Proximate Analysis and Higher Heating Value of Waste Biomass Blends: An Energetic Approach

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Abstract

The increasing demand for renewable energy sources has encouraged the valorization of agro-industrial residues as feedstocks for bioenergy production. This study evaluated the energetic potential of three blends composed of five waste biomasses, namely carnauba stalk, babassu coconut shell, babassu almond cake, cashew nutshell, and green coconut shell, originating from Northeastern Brazil. The materials were cleaned, ground, and sieved before being blended in 1:1 (w/w) ratios. Proximate analyses were performed following national and international standards to determine moisture, volatile matter, ash, and fixed carbon contents, while the Higher Heating Value (HHV) was estimated from empirical correlations based on proximate data. The results demonstrated that all blends exhibited high volatile matter contents (>85%) and low ash fractions (<6%). Among them, the blend of carnauba stalk and babassu coconut shell showed the most promising performance, with 10.66% moisture, 3.15% ash, 88.61% volatile matter, and an HHV of 22.38 MJ kg^{-1}, surpassing the other blends and conventional feedstocks such as sugarcane bagasse (~17–18 MJ kg^{-1}). The results indicate that waste biomass blends can achieve improved combustion quality and higher energy yields through synergistic effects between residues. These findings highlight their potential for renewable energy applications and contribute to the development of sustainable solid biofuels aligned with circular bioeconomy principles and Net Zero strategies.

Keywords: Bioenergy production, biomass blends, solid biofuels, circular bioeconomy, Net Zero strategies.

1. Introduction

The global energy transition demands scalable, low-carbon technologies capable of reducing greenhouse gas emissions while maintaining energy security and supporting Net Zero targets by 2050 (IEA, 2021). Among renewable energy options, biomass stands out as a versatile and carbon-neutral resource adaptable to various conversion routes, including combustion, gasification, and pyrolysis (El-Araby et al., 2024). The sustainable use of agro-industrial residues aligns with circular economic principles by transforming waste into value-added energy products, supporting both decarbonization and regional socioeconomic development (ETC, 2022).

The increasing demand for clean and sustainable energy has led to a global shift toward renewable energy sources. The utilization of lignocellulosic biomass as a source of solid biofuels is acknowledged as a strategic approach, particularly in regions characterized by a surplus of agro-industrial wastes (Sulis et al., 2025). These biofuels contribute to diversifying the energy matrix, reducing greenhouse gas emissions, and valuing underutilized biomass resources (IEA, 2024).

In Brazil, regional biomass wastes have been identified as key resources for expanding the solid biofuel sector and promoting energy decentralization (EPE, 2024). The country possesses vast reserves of agricultural by-products, such as carnauba stalks, babassu coconut shells, cashew nutshells, and green coconut shells, that remain underutilized for energetic purposes. Integrating these residues into the national bioenergy chain could enhance energy security while reducing environmental impacts associated with open field burning and waste accumulation.

Biomass blending has gained traction as an effective method to optimize the physicochemical and combustion properties of heterogeneous feedstocks. By combining materials with complementary compositions, it is possible to balance ash, volatile matter, and fixed carbon contents, leading to improved briquette stability, higher calorific values, and reduced slagging tendencies (Rauen et al., 2014; Santos et al., 2023). Such synergistic effects can make waste-derived biofuels competitive with conventional feedstocks, strengthening the role of biomass within the renewable energy matrix.

Although Brazil maintains one of the cleanest electricity mixes worldwide, fossil fuels still account for more than 40% of its primary energy supply (EPE, 2024). Enhancing the contribution of sustainable solid biofuels from

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residues therefore remains crucial to achieving the nation's decarbonization goals. Experimental data combining proximate analysis and calorific assessment of blended residues are still scarce, limiting the understanding of their thermal behavior and potential for energy recovery (Esteves et al., 2015). Addressing this gap contributes to optimizing resource utilization and advancing circular bioeconomy strategies in tropical regions.

Therefore, this study aims to evaluate the energetic potential of waste biomass blends composed of five regional residues, carnauba stalk, babassu coconut shell, babassu almond cake, cashew nutshell, and green coconut shell, through proximate analysis and estimation of the Higher Heating Value (HHV). The results are compared with conventional lignocellulosic feedstocks to identify promising blends for solid biofuel applications aligned with circular bioeconomy and Net Zero strategies.

2. Materials and methods

2.1 Materials

The waste biomass was collected in Fortaleza, Ceará, Brazil. The babassu almond cake and cashew nutshell were obtained after the babassu oil extraction and cashew nutshell liquid, respectively. Three 50:50 (w:w) biomass blends were prepared: (i) carnauba (*Copernicia prunifera*) stalk and babassu (*Attalea speciosa*) coconut shell; (ii) carnauba stalk and babassu almond cake; and (iii) green coconut (*Cocos nucifera*) shell and cashew (*Anacardium occidentale* L.) nutshell. Biomass pretreatment included the following steps: collection, cleaning, grinding, and sieving to a particle size below 250 µm, as illustrated in Figure 1.

Figure 1: Biomass pretreatment steps: collection, cleaning, grinding, and sieving (Author, 2025).

2.2 Proximate analysis

The contents of moisture, volatile matter, ash, and fixed carbon were determined through proximate analysis following standard procedures. Moisture content and total solid were determinated according to NBR 16550 as shown in Equations (1) and (2).

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

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

where m_{Si} is the mass of sample as received (g) and m_{Sf} is the mass of dry sample (g).

A muffle furnace (Quimis Q318M24) was used at 575 ± 25 °C for 4 h (NBR 16550) to determinate the ash content, and calculated by Equation (3).

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

where m_{Ash} is the mass of total ash (g), m_{Sf} is the dry sample mass (g), m_{Si} is the initial sample mass (g), and TS(%) is the total solids percentage.

According to ASTM D3175, volatile matter was determined by heating 1 g of sample at 950 °C for 7 min, and calculated by Equation (4).

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

where m_i is the initial mass of porcelain crucible with lid plus sample (g), m_f is the final mass of porcelain crucible with lid plus sample (g), m_{c+1} is the mass of porcelain crucible with lid (g), and M(%) is the moisture content.

Fallowing ASTM D3172, fixed carbon was calculated by difference (Equation 5).

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

All measurements were performed in quadruplicate to ensure reproducibility.

2.3 Higher heating value (HHV)

The Higher Heating Value (HHV) was estimated using four empirical correlations (Equations 6–9) based on proximate analysis data, as proposed by Neto et al. (2023). These correlations relate the HHV to the volatile matter (VM), fixed carbon (FC), and ash (A) contents of the samples.

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

$$HHV = -17.507 + (0.3985 \cdot \text{VM}) + (0.2875 \cdot \text{FC}) \quad \text{(eq. 7)}$$

$$HHV = -2.057 - (0.092 \cdot \text{A}) + (0.279 \cdot \text{VM}) \quad \text{(eq. 8)}$$

$$HHV = (0.1905 \cdot \text{VM}) + (0.2521 \cdot \text{FC}) \quad \text{(eq. 9)}$$

The predicted HHV values for each blend were compared with representative lignocellulosic feedstocks commonly reported in the literature, such as sugarcane bagasse, eucalyptus wood, and palm kernel shell, to assess their relative energy performance and contextualize the energetic potential of the evaluated biomass blends.

3. Results and discussions

3.1 Proximate analysis

The results of the proximate analysis of the biomass blends 50:50 (w:w) are presented in Tables 1, 2, and 3. All samples exhibited high volatile matter contents (above 84%) and relatively low ash fractions, confirming their suitability for thermochemical conversion.

Table 1: Proximate analysis of the blend of cashew and green coconut shell (Author, 2025)

Content (%)	Mean	Standard Error	Standard Deviation	Variance
Moisture	12.47	0.47	0.94	0.88
Ash	3.20	0.12	0.23	0.05
Volatile Matter	84.69	0.18	0.36	0.13
Fixed Carbon	12.11	0.15	0.31	0.09

Table 2: Proximate analysis of the blend of carnauba stalk and babassu almond cake (Author, 2025)

Content (%)	Mean	Standard Error	Standard Deviation	Variance
Moisture	11.71	0.39	0.79	0.62
Ash	4.37	0.12	0.24	0.06
Volatile Matter	86.39	0.19	0.39	0.15
Fixed Carbon	9.25	0.27	0.54	0.29

Table 3: Proximate analysis of the blend of carnauba stalk and babassu coconut shell (Author, 2025)

Content (%)	Mean	Standard Error	Standard Deviation	Variance
Moisture	10.66	0.27	0.55	0.29
Ash	3.15	0.11	0.22	0.05
Volatile Matter	88.61	0.34	0.69	0.47
Fixed Carbon	8.23	0.39	0.79	0.63

Among the evaluated materials, the blend of carnauba stalk and babassu coconut shell (50:50 w/w) showed the lowest moisture (10.66%) and ash (3.15%) contents together with the highest volatile matter (88.61%), indicating improved ignition and stable combustion behavior.

The carnauba stalk with babassu almond cake blend also displayed favorable energetic characteristics, with moderate ash (4.37%) and high volatile matter (86.39%). In contrast, the cashew nutshell with green coconut shell blend presented slightly higher moisture (12.47%) and ash (3.20%) contents, which may reduce combustion efficiency. Nevertheless, all compositions remained within the desirable range for solid biofuels with volatile matter higher than 75% and ash above 6%, as reported by Demirbaş (2004) and Protásio et al. (2011).

The obtained values are comparable to those observed in well-established lignocellulosic feedstocks. Sugarcane bagasse contains about 88.5 wt.% volatiles and 2.1 wt.% ash (Pedroso et al., 2021); eucalyptus wood typically shows 82–84 wt.% volatiles and only 0.1–0.2 wt.% ash (Vieira et al., 2023); and palm kernel shell exhibits 75.8 wt.% volatiles and 7.6 wt.% ash (Adeoye et al., 2022). The evaluated blends therefore display intermediate to superior quality, especially the carnauba–babassu shell mixture, which combines low mineral content with high reactivity, features essential for clean and efficient combustion.

3.2 Higher Heating Value (HHV)

Figure 2 shows the Higher Heating Value (HHV) calculated using empirical equations (eq. 1 to 4) based on proximate analysis.

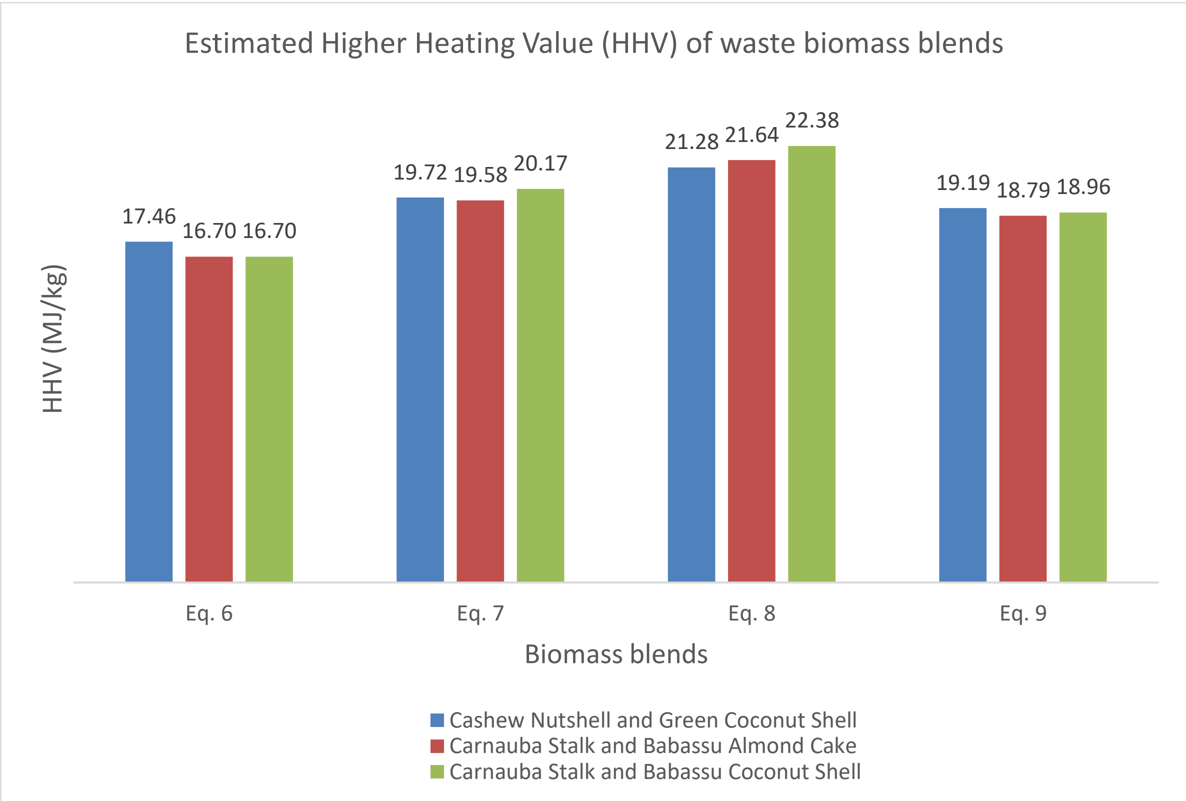

Figure 2: Higher heating value (MJ/kg) estimated by Equations (6)-(9) for the three blends in this study (Author, 2025).

The HHV values ranged from 16.70 to 22.38 MJ kg^{-1} among the studied mixtures. The carnauba stalk with babassu coconut shell blend achieved the highest HHV (22.38 MJ kg^{-1}), followed by carnauba stalk with babassu almond cake (21.64 MJ kg^{-1}) and cashew nutshell with green coconut shell (21.28 MJ kg^{-1}).

This superior energy content reflects the favorable combination of high fixed-carbon fraction and low ash concentration, confirming the blend's potential as a high-quality solid biofuel. The measured HHVs surpass those reported for conventional lignocellulosic feedstocks such as sugarcane bagasse (19.19 MJ kg^{-1}; Pedroso et al., 2021), eucalyptus wood (19.4–20.3 MJ kg^{-1}; Vieira et al., 2023), and palm kernel shell (18.2 MJ kg^{-1}; Adeoye et al., 2022). These findings reinforce the energetic competitiveness of regional biomass mixtures and highlight the relevance of integrating agricultural residues into sustainable energy systems.

3.3 Energetic implications and practical perspectives

The energetic behavior of the studied blends suggests strong potential for thermochemical conversion routes such as combustion, gasification, and pyrolysis. Their high volatile matter contents (> 85%) promote rapid ignition and stable flame propagation, which are desirable for co-firing and small-scale combustion systems (Nunes et al., 2016). The low ash levels (< 5%) reduce slagging and fouling tendencies, facilitating mechanical densification into briquettes or pellets without requiring extensive pretreatment (Kpalo et al., 2020).

With HHV values ranging from 18 to 22 MJ kg^{-1}, the evaluated blends perform on par with, or even above, benchmark feedstocks commonly used in industrial bioenergy systems. Similar calorific ranges have been reported for tropical feedstocks effectively applied in pyrolysis and gasification studies (Adeoye et al., 2022; Sulis et al., 2025). Given their abundance, renewable origin, and favorable combustion characteristics, these residues present a valuable opportunity for distributed bioenergy generation and circular bioeconomy strategies in Brazil's semi-arid and coastal regions (EPE, 2024).

Collectively, the results confirm that biomass blending can enhance both physicochemical and energetic properties, paving the way for the development of locally sourced, low-carbon solid biofuels aligned with Net-Zero and regional sustainability goals.

4. Conclusion

The proximate analysis of the evaluated biomass blends demonstrated favorable properties for thermochemical conversion, with high volatile matter contents (above 84%) and low to moderate ash fractions (3–4%). Among the tested materials, the blend composed of carnauba stalk and babassu coconut shell (50:50, w/w) exhibited the best energetic performance, characterized by the lowest moisture (10.66%), lowest ash (3.15%), and highest volatile matter (88.61%). This composition resulted in a predicted Higher Heating Value (HHV) of 22.38 MJ/kg, surpassing the other blends and exceeding the typical range of conventional lignocellulosic feedstocks such as sugarcane bagasse (19.19 MJ/kg), eucalyptus wood (19.4–20.3 MJ/kg), and palm kernel shell (18.2 MJ/kg). These results confirm the strong energetic potential of regional waste biomass blends for solid biofuel production. The synergistic behavior between residues contributed to improved combustion quality and energy density, validating their suitability for decentralized bioenergy applications. Additionally, the consistent methodology and reproducibility of the proximate analyses reinforce the technical robustness of the study, in accordance with standard procedures. Considering their favorable calorific performance and low ash formation, the studied blends—especially carnauba stalk with babassu shell—present promising characteristics for practical use in combustion, briquetting, or pyrolysis systems. Their local availability, renewable nature, and compatibility with hybrid renewable energy systems make them viable feedstocks for sustainable bioenergy production and circular bioeconomy strategies in tropical regions.

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6. References

ABNT NBR 16550. (2018). Bagaço de Cana-Caracterização Química. ABNT: Brasília, Brasil.

Adeoye, A. O., Quadri, R. O., & Lawal, O. S. (2022). Assessment of biofuel potential of tenera palm kernel shell via fixed bed pyrolysis and thermal characterization. Results in Surfaces and Interfaces, 9, 100091. Available at: https://doi.org/10.1016/j.rsurfi.2022.100091.

ASTM D3175-20. (2020). ASTM International Standard Test Method for Volatile Matter in the Analysis Sample of Coal and Coke. ASTM: West Conshohocken, PA, USA. Pp. 1-14.

ASTM D3172-89. (2021). ASTM International Standard Practice for Proximate Analysis of Coal and Coke. ASTM: West Conshohocken, PA, USA. Pp. 1-2.

Demirbas, A. (2004). Combustion characteristics of different biomass fuels. Progress in Energy and Combustion Science, 30(2), 219–230. Available at: https://doi.org/10.1016/j.pecs.2003.10.004.

El-Araby, R. et al. (2024). Biofuel production: exploring renewable energy solutions for a greener future. Biotechnology for Biofuels and Bioproducts, 17, 129. Available at: https://doi.org/10.1186/s13068-024-02571-9.

Empresa de Pesquisa Energética (EPE). (2024). Balanço Energético Nacional 2024 – Ano base 2023. Rio de Janeiro, RJ. Available at: https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/balanco-energetico-nacional-ben.

Energy Transitions Commission (ETC). (2022). Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible. London: Energy Transitions Commission. Available at: https://www.energy-transitions.org/wp-content/uploads/2022/07/ETC-Bioresources-Report-Final.pdf

Esteves, M. R. L. et al. Avaliação do potencial energético das cascas de coco verde para aproveitamento na produção de briquetes. Scientia Plena, v. 9, n. 6, 2015. Available at: https://www.scientiaplena.org.br/sp/article/view/2230.

International Energy Agency (IEA). (2021). Net Zero by 2050: A Roadmap for the Global Energy Sector. Paris: IEA. Available at: https://www.iea.org/reports/net-zero-by-2050.

International Energy Agency (IEA). (2024). Renewables 2024: Analysis and forecast to 2030. Revised version, October 2024. Available at: https://www.iea.org/reports/renewables-2024.

Kpalo, S. Y., Zainuddin, M. F., Manaf, L. A., Roslan, A. M. (2020). A review of technical and economic aspects of biomass briquetting. Sustainability, 12(11), 4609. Available at: https://doi.org/10.3390/su12114609.

Lima, L. M. de et al. Industrial application of sugar cane bagasse as an alternative energy source in cement production. Ambiente Construído, 2025, e140268. Available at: https://doi.org/10.1590/s1678-86212025000100833.

Neto, F. S. et al. Analysis of the Fuel Properties of the Seed Shell of the Neem Plan (Azadirachta indica). Processes. 2023, 11, 2442. Available at: https://doi.org/10.3390/pr11082442.

Pedroso, D. T., Machin, E. B., Cabrera-Barjas, G., Flores, M., Urra, H. G., de Carvalho, F. S., Santos, M. I. S. dos, Machín, A. B., Canettieri, E. V., Pérez, N. P., et al. (2021). Sugarcane Bagasse Torrefaction for Fluidized Bed Gasification. Applied Sciences, 11(13), 6105. Available at: https://doi.org/10.3390/app11136105.

Rauen, C. C. M. et al. Biochar de casca de babaçu: um estudo termogravimétrico. Anais do XIII Evento de Iniciação Científica da Embrapa Florestas – Evinci. Colombo: Embrapa Florestas, 2014. Available at: https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1010712.

Santos, P. C. T. et al. Caracterização da biomassa do coco verde (Cocos nucifera). In: 62º Congresso Brasileiro de Química, 2023. Anais [...]. Available at: https://www.abq.org.br/cbq/2023/trabalhos/5/25193-29791.html.

Sulis, D. B., Lavoine, N., Sederoff, H., Jiang, X., Marques, B. M., Lan, K., Cofre-Vega, C., Barrangou, R., & Wang, J. P. (2025). Advances in lignocellulosic feedstocks for bioenergy and bioproducts. Nature Communications, 16, 1244. Available at: https://doi.org/10.1038/s41467-025-56472-y.

Vieira, T. A. S., Trugilho, P. F., Carabineiro, S. A. C., Zanuncio, A. J. V., Carvalho, A. G., & Branco-Vieira, M. (2023). Impact of Chemical Composition on Eucalyptus Wood Clones for Sustainable Energy Production. Forests, 14(11), 2240. Available at: https://doi.org/10.3390/f14112240.