REVISTA DE ESTUDOS INTERDISCIPLINARES

THERMAL TREATMENT OF AGRICULTURAL WASTE AS AN ALTERNATIVE FOR PRODUCING SOLID BIOFUELS

TRATAMENTO TÉRMICO DE RESÍDUOS AGRÍCOLAS COMO ALTERNATIVA PARA PRODUÇÃO DE BIOCOMBUSTÍVEIS SÓLIDOS

Received on: 12/23/2024
Resubmitted on: 09/09/2024
Accepted on: 09/21/2024
Published on: 09/10/2024

Márcio Mendes Silva Diniz[1]
Federal Institute of Education, Science, and Technology of Bahia

Carine Tondo Alves[2]
Federal University of the Recôncavo of Bahia

Marcus Luciano Souza de Ferreira Bandeira[3]
Federal Institute of Education, Science, and Technology of Bahia

Allívia Rouse Carregosa Rabbani[4]
Federal Institute of Education, Science, and Technology of Bahia

Allison Gonçalves Silva[5]
Federal Institute of Education, Science, and Technology of Bahia

Abstract: Brazil stands out in terms of the composition of its energy matrix, with biofuels playing an important role, with many different raw materials requiring study. This article seeks to evaluate thermal treatment's effect on different biomass species to improve their energy characteristics, through an analysis of immediate chemical composition (as standardized by the American Society for Testing and Materials), spectroscopy in the infrared region, and thermogravimetry. This paper details the energy potential for each biomass, establishing the torrefaction processes with the best yield from agricultural residue of peanuts (*Arachis hypogaea* L.), cacao (*Theobroma* cacao L.), sugarcane (*Saccharum* spp.), coconut (*Cocos nucifera* L.), palm oil (*Elaeis guineensis* Jacq.), and papaya (*Carica papaya* L.). The thermal treatment of biomass proved effective in obtaining a solid biofuel with a higher heating value, as diagnosed through immediate chemical analyses.

Keyword: Agriculture; Chemistry; Energy potential; Forestry; Residues.

Resumo: O Brasil se destaca na composição de sua matriz energética, tendo os biocombustíveis um papel importante, com diversas matérias-primas necessitando de estudo. Este artigo busca avaliar o efeito da aplicação de tratamento térmico em diferentes espécies de biomassa para melhorar suas características energéticas, através de análise de composição química imediata (padronizada pela *American Society for Testing and Materials*),

---

[1] Federal Institute of Education, Science, and Technology of Bahia (IFBA), DIREN/ Bachelor's Degree in Chemistry, Porto Seguro Campus. E-mail: marciodiniz990@hotmail.com

[2] Professor at Federal University of the Recôncavo of Bahia (UFRB), CETENS. Brazil, Bahia, Feira de Santana. E-mail: carine.alves@ufrb.edu.br

[3] Professor at Federal Institute of Education, Science, and Technology of Bahia (IFBA), DIREN/PPGCTA. Porto Seguro Campus. E-mail: marcusbandeira@ifba.edu.br

[4] Professor at Federal Institute of Education, Science, and Technology of Bahia (IFBA), DIREN/PPGCTA, Porto Seguro Campus. E-mail: alliviarouse@hotmail.com

[5] Professor at Federal Institute of Education, Science, and Technology of Bahia (IFBA), DIREN/PPGCTA, Porto Seguro Campus. E-mail: allisongoncalves@ifba.edu.br

DOI: https://doi.org/10.56579/rei.v6i3.1031

espectroscopia na região do infravermelho, e termogravimetria. Este artigo detalha o potencial energético de cada biomassa, estabelecendo os processos de torrefação com melhor rendimento a partir de resíduos agrícolas de amendoim (*Arachis hypogaea* L.), cacau (*Theobroma cacao* L.), cana-de-açúcar (*Saccharum* spp.), coco (*Cocos nucifera* L., óleo de palma (*Elaeis guineensis* Jacq.) e mamão (*Carica papaya* L.). O tratamento térmico da biomassa mostrou-se eficaz na obtenção de um biocombustível sólido com maior poder calorífico, diagnosticado através de análises químicas imediatas.

Palavras-chave: Agricultura; Química; Potencial energético; Silvicultura; Resíduos.

INTRODUCTION

The drastically expanded global demand for energy over the last century, through the process of economic globalization associated with abusive use of fossil fuels, has caused serious environmental problems that affect climatic and biological conditions all over the planet. Alternatives are growing, however, and new technologies are currently being developed (GUERRA, 2022; KHAN *et al.*, 2020; BUTT *et al.*, 2020; GRUBLER *et al.*, 2018; OMER, 2008). Biomass is a source of renewable energy that can help achieve the carbon-neutral cycle in countries with an efficient policy for the protection and use of natural resources (DINCER, 2000; FAVERO *et al.*, 2020).

Brazil stands out among the countries that have an energy matrix composed mostly of renewable sources (MME, 2020). According to the Brazilian government, 48% of the energy matrix is renewable, and 61% of this total is made up of bioenergy sources (MME, 2021). Biomass is among the most promising sources of energy generation at both national and international levels because it is considered one of the principal alternatives for diversifying heat and energy production (MAO *et al.*, 2018). According to the International Energy Agency, a 16% increase in worldwide demand for renewable energy from biomass is expected by 2028 (IEA, 2022).

Forestry and agriculture are the predominant forms of land utilization worldwide, encompassing significant economic, social, and cultural endeavors (TORRES *et al.*, 2022). Nonetheless, waste generation occurs within this land utilization endeavor, waste generation occurs. This demonstrates the importance of developing procedures and technologies that improve the energy potential of these residues, to contribute as significantly as possible to the world's energy matrix.

There are different ways of using biomass as raw material to produce energy. The oldest methods of thermal reduction are combustion and pyrolysis. Combustion is an oxidation reaction that transforms the fuel into gases, leaving the residue as ash. Pyrolysis is a controlled degradation between 225°C and 500°C (MARTINS, 1980).

DOI: https://doi.org/10.56579/rei.v6i3.1031

Torrefaction is a thermal treatment, with temperatures ranging between 200°C and 300°C in an environment with partial or complete no oxidizing agents. The benefits of this treatment are associated with the increase in the energy potential of the solid biofuel and the granulometric homogenization and fluidized bed combustion. The process allows for the removal of the volatile components of higher heating value, and the final product is composed mainly of cellulose, lignin, and degraded hemicellulose. The degraded hemicellulose characterizes the hydrophobic aspects of the torrefied biofuel and promotes resistance to microbial degradation, allowing for longer storage periods (SILVA *et al.*, 2013; GIL *et al.*, 2015).

The torrefaction process, which determines the detailed energy potential for each biomass, can help identify the most advantageous products through a thermal analysis technique that analyzes the physical properties of a substance and/or its products, while the samples are subjected to a controlled temperature regime. There are two basic approaches to studies that apply thermal analysis techniques: isothermal and non-isothermal or dynamic (IONASHIRO; GIOLITO, 1980).

In thermal analysis, mass variations are measured using thermogravimetry (TG), while energy variation measurements form the technical basis of differential scanning calorimetry (DSC). TG provides information on the composition and thermal stability and is applied to measure mass changes resulting from a physical transformation (sublimation, evaporation, condensation) or chemical transformation (degradation, decomposition, oxidation), as a function of temperature or time (MOHTÉ; AZEVEDO, 2002; MIRANDA, 2011).

DSC is a technique in which the difference in energy supplied to the substance and a thermally inert reference material is measured as a function of temperature, while the substance and reference material are subjected to a controlled temperature schedule, keeping both the sample and the reference in isothermal conditions (IONASHIRO; GIOLITO, 2004).

The objective of this study is to evaluate the energy potential of biomass residues from peanut (*Arachis hypogaea* L.), coconut (*Cocos nucifera* L.), cocoa (*Theobroma cacao* L.), sugarcane (*Saccharum* spp.), palm heart (*Elaeis guineensis* Jacq.), and papaya (*Carica papaya* L.) through thermal analysis and torrefaction treatments.

The innovation of this study lies in the detailed characterization of the thermogravimetric behavior of these residues, exploring new combinations of residual binders, such as glycerin and black liquor, to optimize the energy yield of solid biofuels. This approach

DOI: https://doi.org/10.56579/rei.v6i3.1031

not only aims to increase the energy potential of these biomasses but also contributes to sustainability by reducing the environmental impact of industrial waste. The practical application may provide viable and sustainable alternatives for the diversification of the regional and national energy matrix, addressing the growing global demand for renewable energy.

MATERIALS AND METHODS

This research was conducted using a quantitative approach, focusing on bioenergy and agro-industrial residues. Samples were obtained from companies, open-air markets, and beach stalls in the city of Porto Seguro, Brazil, in the year 2022, and included peanut, coconut, and cocoa shells, sugarcane bagasse, palm fiber, and papaya. The samples were collected and characterized in the laboratories of IFBA (Federal Institute of Education, Science, and Technology of Bahia). To identify the energy potential of each type of residue, proximate analyses were performed, including total ash, volatile matter, and fixed carbon. Based on this data, the higher heating value (HHV, $MJKg^{-1}$) was calculated for each biomass, as well as the gravimetric yield. The residues were characterized by Fourier-transform infrared spectroscopy (FTIR) and thermogravimetric analysis (TGA).

The methodological approach was experimental, using raw samples that were cut with knives into pieces smaller than 50 mm and placed in the oven at a temperature of 105°C for 24 hours, by ASTM E 871-82 from the American Society for Testing and Materials (ASTM, 2019a). Following this, the samples were removed from the heat and cooled to room temperature. The dried biomasses were then processed in the Willye Super®, model STAR FT-80. The processed biomasses were filtered into particle sizes of less than 3.0 mm using a sieve.

The torrefaction process, based on Cao *et al.* (2015), Zhang *et al.* (2018), and Silva *et al.* (2017), was performed on all samples. For this purpose, a muffle-type reactor was used, with a pressurized cylinder of nitrogen gas connected to the reactor. The biomass samples were torrefied at temperatures of 230°C, 240°C, and 250°C for 01 (one) hour. Approximately 10 g of fresh biomass was placed in a previously weighed aluminum crucible. After the period of heating, the samples were cooled inside the reactor, in an inert medium, for approximately 01 (one) hour. The torrefied products were stored separately in flasks for subsequent analyses.

DOI: https://doi.org/10.56579/rei.v6i3.1031

Four analyses in line with ASTM (2019ab, 2021) were carried out: moisture measurements (ASTM E 871-82), volatile materials (ASTM E 872-82), fixed carbon and total ash (ASTM D 1102-84).

The HHV for the samples under study were estimated, in MJKg^{-1}, according to Parikh *et al.* (2005), whereby it was possible to estimate the HHV of materials ranging from solid carbonaceous substances to all types of biomass material and waste-derived fuel coal, through immediate analysis. Regression analysis was used to estimate the relationship between moisture content and volatile material concentration; as well as the correlation between fixed carbon content and the higher heating value of the biomass, using Excel® (MICROSOFT, 2023).

The gravimetric yields of solid material from torrefaction were obtained by calculating the ratio between the mass of the material after treatment and the mass of previously dried material.

For the determination of energy density, the methodology proposed by Bergman *et al*. (2004) was used, which is a measure of the potential energy that a given volume of biomass should produce. This concept relates the apparent density to the heating value of the fuel and thus provides the amount of energy in calories or joules present in one (1) cubic meter (MJm^{-3}).

For the FTIR analyses, the Shidmazu® IRAffinity -1S model was used, with analysis performed in the range of 4000 to 400 cm^{-1}, with a resolution of 4 cm^{-1} and a total of 128 scans. The samples were prepared using potassium bromide (KBr) pellets (1:300 mg, sample). This technique was used to characterize the biomass samples, mainly concerning the identification of hemicellulose, which decreases the heating power of the residues studied. The positions of the infrared absorption bands found were compared with the bands already described in the literature (PANDEY, 2002). The results were plotted using Origin software, version 7.0 (EDWARDS, 2002).

To thermogravimetrically analyze the biomass residue, the following methodology was used. The samples were submitted to pyrolysis in a nitrogen atmosphere using a Shidmazu® Model H60, at a temperature up to 850ºC. Before each procedure, the thermal analysis system was purged with nitrogen and the sample was pre-treated by heating it up to 110ºC for 30 minutes. The results were plotted using Origin software, version 7.0 (EDWARDS, 2002).

RESULTS AND DISCUSSION

The moisture content (M), volatile matter content (VM), ash content (AC) and, consequently, the fixed carbon content (FC), were determined for the *in natura* and torrefied samples. The values obtained for the immediate chemical analysis of the raw and torrefied biomass, the increase in gross calorific value for each biomass as a function of the temperature of their respective thermal conditionings, and the gravimetric and energy yield from biomasses submitted to the torrefaction process are shown in Table 1.

Table 1 - Immediate chemical analysis of peanut shells (*Arachis hypogaea* L.), cacao shells (*Theobroma cacao* L.), sugar cane bagasse (*Saccharum* spp.), coconut (*Cocos nucifera* L.), palm fiber (*Elaeis guineensis* Jacq.), and papaya (*Carica papaya* L.) biomass. M - moisture content; MV- volatile material content; AC - ash content; FC - fixed carbon content; ηm - gravimetric yield; ηe - energy yield; and HHV – higher heating value.

Plant residue	Heat (°C)	Variables (%)				Standard Deviation			Coefficient of variation (%)			η_m (%)	ηe (%)	HHV(MJ Kg^{-1})
		M	MV	AC	FC	M	MV	AC	M	MV	AC			
Peanut	0	12.23	79.26	2.33	18.41	0.91	1.89	0.32	7.44	2.39	13.84	-	-	18.90
	230	3.42	54.55	4.22	41.23	0.14	2.97	0.26	4.23	5.44	6.15	63.41	77.33	23.05
	240	3.21	52.94	5.02	42.04	0.08	0.67	0.38	2.61	1.27	7.64	58.75	71.74	23.08
	250	3.03	50.98	5.34	43.68	0.09	1.47	0.20	2.94	2.89	3.71	57.22	70.69	23.35
Cacao	0	9.35	71.14	6.02	22.83	0.09	10.21	1.29	0.97	14.35	21.47	-	-	19.11
	230	1.46	47.59	9.44	42.97	0.05	3.53	1.31	3.24	7.41	13.89	77.36	91.25	22.54
	240	1.41	41.01	9.57	49.42	0.03	7.33	0.63	2.45	17.87	6.54	68.51	85.29	23.79
	250	1.16	40.32	11.48	48.20	0.03	0.95	0.61	2.58	2.35	5.36	65.97	80.23	23.24
Sugar cane	0	16.75	87.34	0.93	11.73	1.07	4.17	0.51	6.41	4.78	54.36	-	-	17.75
	230	6.24	68.67	1.80	29.53	0.16	11.49	0.60	2.63	16.74	33.12	79.14	94.21	21.13
	240	5.87	51.50	2.11	46.39	0.22	11.16	0.88	3.77	21.67	41.56	66.38	91.29	24.41
	250	5.42	50.53	2.34	47.13	0.15	4.52	0.70	2.84	8.95	29.75	64.87	89.61	24.52
Coco	0	10.21	78.88	1.28	19.84	0.14	1.81	0.44	1.38	2.30	34.57	-	-	19.30
	230	4.98	58.50	3.23	38.27	0.27	4.36	0.36	5.46	7.45	11.26	76.08	89.21	22.63
	240	3.42	46.85	4.23	48.92	0.12	5.61	0.62	3.42	11.98	14.59	69.74	88.78	24.57
	250	3.20	46.16	4.55	49.29	0.09	3.17	0.31	2.90	6.87	6.78	64.05	81.61	24.59
Palm	0	9.42	79.87	3.24	16.89	0.44	5.69	1.12	4.72	7.12	34.52	-	-	18.39
	230	5.28	53.99	5.24	40.67	0.36	8.87	0.78	6.82	16.43	14.95	77.42	95.56	22.70
	240	3.91	53.16	5.41	41.43	0.06	5.19	0.41	1.64	9.76	7.64	75.70	94.22	22.89
	250	3.63	50.08	5.56	44.46	0.09	2.29	0.40	2.37	4.58	7.29	70.12	89.76	23.54
Papaya	0	16.44	78.79	6.49	14.72	1.02	10.60	1.37	6.23	13.46	21.17	-	-	17.44
	230	5.98	55.26	15.67	29.07	0.25	26.94	5.44	4.17	48.75	34.73	53.81	57.91	18.77
	240	5.71	53.24	16.29	30.47	0.49	16.72	1.13	8.62	31.40	6.92	51.49	55.92	18.94
	250	4.94	49.77	16.04	34.19	0.16	8.67	2.31	3.21	17.42	14.38	48.76	55.02	19.68

Elaboration: By the authors, 2022.

As the temperature increased during the thermal conditioning of these biomass materials, their moisture content was progressively reduced. This confirms the hypothesis of the degradation of hydrophilic components (hemicellulose) of biomass as a function of temperature. The biomass samples, on average, lost relatively 67.9% of total moisture after the torrefaction process compared to their respective biomasses *in natura*, considering the three temperatures at which the thermal treatment was performed. The greatest loss was observed for cacao shell, which had an average moisture reduction of 85.6%.

Consequently, cacao shell was also the biomass with the highest relative loss, an average reduction of 39.6% in the final concentration of the torrefied product, when considering the

DOI: https://doi.org/10.56579/rei.v6i3.1031

three temperatures. The reduction in the concentration of volatile materials for the biomass samples studied was, on average 29.0%, 37.2%, and 39.5% at torrefaction temperatures of 230°C, 240°C, and 250°C, respectively. The volatile material contents after thermal treatment agreed with those found by Prins *et al.* (2006), which indicate a decrease in the concentration of volatile materials from 80% to 60%, a reduction of approximately 25% at a torrefaction temperature of 220°C.

In general, the hydrophilic nature of volatile materials can be observed in the correlation between the volatile material content and the moisture content. As the volatile matter is degraded during thermal treatment, moisture is reduced exponentially, showing that the component responsible for the adsorption of water, hemicellulose, is degraded. It is a low energy density constituent, due to water retention in the biofuel, which is undesirable for energy purposes. In practical terms, this means that increased degradation of hydrophilic compounds does not represent a significant gain in terms of preventing microbial degradation of the torrefied biomass, because of the water present in the material.

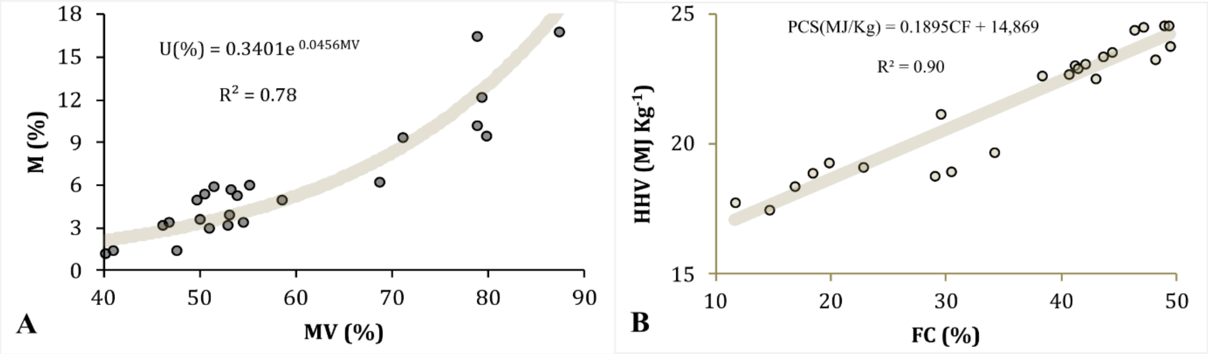
The HHV averages obtained were consistent with those found in the literature (DOAT, 1985; ARIAS *et al.*, 2008; FELFLI *et al.*, 2005). The increase in HHV is due to a higher concentration of fixed carbon verified in the torrefied biomass (PARIKH *et al.*, 2005). The increase in fixed carbon is intrinsically associated with the reduction of volatile materials. However, a progressive increase in temperature gradually reduces the gravimetric yield, and consequently, reduces the final energy yield of the solid biofuel, since it increases the release of volatile constituent materials from *in natura* biomass. The losses of volatile matter as a function of the temperature of the thermal treatment for the respective biomass samples determine the gravimetric yield of each procedure.

Papaya was the biomass that presented the worst gravimetric yield result from the torrefaction processes. A slight increase in HHV can be observed after the torrefaction process, as a function of the concentration of fixed carbon. The HHV increase for torrefied biomass varied on average from 21.3% (cocoa husk) to 31.6% (sugarcane bagasse), while papaya showed an increase of only 9.7%. This poor result can be justified by another aggravating factor, the high concentrations of ash. Papaya was the only biomass to present ash content values greater than 15.0%, the next closest begin cacao shell at 250°C, with an ash content value of 11.5%.

DOI: https://doi.org/10.56579/rei.v6i3.1031

The function obtained from the correlation between fixed carbon and HHV (Figure 1), makes it possible to extrapolate the energy potential of the biomasses, given its high coefficient of determination. Biomass found in nature that has a fixed carbon content close to 5% would have a relative energy potential of 16.45 $MJKg^{-1}$, while a thermally conditioned sample that reached concentrations of fixed carbon close to 70% would have an energy potential estimated at approximately 28.00 $MJKg^{-1}$.

Figure 1 - (A) Correlation between moisture (M) content as a function of volatile material (MV) concentration; and (B) Between fixed carbon (FC) content and higher heating value (HHV) from peanut shells (*Arachis hypogaea* L.), cacao shells (*Theobroma cacao* L.), sugar cane bagasse (*Saccharum* spp.), coconut (*Cocos nucifera* L.), palm fiber (*Elaeis guineensis* Jacq.), and papaya (*Carica papaya* L.) biomass.



Elaboration: By the authors, 2022.

The mass efficiency and energy efficiency tend to decrease as temperature increases, with part of the energy dissipated by the gases produced during the torrefaction process. According to Araújo (2004), cellulose is degraded in a temperature range from 240°C to 400°C, causing the release of CO, CO_2, and H_2O.

Coconut husk and sugarcane bagasse showed similar changes, with a significant gain in HHV for biomass torrefied at 240°C compared to that torrefied at 230°C. For papaya and palm fiber, there was an increase in HHV when the biomass was subjected to heat treatment at 250°C. Unlike what happened with cocoa husk, there was a sudden increase in the concentration of ash. Another exception for the papaya was that the mineral content was reduced.

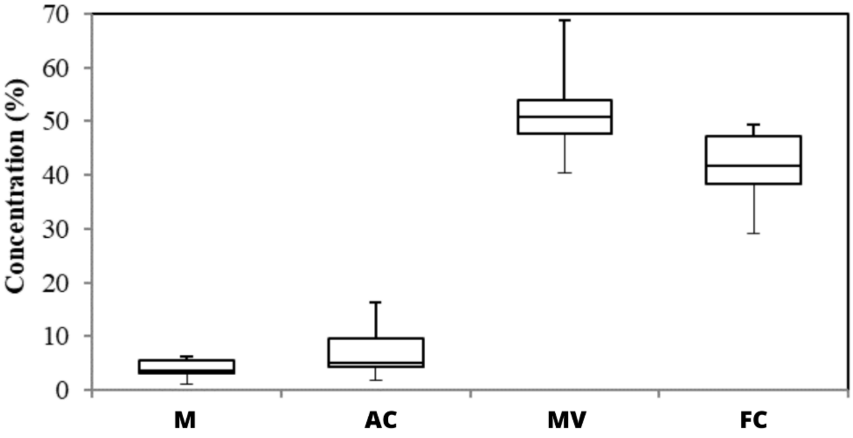
The ash content increased after the torrefaction process, with values above 7% being undesirable, as they can cause some inconvenience during the combustion of the fuel, such as partial burning, which can cause solid particulates to move and increase the incrustations in the

DOI: https://doi.org/10.56579/rei.v6i3.1031

internal part of the fuel boiler, reducing its efficiency (VIEIRA, 2012). In this study, cacao shell and papaya returned unsatisfactory results.

The corresponding quartiles were symmetrical concerning data dispersion (Figure 2), with the dispersion increasing for the minimum value, due to the greater degradation of the cacao shell compounds at high temperatures (240°C and 250°C) and, especially, for the maximum value, where the greatest discrepancy between measurements was recorded, with sugarcane bagasse at 230°C retaining 68.7% of its volatile matter. To understand the size of the discrepancy, the second highest retention was found for coconut shell at 230°C, with a content of 58.5%.

Figure 2 - Dispersion of data from the immediate analyses of the torrefied biomass of peanut shells (*Arachis hypogaea* L.), cacao shells (*Theobroma cacao* L.), sugar cane bagasse (*Saccharum* spp.), coconut (*Cocos nucifera* L.), palm fiber (*Elaeis guineensis* Jacq.), and papaya (*Carica papaya* L.). M - moisture content; MV- volatile material content; AC - ash content; FC - fixed carbon content.

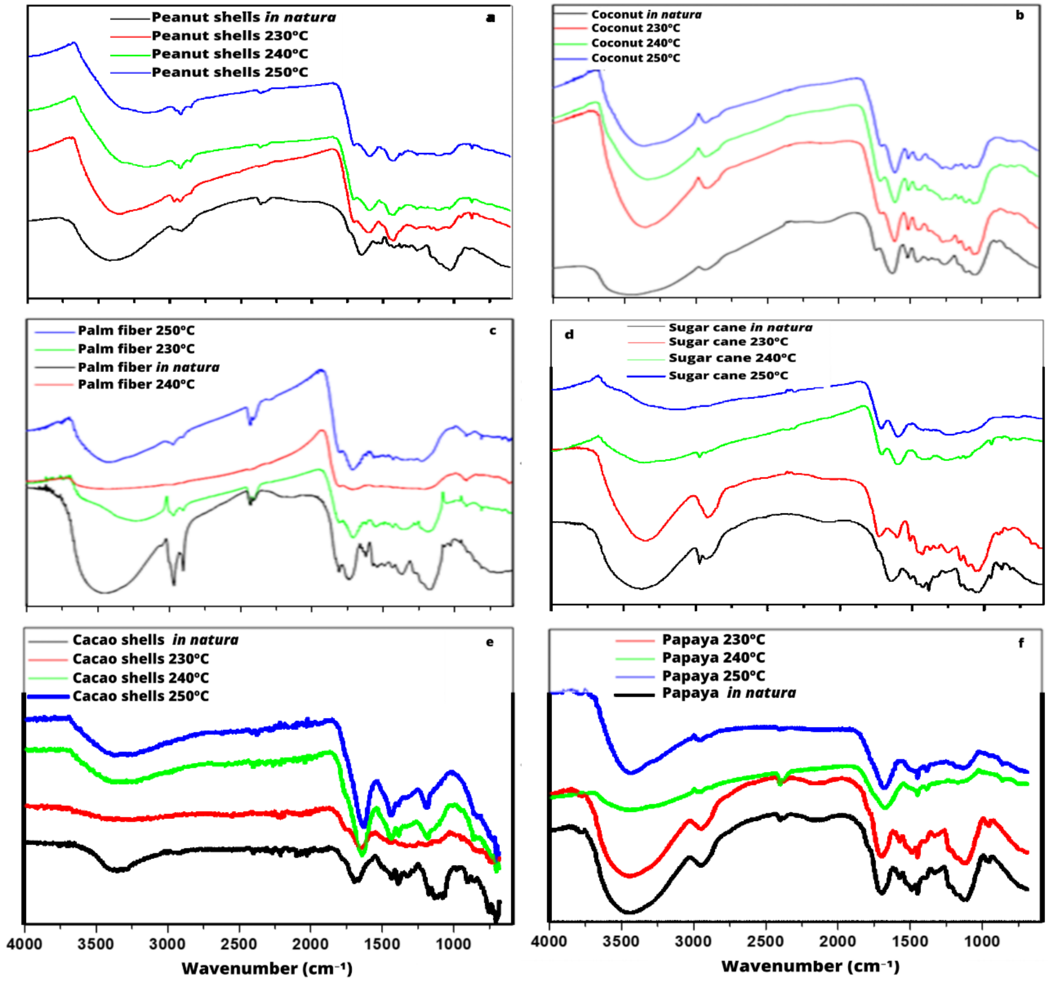


Elaboration: By the authors, 2022.

Hemicellulose degradation during the thermal conditioning of the biomass can be verified from the infrared absorption spectra (Figure 3), by observing their respective structural changes and comparing the bands in the spectra at different torrefaction temperatures. A significant decrease in the bands that refer to hemicellulose (1075 cm^{-1}) can be noted. The intensity of transmittance increases with increased roasting temperature, signaling an increase in hemicellulose degradation.

DOI: https://doi.org/10.56579/rei.v6i3.1031

Figure 3 - Infrared spectroscopy (FTIR) of (a) peanut shells (*Arachis hypogaea* L.), (b) coconut (*Cocos nucifera* L.), (c) palm fiber (*Elaeis guineensis* Jacq.), (d) sugar cane bagasse (*Saccharum* spp.), (e) cacao shells (*Theobroma cacao* L.), and (f) papaya (*Carica papaya* L.).



Elaboration: By the authors, 2022.

Another band that makes it possible to verify the degradation of hemicellulose is the range from 3200 to 3500 cm^{-1}, which corresponds to the hydroxyl radicals. Gonçalves *et al.* (2014) and Brígida *et al.* (2010) reported transmittance profiles for green coconut fiber similar to the one illustrated in Figure 3, which also presents some of the peaks highlighted, with different profiles related to each pre-treatment. At a wavelength of 3348 cm^{-1}, the axial deformation of the (O-H) group occurs, resulting from the narrow vibration of cellulose and lignin in the fiber. Further peaks can be seen at 2917 cm^{-1}, caused by axial deformation vibrations of the (C-H) group; at 1727 cm^{-1}, related to properties of carbonyl (C=O) attributed to hemicellulose; and at 1243 cm^{-1}, due to are bonds (C-O) from esters, ethers, and phenolic compounds such as waxes or extractables. The absence of peaks in the wavelength region from

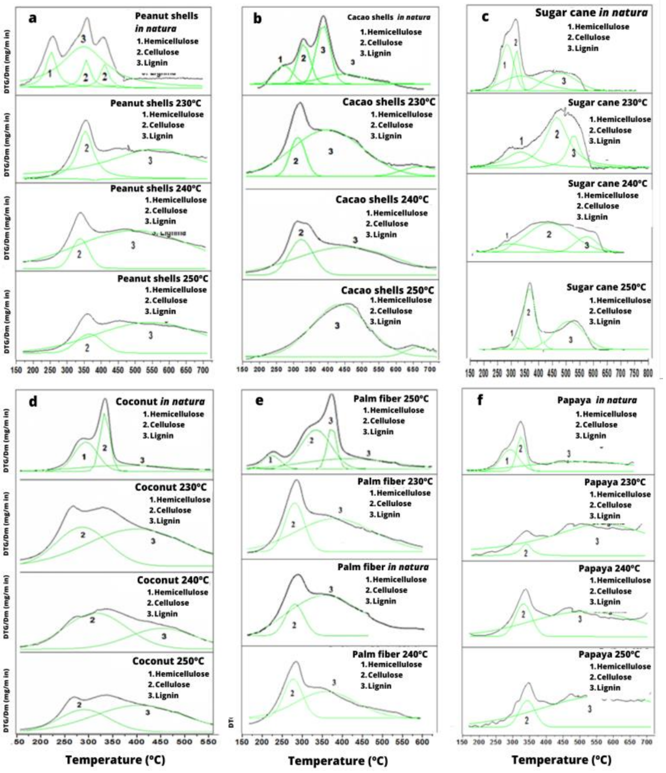
DOI: https://doi.org/10.56579/rei.v6i3.1031

1370 to 1390 cm^{-1} refers to the symmetrical structure and asymmetrical deformation of cellulose and hemicellulose, indicating that cellulose and hemicellulose are more exposed on the fiber surface.

The only spectrum not available for data analysis was that for peanut shells torrefied at 250°C. However, from the spectra obtained from the samples at temperatures of 230°C and 240°C, it is possible to estimate higher transmittance in the 1075 cm^{-1} and 1740 cm^{-1} bands, related to the degradation of hemicellulose.

Hemicellulose is formed from polysaccharides that contain many hydroxyl groups and, due to the presence of hydrogen bonds in these groups, the more hemicellulose found in the composition of the biomass, the greater the absorption of water and the lower its higher heating value. The TG curves (Figure 4) show the theoretical estimates regarding the decomposition of the main macro components of the studied biomasses. For all biomasses, hemicellulose degradation is represented by curve 1, cellulose is associated with curve 2, and lignin is represented by curve 3.

Figure 4 - Derivative thermogravimetry (DTG) and deconvolution (Dm) for the *in natura* and torrefied biomass residue samples from (a) peanut shells (*Arachis hypogaea* L.), (b) cacao shells (*Theobroma cacao* L.), (c) sugar cane bagasse (*Saccharum* spp.), (d) coconut (*Cocos nucifera* L.), (e) palm fiber (*Elaeis guineensis* Jacq.), and (f) papaya (*Carica papaya* L.) at temperatures of 230°C, 240°C, and 250°C.



Elaboration: By the authors, 2022.

DOI: https://doi.org/10.56579/rei.v6i3.1031

The estimation of devolatilization products through derivative thermogravimetry (DTG) curves also points to a decrease in the percentage of hemicellulose in the biomass after torrefaction, as expected, showing once again that the thermal treatment contributes to an increase in HHV for the residues under study. According to the deconvolution curves, the *in natura* biomass materials have the most accentuated peaks for hemicellulose. However, following torrefaction at 230°C, the peaks are only noticeable for sugarcane bagasse.

The macro components (hemicellulose, cellulose, and lignin) were quantified through thermogravimetric analysis. After cellulose, lignin is the most abundant macromolecule that exists in the biosphere. It is defined as a hydrophobic substance, with a three-dimensional, amorphous, and highly-branched structure (SILVA, 2010). It is the third main component of the plant cell wall, corresponding to between 20 and 30% of the material. Lignin is synthesized from three monomeric precursors: coniferyl alcohol, sinapyl alcohol, and p-coumaryyl alcohol (NASCIMENTO, 2006).

The data obtained from the integration under the curves of the graphs support the tendency of hemicellulose to degrade, demonstrating that, at higher temperatures, its presence becomes imperceptible. This makes it possible to identify the appropriate torrefaction temperature for obtaining solid biofuel that has the highest possible energy yield. In this case, torrefaction temperatures of up to 230°C proved to be sufficient to degrade all the hemicellulose for most biomasses, with only one exception: sugarcane bagasse. This material did, however, confirm the degradation of hemicellulose as a function of roasting temperature.

Arias *et al.* (2014) used thermogravimetric analysis to study the reactivity of biomass samples in air, having also found only two peaks in the curve for torrefied biomass. Chen e Kuo (2014) mentioned the advantages of analyzing torrefied materials through thermogravimetry, due to the great precision with which it is possible to measure the loss of biomass weight, which was highly relevant to the authors, who were especially interested in the impact of the torrefaction and pyrolysis processes on the lignocellulosic structures of biomasses.

FINAL CONSIDERATIONS

The torrefaction of biomass residues proved to be an efficient technique for enhancing the energy characteristics of solid biofuels, notably by increasing the higher heating value, as identified through proximate chemical analyses. The study revealed that, in addition to

DOI: https://doi.org/10.56579/rei.v6i3.1031

optimizing the energy potential, the thermal treatment significantly reduced hemicellulose content, as confirmed by thermogravimetric and infrared spectroscopy analyses, making the biomass more resistant to microbial degradation and therefore suitable for prolonged storage.

Another important aspect observed was the feasibility of using widely available agro-industrial residues, such as those studied, for renewable energy generation. By exploring these residual biomasses, the study paves the way for a sustainable and circular approach, where materials traditionally discarded can be repurposed as clean energy sources. This not only contributes to the diversification of the energy matrix but also mitigates environmental impact by preventing improper disposal of waste.

The development of solid biofuels from the residues used in this research, combined with the use of industrial binders such as residual glycerin and black liquor, offers a promising opportunity to further increase the energy yield of these materials. The application of such techniques can expand the use of biomass as a viable and efficient alternative to fossil fuels, aligning with global goals of reducing greenhouse gas emissions and promoting a transition to more sustainable and less polluting energy sources.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude for the material and financial support obtained through the institutional programs promoted by PRPGI/IFBA (Call 19/2020/PRPGI/IFBA and Call 14/2022/PRPGI/IFBA), as well as to PRPGI/IFBA/FAPESB for granting the scholarship.

REFERENCES

ARAÚJO, L. V. C.; LEITE, J. A. N.; PAES, J. B. Estimativa da produção de biomassa de um povoamento de jurema-preta (*Mimosa tenuiflora* (Willd.) Poiret. com cinco anos de idade. **Biomassa & Energia**, v. 1, n. 4, p. 347-352, 2004.

ARIAS, B. et al. Influence of torrefaction on the grindability and reactivity of woody biomass. **Fuel Processing Technology**, v. 89, n. 2, p. 169–175, 2008. https://doi.org/10.1016/j.fuproc.2007.09.002

ASTM - American Society For Testing and Materials. **ASTM, D. 1102-84**: Standard test method for ash solubility of wood. American Society for Testing and Materials. Estados Unidos da América. 2001. https://www.astm.org/d1102-84r21.html

DOI: https://doi.org/10.56579/rei.v6i3.1031

ASTM - American Society For Testing and Materials. **ASTM, E. 871-82**: Standard Method for Moisture Analysis of Particulate Wood Fuels. Estados Unidos da América. 2019a. https://www.astm.org/e0871-82r19.html

ASTM - American Society For Testing and Materials. **ASTM, E. 872-82**: Standard Test Method for Volatile Matter in the Analysis of Particulate Wood Fuels. Estados Unidos da América. 2019b. Available at: https://www.astm.org/e0872-82r19.html

BUTT, O. M.; ZULQARNAIN, M.; BUTT, T. M. Recent advancement in smart grid technology: Future prospects in the electrical power network. **Ain Shams Engineering Journal**, v. 12, n. 1, 2020. https://doi.org/10.1016/j.asej.2020.05.004

CAO, L. et al. Complementary effects of torrefaction and co-pelletization: Energy consumption and characteristics of pellets. v. 185, p. 254–262, 2015. **Bioresource Technology**, https://doi.org/10.1016/j.biortech.2015.02.045

DINCER, I. Renewable energy and sustainable development: a crucial review. **Renewable and Sustainable Energy Reviews**, v. 4, n. 2, p. 157–175, 2000. https://doi.org/10.1016/s1364-0321(99)00011-8

EDWARDS, P. M. Origin 7.0: Scientific Graphing and Data Analysis Software. **Journal of Chemical Information and Computer Sciences**, v. 42, n. 5, p. 1270–1271, 2002. https://doi.org/10.1021/ci0255432

FAVERO, A.; DAIGNEAULT, A.; SOHNGEN, B. Forests: Carbon sequestration, biomass energy, or both? **Science Advances**, v. 6, n. 13, p. eaay6792, 2020. https://doi.org/10.1126/sciadv.aay6792

GIL, M. V. et al. Grindability and combustion behavior of coal and torrefied biomass blends. **Bioresource Technology**, v. 191, p. 205–212, 2015. https://doi.org/10.1016/j.biortech.2015.04.117

GUERRA, P. J. C. A cana-de-açúcar e a sustentabilidade: desafios para a readequação do setor sucroenergético nos estados das antigas capitanias do norte. **Revista de Estudos Interdisciplinares**, v. 4, n. 5, p. 77–88, 2023. https://revistas.ceeinter.com.br/revistadeestudosinterdisciplinar/article/view/474.

GRUBLER, A. et al. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. **Nature Energy**, v. 3, n. 6, p. 515–527, 2018. https://doi.org/10.1038/s41560-018-0172-6

IEA - International Energy Agency. **World Energy Outlook 2022**: Analysis. 2022. https://www.iea.org/reports/world-energy-outlook-2022

IONASHIRO M, GIOLITO I**. Nomenclatura, padrões e apresentação dos resultados em análise térmica**. 1980. http://www.labcat.unb.br/images/PDF/Aulas/AnalisesTermicas-Nomenclatura-ABRATEC.pdf

DOI: https://doi.org/10.56579/rei.v6i3.1031

KHAN, H.; KHAN, I.; BINH, T. T. The heterogeneity of renewable energy consumption, carbon emission and financial development in the globe: A panel quantile regression approach. **Energy Reports**, v. 6, p. 859–867, 2020. https://doi.org/10.1016/j.egyr.2020.04.002

MAO, G. et al. Research on biomass energy and environment from the past to the future: A bibliometric analysis. **Science of The Total Environment**, v. 635, p. 1081–1090, 2018. https://doi.org/10.1016/j.scitotenv.2018.04.173

MICROSOFT. Microsoft 365. **Excel**. 2023. https://www.microsoft.com/microsoft-365

MME - Ministério de Minas e Energia. **Relatório Síntese** - Balanço Energético Nacional 2021. Sistema de Informações Energéticas (SIE Brasil). Ministério de Minas e Energia, Brasília, Brazil. 2021. https://www.mme.gov.br/SIEBRASIL/

MME - Ministério de Minas e Energia. **Resenha Energética Brasileira**: oferta e demanda da energia, instalações elétricas, energia no mundo. MME, Brasília, Brazil. 2020. http://antigo.mme.gov.br/web/guest/secretarias/planejamento-e-desenvolvimento-energetico/publicacoes/resenha-energetica-brasileira

OMER, A. M. Energy, environment and sustainable development. **Renewable and Sustainable Energy Reviews,** v. 12, n. 9, p. 2265–2300, 2008. https://doi.org/10.1016/j.rser.2007.05.001

PANDEY, K. K.; PITMAN, A. J. FTIR studies of the changes in wood chemistry following decay by brown-rot and white-rot fungi. **International Biodeterioration & Biodegradation**, v. 52, n. 3, p. 151–160, 2003. https://doi.org/10.1016/s0964-8305(03)00052-0

PARIKH, J.; CHANNIWALA, S.; GHOSAL, G. A correlation for calculating HHV from proximate analysis of solid fuels. **Fuel**, v. 84, n. 5, p. 487–494, 2005. https://doi.org/10.1016/j.fuel.2004.10.010

PRINS, M. J.; PTASINSKI, K. J.; JANSSEN, F. J. J. G. More efficient biomass gasification via torrefaction. **Energy**, v. 31, n. 15, p. 3458–3470, 2006. https://doi.org/10.1016/j.energy.2006.03.008

TORRES, G. A. L. et al. Exposure To Climate Risk: A Case Study For Coffee Farming In The Region Of Alta Mogiana, São Paulo. **Anais da Academia Brasileira de Ciências**, v. 94, n. suppl 4, e2021137, 2022. https://doi.org/10.1590/0001-3765202220211379

SILVA, A. G. et al. Estudo do processo de torrefação de resíduos de biomassas para fins energéticos. **Revista Brasileira de Ciências Ambientais (Online)**, n. 45, p. 86–99, 2017. https://doi.org/10.5327/Z2176-947820170230

ZHANG, C. et al. Torrefaction performance and energy usage of biomass wastes and their correlations with torrefaction severity index. **Applied Energy**, v. 220, p. 598–604, 2018. https://doi.org/10.1016/j.apenergy.2018.03.129

DOI: https://doi.org/10.56579/rei.v6i3.1031