon	56.13±0.01	49.43±0.02	46.13±0.01
Hydrogen	7.85±0.02	6.27±0.01	5.94±0.01
Oxygen	35.01±0.01	42.15±0.02	47.07±0.02
Specific properties - biomass			
Chemical formula	CH1.7O0.47N0.01	CH1.5O0.64N0.04	CH1.5O0.77N0.02
HHV (MJ/kg)	24.26±0.02	21.32±0.01	19.27±0.02
LHV (MJ/kg)	20.31±0.02	20.72±0.01	18.80±0.02
Bulk density (g/cm ³)	0.348±0.002	0.584±0.003	0.296±0.018
Yield of biomass pyrolysis (%)			
Charcoal	30.0±1.27	30.54±3.27	36.80±2.31
Bio-oil	54.04±3.02	48.00±2.08	41.40±4.01
Non condensable gases	15.96±4.19	21.30±5.76	21.80±2.63
Immediate analysis of charcoal (%)			
Fixed carbon	66.11±0.05	71.05±0.03	66.17±0.08
Volatile	29.57±0.06	23.54±0.07	24.42±0.05
Ash	4.32±0.02	5.42±0.03	9.42±0.03
Elemental analysis – charcoal			
Carbon	77.70±0.04	79.11±0.03	76.02±0.04
Hydrogen	4.62±0.02	3.45±0.04	2.61±0.02
Oxygen	13.63±0.05	15.64±0.03	16.01±0.05
Specific properties - charcoal			
Chemical Formula	CH0.7O0.13	CH0.52O0.14	CH0.34O0.16
HHV (MJ/kg)	30.63±0.02	31.23±0.01	29.43±0.02
LHV (MJ/kg)	29.62±0.02	30.47±0.01	28.96±0.02
Bulk density (g/cm ³)	0.48	0.62	0.36
Mean pore size (nm)	18.50	15.78	20.82

Source: the authors (2024)

The samples underwent thermal degradation within the prescribed temperature range for 400 minutes. Macaúba samples were thermally degraded for about 240 minutes at 330-420 °C, followed by 110 minutes at 420 °C, totaling 350 minutes. Cupuaçu experienced a transient

phase of 255 minutes, with temperatures rising from 290 to 360 °C, then held at 360 °C for 180 minutes, amounting to 435 minutes in the specified range. These conditions ensured the complete degradation of cellulose and hemicellulose. Tucumã and macaúba produced intact, strong charcoal pieces, while cupuaçu resulted in fragile, light charcoal bits (Fig. 2).

Table 2 shows that cupuaçu achieved the highest solid yield (36.8%), followed by macaúba (30.54%) and tucumã (30.0%). Tucumã had the highest bio-oil production (54%), followed by macaúba (48%) and cupuaçu (41.4%). Non-condensable gas yields ranged from 16 to 22%, with tucumã producing the least. Thermal degradation increased the original feedstock's carbon content more than two-fold, reaching 66 to 71%, while volatile matter ranged from 23 to 30%, indicating high-grade charcoal. Ash content varied from 4.0 to 10%, with cupuaçu having the highest (9.42%). Elemental composition showed carbon, hydrogen, and oxygen contents ranging from 76 to 78%, 2.6 to 4.6%, and 13.6 to 16%, respectively. Charcoal bulk density varied from 7 to 37%, with tucumã having the highest and macaúba the lowest. Charcoal's mean pore size ranged from 15-21 nm, with cupuaçu having the largest and tucumã the smallest, enhancing charcoal reactivity for combustion and gasification.

The elemental analysis allowed us to suggest an approximate chemical formula for the feedstocks (Table 2). This information is crucial for modeling combustion and gasification processes. The heating values of the feedstocks after carbonization were around 30 MJ/kg, representing an average increase of 40% over their parent biomasses. The Van Krevelen diagram (Fig. 3) illustrates the changes in the parent biomasses and charcoals, showing a linear correlation for the degree of conversion. Higher pyrolysis temperatures (>500 °C) would further decrease O/C and H/C ratios but require more energy and time.

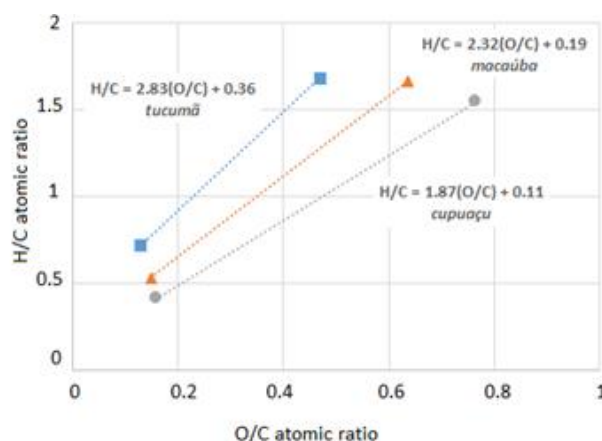


Figure 2. Van Krevelen diagram for the parent biomasses (higher O/C and H/C plots) and their respective charcoals. Source: the authors (2024).

Considering these charcoals as feedstocks for gasification, the remaining volatile matter (23-30%) facilitates particle ignition and heat production through oxidative gas phase reactions, preserving solid carbon for carbon reduction. The carbonization process made the charcoals' compositions more similar, as shown on the Van Krevelen diagram. This level of carbonization is satisfactory for further air-steam gasification, investigated using a thermochemical equilibrium model.

3.2 Bio-oil and Pyrolysis Gas Characterization

The liquid fraction from the slow pyrolysis of biomass is rich in chemicals distinct from fossil fuels due to high water content and oxygenated compounds. Compared to the parent biomass, this fraction has higher energy density and is easier to store and transport. The main constituents of bio-oil from cupuaçu are ethyl oleate (48.65%), linoleic acid (22.46%), and palmitic acid ethyl ester (12.11%). Macaúba bio-oil contains 46.03% oleic acid and 21.23% oxalic acid. For cupuaçu, n-tricosane (30.46%), linoleic acid (30.92%), and ethyl oleate (27.75%) are prevalent. The bio-oil's low heating value ranges from 13 to 18 MJ/kg, influenced by water and oxygen content. Further studies are needed to explore using pyrolytic oil for electricity and heat production in isolated communities. A blend of diesel and pyrolytic oil could be used to pilot the air-gas mixture of dual fuel engines. The liquid fraction collected during carbonization should be included in remote communities' energy plans or commercialized locally.

Thermal degradation of biomass produces char and gases, including condensable tarry products and non-condensable light gases. Figure 4 shows the TG and DTG curves of the three biomasses up to 400 °C. The first peaks, between 197-203 °C, indicate hemicellulose degradation, while peaks between 289-329 °C correspond to cellulose degradation. Lignin degradation occurs at a slower rate than cellulose and hemicellulose.

At 400 °C, degradation levels were 32% for cupuaçu, 34% for macaúba, and 36% for tucumã, making these charcoals suitable for a two-step energy conversion process. The FTIR spectra from cellulose peaks (Fig. 6) are shown in Fig. 5, with wavenumber bands and gas functional groups referenced from Wu et al. (2018). The transmittance profiles were similar across biomasses, with notable CO₂ peaks at 2360 cm⁻¹ and steam in the 3850-3650 cm⁻¹ range. Saturated aliphatic ester peaks were at 1750-1735 cm⁻¹ and unsaturated esters at 1730-1715 cm⁻¹. Macaúba and cupuaçu gases had a peak at 1716 cm⁻¹, indicating saturated aliphatic ketones, while tucumã peaked at 1764 cm⁻¹, likely from ethyl acetate. Nitroalkanes from

cupuaçu appeared at 1540 cm^{-1} , and for tucumã and macaúba at 1507 cm^{-1} . Lower wavenumber peaks at 669 cm^{-1} suggest aliphatic (C-C) compounds or CO_2 formation.

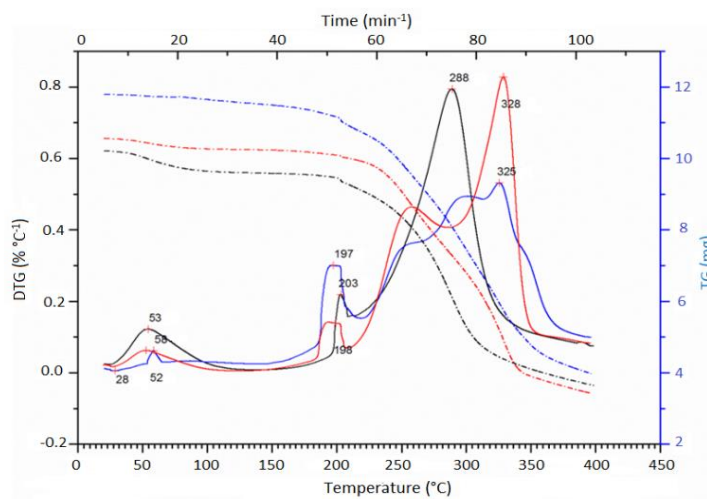


Figure 3. TG/DTG plots for the biomasses (cupuaçu-black; macaúba-blue; tucumã-red)

Source: the authors

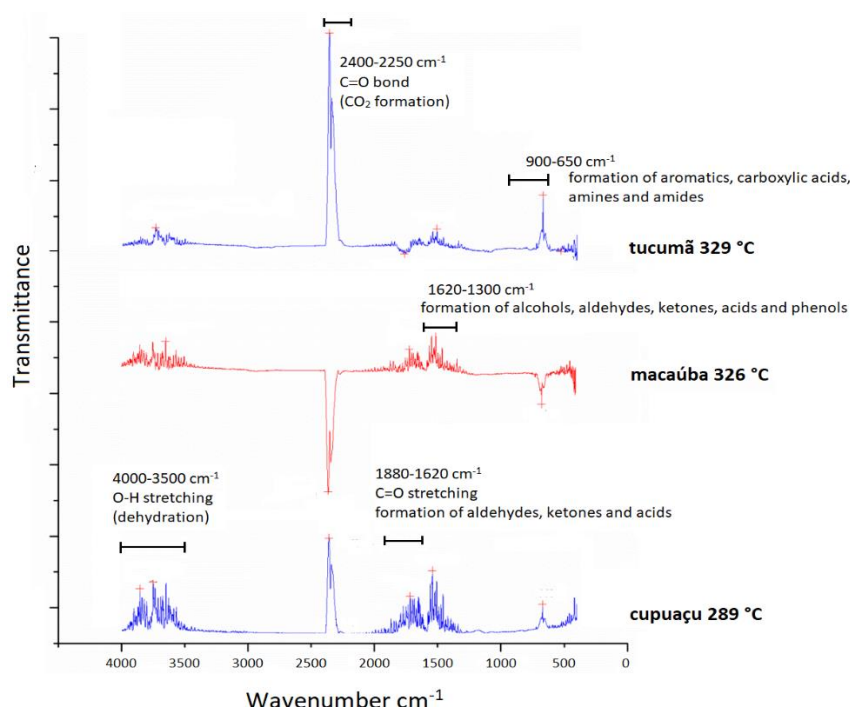


Figure 4. Infrared spectra of gases evolved from thermogravimetric analysis of the studied biomasses. Source: the authors (2023)

3.4 Feedstock Gasification

Since the code solves the energy equation, we prescribed a gasification equivalence ratio aiming to optimize cold gas efficiency at low (600 °C) and high (900 °C) system temperature,

depending on the type of feedstock. Charcoal gasification was set to take place at a relatively lower temperature because tar cracking should not be a primary concern. Conversely, biomass gasification occurs near 900 °C to improve thermal tar cracking. It was assumed a 10% heat loss from the reactor to the surroundings, based on the feedstock thermal input. Char losses were equivalent to 2% of the input feedstock (dry basis). CH₄ concentration in producer gas was set from the correlation proposed in (Mendiburu; Carvalho; Coronado, 2014). Tar concentration (C₆H₁₂,1-hexene) in syngas was adjusted based on the type of gasifier (Milne; Evans; Abatzaglou, 1998). Steam for biomass gasification was provided by the moisture in feedstock and was added to the airflow when the feedstock was dried charcoal. The preheated air mass flow rate was calculated based on the optimal process equivalence ratio ($2.5 < F < 5.0$), depending on the feedstock elemental composition. Thermal equilibrium predictions for charcoal were conducted using preheated air and steam with steam to dry ash-free charcoal ratio of 0.15. Feedstock composition, calorific value, ash, and moisture contents were taken from Table 2. It was also assumed a 1% moisture in charcoal.

Table 3 summarizes the output parameters as predicted by the equilibrium code. As can be seen from Table 3, the producer gas from the gasification of the biomasses and the derived charcoal retained 77 to 80% of the feedstock input energy based on the cold gas efficiency.

Table 3. Performance predictions from gasification of parent biomass and its charcoal

	Tucumã biomass charcoal		Macaúba biomass charcoal		Cupuaçu biomass charcoal	
Gasification Temperature (°C)	903	600	903	601	902	612
Equivalence ratio (Φ)	3.29	2.5	4.34	2.94	4.93	2.74
Mass flow (kg/h)						
Feedstock (daf)	10	10	10	10	10	10
Air (preheated)	23.4	41.98	14.1	33.27	10.8	34.26
Steam	-	1.5	-	1.5	-	1,5
Moisture in feedstock	1.16	0.11	1.04	0.11	1.03	0.11
Ash in feedstock	0.29	0.45	0.16	0.57	0.29	1.04
Total feedstock	11.44	10.56	11. 20	10.68	11.32	11.15
Gas composition (dry wt%)						
CO	24.66	26.81	30.59	35.30	31.78	34.05
CO ₂	6.48	4.78	6.51	0.79	7.88	2.11
H ₂	21.41	14.46	24.85	13.74	26.5	11.87
CH ₄ (prescribed)	1.98	0.2	1.82	0.18	1.76	0.15
Energy parameters						
Thermal input (kW)	67.39	85.26	59.22	86.75	53.53	81.75

LHV (kJ/Nm ³)	5,547	4,506	6,508	5,453	6,786	5,096
Cold Gas Efficiency (%)	79.49	77.71	80.48	78.93	80.41	77.69

Source: the authors

It is essential to highlight that the similarities in cold gas efficiency were attained at different reaction temperatures, for the charcoals and the parent biomasses. Despite their similarities in performance, charcoal gasification requires a much simpler gas cleaning process, due to the expected low tar content in the producer gas. Nevertheless, gasification experiments should be conducted to sustain such conclusions. Tar concentration in the syngas is strongly related to the system's gasification technology and other parameters. As regards the gas composition from biomass gasification, CO and H₂ concentrations ranged from 23.5 to 30% and 22 to 27%, respectively. Concentrations of CO and H₂ for charcoal were in the range of 28 to 35% and 8.7 to 9.3%, respectively. Lower heating value of biomass and charcoal were in excess of 5,000 kJ/Nm³ for most of the gasification predictions.

3.5 Integrated charcoal gasification dual-fuel engine cycle

The proposed energy conversion pathway is based on the integration of a charcoal gasifier into a diesel engine operating in dual-fuel mode. By such means, it is possible to eliminate complex gas cleaning systems and secondary waste generation, which is an essential requirement of the proposed energy extraction pathway. The diagram in Fig. 7 illustrates the mass and energy flows of the suggested combined system configuration. Charcoal thermal input was set to 85.1 kW, equivalent to the gasification of 11 kg/h of carbonized tucumã (Table 3). This amount of feedstock would claim the carbonization of 37.6 kg/h of as received tucumã (218.8 kW), considering the yields of the charcoal (30%) given in Table 2 for the specified biomass. The pyrolysis process would also generate about 20.3 and 5.9 kg/h of bio-oil and light gases, respectively. Light gases were assumed to have 16,224 kJ/kg of calorific value (ATSONIOS et al., 2015). The bio-oil heating value was estimated as 15,000 kJ/kg, assuming 25% of water content in the condensed pyrolysis liquid (Lehto et al., 2013). The input energy necessary for carbonization (kJ/kg) taken from Atsonios et al. (2015), in a dry ash-free basis is given by

$$\Delta h_{carb} = 991.5 + 3392 \frac{\mu_w}{1 - (\mu_w - \mu_a)} \quad (7)$$

In Eq. (7) μ_w and μ_a refers to the water and ash content of the feedstock, respectively. Therefore, the auger pyrolysis reactor would claim 14.1 kW for feedstock carbonization ($\Delta h_{carb} = 1,362 \text{ kJ/kg}$).

The combustion of light gases would produce 26.6 kW of heat, sufficient to sustain the carbonization process. The bio-oil produced would retain 85.4 kW of thermal power. The carbonization plant's efficiency in terms of energy retained in charcoal and bio-oil would be 87.8%. Bio-oil can be commercialized to the nearest city for upgrading or further energy conversion in a more centralized way.

Regarding the integrated charcoal gasification power cycle, 85.3 kW of thermal input from charcoal would be available, from which 71 kW would be retained in the producer gas ($4,980 \text{ kJ/m}^3$). The dual-fuel engine was set to operate at a 0.85 equivalence ratio. Pilot ignition would be provided by straight vegetable oil (SVO), preferably from the seeds of tucumã with oil substitution set to 70% in terms of electric output power. Our previous research indicated that a small diesel generator set could produce electric power with pure straight vegetable oil at 423 g/kWh of specific fuel consumption. Engine operation with syngas as the primary source of energy and straight vegetable oil for pilot ignition reduced the oil specific fuel consumption to 140 g/kWh with the remaining power given by the combustion of premixed air and syngas with overall efficiency estimated as 27% (Rodrigues et al., 2009).

Based on these figures, the dual-fuel engine's power input would be 107.4 kW, from which 67.1 kW would be provided by the producer gas and 40.2 kW from tucumã seed oil for pilot ignition. Tucumã seed oil higher heating value of $39,381 \text{ kJ/kg}$ (Fassinou, 2012) was estimated from its main fatty acid composition (Costa et al., 2016). At 27% conversion efficiency, the output electric power would be 28.9 kW_e . Engine exhaust gases would convey another 13.45 kW, corresponding to an exhaust temperature of 320°C .

CHP efficiency, based on the higher heating value of tucumã charcoal and seed oil, of the charcoal integrated gasification dual-fuel engine cycle was inferred as 40.3%. The remaining waste heat was considered irrecoverable. The carbonization process can be conducted at 76.6% efficiency, and bio-oil can be used to process heat or even commercialized in the nearest municipality. The system's overall efficiency would be 50.2%, based on the higher heating value of as received tucumã (biomass) and seed oil. Heat losses from the carbonization plant were also taken as irrecoverable, for simplicity.

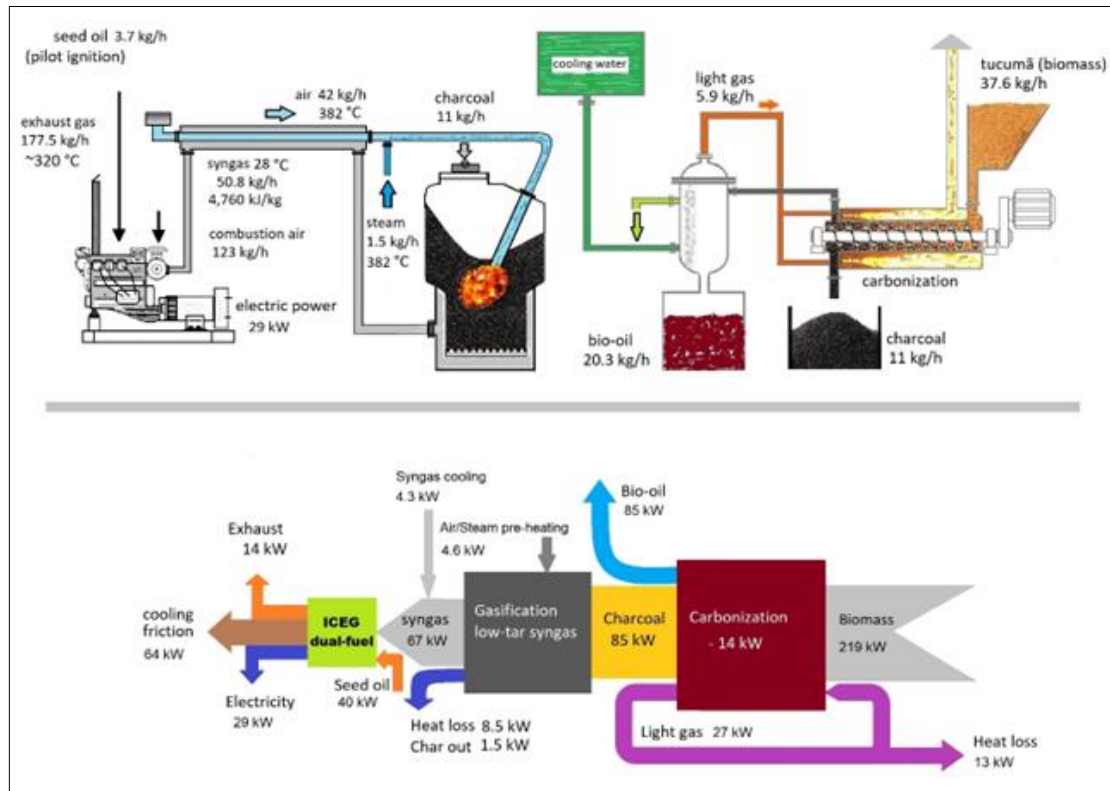


Figure 5. Mass and energy flows for the proposed energy conversion pathway

Source: the authors

Based on cost-effective and straightforward off-the-shelf hardware, the proposed energy extraction pathway seems very opportune for remote communities' electrification in the Amazon. The integrated charcoal gasification dual-fuel engine cycle would rely exclusively on renewable energy resources, paving the way to the sustainable development of the Brazilian rainforest's isolated communities. On a regional scale, the annual harvest of *T. grandiflorum* (cupuaçu) is about 6 million fruits. The shells make up about 1,440 metric tons of renewable feedstock, from which 533 metric tons of high-quality charcoal can be obtained. This charcoal amount represents 1.54×10^7 MJ of thermal energy capable of producing up to 1,131 MWh of clean electricity per year, considering a charcoal specific fuel consumption of 470 kg/MWh. The production of *A. aculeatum* (tucumã), as for the year 2012, was 368 metric tons, from which 140 metric tons of seeds can potentially be used as a renewable energy resource. The carbonization of 140 tons of tucumã seeds yields 42 metric tons of high-quality charcoal, from which up to 89 MWh of electricity could be produced regionally throughout the year. As for *A. aculeata* (macaúba), the fruit is not cultivated on a large scale in the Amazon region but extracted from the forest. However, there are studies to initiate macaúba palm trees' cultivation in degraded and poor soils of the Amazon basin.

Notwithstanding, the proposed waste to the energy route of tucumã and cupuaçu alone could produce, on a regional basis, up to 1,220 MWh of clean and renewable electricity per year. Taking the specific fuel consumption of modern diesel engines as 210 kg/MWh, the substitution of fossil fuel from the proposed energy conversion pathway would reach 256,200 liters per year, or 686 metric tons of CO₂ emissions avoided. In the Amazon region, diesel price ranges from 0.8 to 1.2 American dollars per liter, as for 2020 figures. Therefore, savings from oil substitution would reach a quarter of a million dollars per year if local communities rely on power generation from biomass waste. Bio-oil commercialization would also add revenue to the community.

4. Conclusions

This work aimed to evaluate the potential of three Amazon biomasses for distributed combined heat and power generation. The proposed energy extraction pathway was based on low-tar gas production from the gasification of charcoal to feed a heat engine without a complex cleaning system and generation of secondary waste. For that, as received, biomass was thermally degraded in the range of 290 to 430 °C for about 420 min yielding high-quality charcoal and bio-oil. Thermodynamic equilibrium predictions of charcoal gasification at about 600 °C resulted in cold gas efficiency over 77%. Fuel gas could be produced with no less than 4,500 kJ Nm⁻³ of calorific value. Producer gas from charcoal gasification would be consumed in a dual-fuel engine relying on straight vegetable oil for pilot ignition. The CHP plant's predicted efficiency was 40%, and the overall efficiency of the combined carbonization and power generation plants was calculated as 50%. The proposed waste-to-energy conversion route would be very effective in providing electricity, up to 1,220 MWh per year, and some income level for isolated communities of the Brazilian rainforest. By such means, local communities could generate electric power with more than 680 metric tons of CO₂ emissions avoided, on an annual basis.

6. References

- Aklouche, F. Z. et al. Predictive model of the diesel engine operating in dual-fuel mode fuelled with different gaseous fuels. **Fuel**, v. 220, p. 599–606, maio 2018.
- Atsonios, K. et al. Biomass fast pyrolysis energy balance of a 1kg/h test rig. **International journal of thermodynamics**, v. 18, n. 4, p. 267–275, 2015.
- Brandt, P.; Larsen, E.; Henriksen, U. High Tar Reduction in a Two-Stage Gasifier. **Energy & Fuels**, v. 14, n. 4, p. 816–819, 1 jul. 2000.
- Bridgewater, A. V. Biomass fast pyrolysis. **Thermal Science**, v. 8, n. 2, p. 50, 2004.

- Cerón, I. X.; Higueta, J. C.; Cardona, C. A. Analysis of a biorefinery based on *Theobroma grandiflorum* (cipoazu) fruit. **Biomass conversion and biorefinery**, v. 5, p. 183–194, 2015.
- Ciconini, G. et al. Biometry and oil contents of *Acrocomia aculeata* fruits from the Cerrados and Pantanal biomes in Mato Grosso do Sul, Brazil. **Industrial Crops and Products**, v. 45, p. 208–214, 1 fev. 2013.
- Corsini, A. et al. Vegetable Oils as Fuels in Diesel Engine. Engine Performance and Emissions. **69th Conference of the Italian Thermal Engineering Association, ATI 2014**, v. 81, p. 942–949, dez. 2015.
- Costa, B. E. T. et al. Comparative study on the quality of oil extracted from two tucumã varieties using supercritical carbon dioxide. **Food Science and Technology**, v. 36, 2016.
- Di Lascio, M. A.; Fagundes Barreto, E. J. **Energia e Desenvolvimento Sustentável para a Amazônia Rural Brasileira : Eletrificação de Comunidades Isoladas**. [s.l: s.n.].
- Fassinou, W. F. Higher heating value (HHV) of vegetable oils, fats and biodiesels evaluation based on their pure fatty acids' HHV. **Energy**, v. 45, n. 1, p. 798–805, 2012.
- Fortes, I. C. P.; Baugh, P. J. Pyrolysis-GC/MS studies of vegetable oils from Macauba fruit. **Journal of Analytical and Applied Pyrolysis**, v. 72, n. 1, p. 103–111, 2004.
- Gómez-Barea, A.; Leckner, B. Modeling of biomass gasification in fluidized bed. **Progress in Energy and Combustion Science**, v. 36, n. 4, p. 444–509, 2010.
- Henriksen, U. et al. The design, construction and operation of a 75 kW two-stage gasifier. **Energy**, v. 31, n. 10–11, p. 1542–1553, 1 ago. 2006.
- Idris, J. et al. Improved yield and higher heating value of biochar from oil palm biomass at low retention time under self-sustained carbonization. **Journal of Cleaner Production**, v. 104, p. 475–479, 1 out. 2015.
- Kan, T.; Strezov, V.; Evans, T. J. Lignocellulosic biomass pyrolysis: A review of product properties and effects of pyrolysis parameters. **Renewable and Sustainable Energy Reviews**, v. 57, p. 1126–1140, 1 maio 2016.
- Lehto, J. et al. **Fuel oil quality and combustion of fast pyrolysis bio-oils**. [s.l.] VTT Espoo, Finland, 2013. v. 87
- Lira, C. S. et al. Fast pyrolysis of Amazon tucumã (*Astrocaryum aculeatum*) seeds in a bubbling fluidized bed reactor. **Journal of Analytical and Applied Pyrolysis**, v. 99, p. 23–31, 2013a.
- Lira, C. S. et al. Fast pyrolysis of Amazon tucumã (*Astrocaryum aculeatum*) seeds in a bubbling fluidized bed reactor. **Journal of Analytical and Applied Pyrolysis**, v. 99, p. 23–31, 1 jan. 2013b.
- Mendiburu, A. Z.; Carvalho, J. A.; Coronado, C. J. R. Thermochemical equilibrium modeling of biomass downdraft gasifier: Stoichiometric models. **Energy**, v. 66, p. 189–201, 1 mar. 2014.
- Milne, T. A.; Evans, R. J.; Abatzoglou, N. Biomass gasifier "Tars": their nature, formation, and conversion. 1998.
- Miranda, M. R. Da S.; Veras, C. A. G.; Ghesti, G. F. Charcoal production from waste pequi seeds for heat and power generation. **Waste Management**, v. 103, p. 177–186, 15 fev. 2020.
- Motta, P. E. F. Da et al. Ocorrência da macaúba em Minas Gerais: relação com atributos climáticos, pedológicos e vegetacionais. **Pesquisa Agropecuária Brasileira**, v. 37, 2002.
- Müller, C. H. et al. **The Culture of Cupuacu**. Brasília DF: EMBRAPA-SPI, 1995.

Narula, S. A.; Bhattacharyya, S. Off-grid electricity interventions for cleaner livelihoods: A case study of value chain development in Dhenkanal district of Odisha. **Journal of Cleaner Production**, v. 142, p. 191–202, 20 Jan. 2017.

ONS, O. N. Do S. E. **Maps of SIN ONS**. Disponível em: <<http://ons.org.br/pt/paginas/sobre-ons/mapas>>. Acesso em: 7 nov. 2018.

Rodrigues, A. C. et al. **Small Scale Electricity Generation from Simultaneous Burning of Straight Vegetable Oil and Syngas in Compression Ignition Engines**. 22nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems - ECOS. **Anais...**Foz do Iguaçu: 2009.

Safarian, S.; Unnpórsson, R.; Richter, C. A review of biomass gasification modelling. **Renewable and Sustainable Energy Reviews**, v. 110, p. 378–391, 2019.

Van Els, R. H.; De Souza Vianna, J. N.; Brasil Jr, A. C. P. The Brazilian experience of rural electrification in the Amazon with decentralized generation—The need to change the paradigm from electrification to development. **Renewable and Sustainable Energy Reviews**, v. 16, n. 3, p. 1450–1461, 2012.