Physicochemical Characterization of Macaúba (*Acrocomia Aculeata*) Focusing on Energy Applications

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Abstract

This study presents the physicochemical characterization of *Acrocomia aculeata* (macaúba) fractions, including the epicarp, mesocarp post-oil extraction, endocarp, and almond cake post-oil extraction, focusing on their potential for renewable energy applications. The characterization included proximate analysis and the estimation of the Higher Heating Value (HHV) to assess the energetic quality of each fraction. The results showed moisture contents between 8.88% and 10.36%, volatile matter above 84%, ash contents ranging from 2.19% to 5.63%, and fixed carbon between 7.51% and 12.01%. The predicted HHV values varied from 17.54 to 18.53 MJ/kg, comparable to or higher than several conventional lignocellulosic feedstocks such as sugarcane bagasse and rice husk. These findings demonstrate that macaúba residues present favorable physicochemical properties for bioenergy production, reinforcing their potential as a sustainable biomass source. The valorization of these by-products aligns with circular bioeconomy principles and contributes to expanding Brazil's renewable energy matrix beyond solar-based systems.

Keywords: Lignocellulosic feedstocks, macaúba residues, bioenergy, circular bioeconomy, energy matrix.

1. Introduction

The increase in global energy consumption, combined with the intensification of extreme weather events caused by fossil fuels, highlights the urgent need to transition to more sustainable energy sources. 2024 was the hottest year recorded globally, causing extreme weather events across different regions. Europe experienced severe floods, including in Spain, and Brazil had a historic drought in the Amazon and devastating floods in Rio Grande do Sul (Copernicus and WMO, 2025; WMO, 2024). In the United States, particularly in Los Angeles, California, intense wildfires were attributed to climate change (Yale Climate Connections, 2025).

Established in 2015, the Paris Agreement set the goal of limiting the global temperature rise to 1.5 °C above pre-industrial levels. However, data from 2024 show that the planet already reached this threshold, evidencing delays in mitigation efforts (UNFCCC, 2015; Copernicus, 2024). Fossil fuel dependence remains high, for instance, global coal demand reached 8.53 billion tonnes in 2023 (IEA, 2023), showing that climate commitments alone are insufficient without deeper structural changes.

In this scenario, biomass is a key renewable alternative due to its versatility, availability, and ability to support energy matrices during periods of low solar incidence. Recent investments in Brazil, such as the development of macaúba-based biorefineries in Bahia by Acelen/Mubadala, highlight the growing interest in biomass valorization (Globo Rural, 2025; Capital Reset, 2025). Macaúba is highly productive, yielding up to 6,000 liters of oil per hectare and generating sustainable by-products (WWF-Brazil, 2022).

The physicochemical characterization of macaúba fractions provides essential information to assess their energy potential. Parameters such as moisture, volatile matter, ash, and fixed carbon are critical for evaluating efficiency and determining their suitability as renewable fuels (Demirbaş, 2004; Van Loo & Koppejan, 2012). The higher heating value (HHV) is particularly relevant as an indicator of energy quality, guiding the application of macaúba residues in thermal conversion systems and hydrid renewable setups.

This work aims to determine the physicochemical properties of macaúba residues, contributing to its potential for energy applications beyond solar. Additionally, comparative analysis was carried out with other biomass already utilized in hybrid energy systems worldwide, reinforcing its relevance in expanding the renewable energy matrix and supporting circular economy initiatives.

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2. Materials and methods

2.1. Materials

This study was conducted in Brazil to characterize macaúba fractions (epicarp, mesocarp (post-oil extraction), endocarp, and almond cake (post-oil extraction)). The samples were collected in the state of Ceará and processed to obtain homogeneous particle size suitable for energy characterization. The preparation steps included collection, separation, grinding, and sieving (particle size < 150 µm), as shown in Figure 1.

Figure 1: Preparation steps of macaúba fractions: collection, separation, grinding, and sieving (Author, 2025).

2.2. Proximate analysis

The proximate analysis determined the contents of moisture, volatile matter, ash, and fixed carbon, according to standard procedures. Moisture content and total solid were determined following NBR 16550 (drying oven at 105°C) as showed in Equations (1) and (2).

$$Moisture\ (\%) = (\frac{m_{Si} - m_{Sf}}{m_{Si}})\ x\ 100 \qquad \text{(eq. 1)}$$

$$Total\ Solids\ (\%) = (\frac{m_{Sf}}{m_{Si}})\ x\ 100 \qquad \text{(eq. 2)}$$

where: m_{Si} = mass sample as received (g) and m_{Sf} = mass dry sample (g).

The ash content was determined using a muffle furnace (Quimis Q318M24) at 575 ± 25 °C for 4 h (NBR 16550) and calculated using Equation (3).

$$Ash\ (\%) = \left(\frac{m_{Ash}}{m_{Sf}}\right) x\ 100 = \left(\frac{m_{Ash}\ x\ 100}{m_{Si} x\ TS(\%)}\right) x\ 100 \qquad \text{(eq. 3)}$$

where: m_{Ash} = mass of total ash (g); m_{Sf} = mass dry sample (g); : m_{Si} = mass sample as received (g); and TS(%) = total solid percentage.

Volatile matter was determined according to ASTM D3175 by heating 1 g of sample at 950 °C for 7 min. The content was calculated by Equation (4).

$$Volatile\ Matter\ (\%) = \left[\left(\frac{m_i - m_f}{m_f + m_{c+1}}\right) x\ 100\right] - M(\%) \qquad \text{(eq. 4)}$$

where: m_i = initial mass of porcelain crucible with lid plus sample (g); m_f = final mass of porcelain crucible with lid plus sample (g); : m_{c+1} = mass of porcelain crucible with lid (g); and M(%) = moisture percentage.

Fixed carbon was calculated by difference (Equation 5), following ASTM D3172.

$$Fixed\ Carbon\ (\%) = 100 - \text{Ash}(\%) - \text{Volatile Matter}(\%) \quad \text{(eq. 5)}$$

All measurements were performed in duplicate to ensure reproducibility.

2.3. Higher heating value (HHV)

The higher heating value (HHV) was estimated through empirical equations (eq.6 and eq. 7) based on proximate analysis.

$$HHV = (0.3536 * \text{FC}) + (0.1559 * \text{VM}) - (0.0078 * \text{A}) \quad \text{(eq. 6)}$$

$$HHV = 19.914 - (0.2324 * \text{A}) \quad \text{(eq. 7)}$$

The predicted HHV values were compared with those of conventional lignocellulosic feedstocks such as sugarcane bagasse, rice husk, neem leaves, soy hull, and woody biomass, available in literature.

3. Results and discussions

3.1. Proximate analysis

The proximate analysis of *Acrocomia aculeata* fractions and reference biomasses is presented in Table 1, where VM represents volatile matter and FC represents fixed carbon.

Table 1: Proximate analysis of the Macaúba fractions and other biomasses from the literature (Author, 2025).

Biomass	Moisture (%)	VM (%)	FC (%)	Ash (%)	Reference
Acrocomia Epicarp	10.36 ± 0.51	84.92 ± 0.2	10.1 ± 0.1	4.97 ± 0.05	This work
Acrocomia Mesocarp (Post-Oil Extraction)	8.88 ± 0.01	88.57 ± 0.02	7.51 ± 0.06	3.92 ± 0.07	This work
Acrocomia Endocarp	9.11 ± 0.16	85.8 ± 0.41	12.01 ± 0.24	2.19 ± 0.17	This work
Acrocomia Almond Cake (Post-Oil Extraction)	9.43 ± 0.19	85.05 ± 0.28	9.32 ± 0.5	5.63 ± 0.23	This work
Sugarcane Bagasse	5.4	80.2	11.3	3.1	[Varma and Mondal, 2016]
Rice Husk	9.8	54.63	20.76	14.81	[Lala et al., 2025]
Woody Biomass	-	78.9	19.86	1.24	[Olabisi et al., 2023]
Neem seed shell	12.68 ± 0.16	81.76 ± 1.30	14.44 ± 1.74	3.80 ± 0.44	[Neto et al., 2023]
Soy Hull	6.5	78.2	10.7	4.6	[Sadiq et al., 2021]

Volatile matter contents exceeded 84 % for all macaúba fractions, confirming their high reactivity and potential for thermochemical conversion. The ash content ranged from 2.13 % to 5.61 %, while fixed carbon varied between 7.58 % and 12.14 %. These results are typical of lignocellulosic feedstocks used for bioenergy applications, such as sugarcane bagasse and rice husk (Varma and Mondal, 2016; Lala et al., 2025).

Among the studied fractions, the endocarp (MC03) exhibited the highest fixed carbon (12.14 %) and the lowest ash content (2.13 %), suggesting greater char yield potential. In contrast, the mesocarp (MC02) presented the highest volatile matter (88.53 %), indicating a higher reactivity and faster devolatilization during combustion or pyrolysis. The epicarp and almond cake fractions also showed balanced compositions, which are favorable for stable combustion performance. Compared to reference biomasses, the ash levels of macaúba fractions were lower than those observed for rice husk (14.81 %) and within the range of woody biomass (1.24 %) and soy hull (4.6 %) (Olabisi et al., 2023; Sadiq et al., 2021).

3.2. Higher heating value (HHV)

The higher heating value (HHV) of macaúba fractions and reference biomasses is presented in Figure 2, where MC01 refers to the epicarp, MC02 to the mesocarp after oil extraction, MC03 to the endocarp, and MC04 to the almond cake residue obtained after oil extraction.

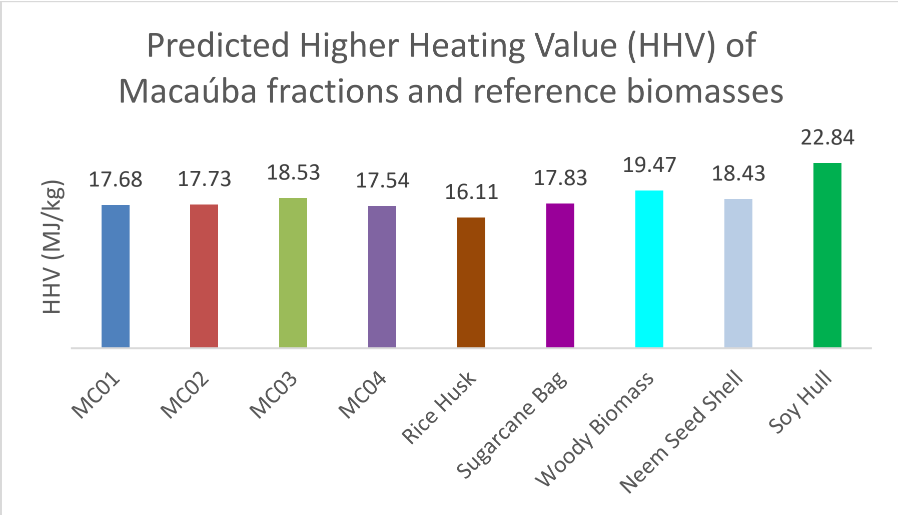

Figure 2: Higher heating value (MJ/kg) estimated by Equations (1) and (2) for Macaúba fractions and other biomasses from the literature (Author, 2025).

The predicted Higher Heating Values (HHV) of macaúba fractions ranged from 17.54 to 18.53 MJ kg^{-1} (Fig. 2), comparable to sugarcane bagasse (17.83 MJ kg^{-1}) and higher than rice husk (16.11 MJ kg^{-1}). Woody biomass (19.47 MJ kg^{-1}) and soy hull (22.84 MJ kg^{-1}) exhibited higher HHV values due to their elevated fixed carbon and lower ash contents. Neem seed shell (18.43 MJ kg^{-1}) showed intermediate performance, aligning closely with the endocarp fraction of macaúba, which highlights its viability as a complementary feedstock (Neto et al., 2023; Sadiq et al., 2021). These comparisons confirm that macaúba residues possess energy quality within the range of conventional biomass feedstocks commonly used for renewable energy generation.

From a technological standpoint, the energy potential of macaúba fractions supports their use in various thermochemical conversion processes such as combustion, briquetting, or pyrolysis. Their moderate HHV and balanced proximate composition make them suitable for industrial and rural applications, particularly in hybrid solar–biomass systems, where they can complement solar energy during periods of low irradiation (Korpeh et al., 2024). Moreover, the valorization of macaúba residues aligns with circular economy principles, reducing waste disposal and adding value to agro-industrial by-products.

Overall, these findings reinforce the strategic importance of Acrocomia aculeata in advancing Brazil's renewable energy goals. Considering ongoing national investments in macaúba-based biorefineries and global net-zero emission targets (EPE, 2024), this biomass represents a viable and sustainable resource for decentralized energy systems.

Recent studies have also emphasized the relevance of *Acrocomia aculeata* as a promising feedstock to produce advanced biofuels and bioproducts, due to its balanced lignocellulosic composition and high oil yield potential. Its ability to grow in marginal or semi-arid areas without competing directly with food crops strengthens its role within sustainable land-use strategies. Furthermore, the species shows adaptability to climate variability and contributes to soil recovery and carbon sequestration, reinforcing its alignment with global climate mitigation goals (Colombo et al., 2018; Vargas-Carpintero et al., 2022). These aspects highlight that beyond its favorable physicochemical parameters, macaúba also presents strong socioeconomic and environmental advantages for bioenergy production in tropical countries. The use of its residues in thermal conversion processes, such as combustion, pyrolysis, and gasification, can integrate agricultural production chains, reduce waste generation, and diversify income sources for rural communities. Thus, the energetic use of macaúba residues supports both environmental sustainability and regional development objectives.

Similar hybrid configurations combining solar energy and biomass gasification have demonstrated improved system efficiency, operational flexibility, and lower environmental impact. For instance, Wu et al. (2024) reported that the integration of solar collectors with biomass-based distributed energy systems increased overall energy conversion efficiency while reducing CO_2 emissions through optimized H_2O/CO_2 gasification. Such findings suggest that coupling solar and biomass resources can provide stable and dispatchable renewable energy, overcoming intermittency limitations typical of solar-only systems. In this context, macaúba residues emerge as an attractive biomass resource for hybrid configurations. Their moderate HHV, low ash content, and high volatile fraction enable stable combustion and co-firing behavior when integrated with other agricultural residues or fossil co-fuels. Additionally, their local availability and favorable logistics make them especially suitable for decentralized rural energy systems in tropical regions. As highlighted by the *Bioeconomy of Knowledge Report* (ICC, 2025), such biomass utilization pathways can foster regional innovation, technological development, and circular economy models that align with Brazil's renewable energy expansion strategies.

4. Conclusion

The proximate analysis of *Acrocomia aculeata* fractions revealed a favorable composition for thermochemical conversion, with high volatile matter content (>84%), moderate ash levels (2.19–5.63%), and fixed carbon between 7.51% and 12.01%. These characteristics indicate high reactivity and suitability for direct energy generation through combustion or pyrolysis. The predicted Higher Heating Values (HHV), ranging from 17.54 to 18.53 MJ kg^{-1}, are comparable to conventional feedstocks such as sugarcane bagasse and woody biomass, confirming the energetic quality of macaúba residues. The results demonstrate that macaúba fractions can be effectively used as an independent biofuel source, promoting the recovery of agro-industrial residues and contributing to a circular bioeconomy. In addition, their properties make them suitable for integration into hybrid renewable systems, ensuring energy reliability in periods of low solar availability. Given their wide availability, favorable fuel composition, and alignment with national and global renewable energy goals, macaúba residues represent a strategic and sustainable feedstock for decentralized bioenergy generation and large-scale applications in low-carbon energy systems.

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