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USE OF RAW AND TORREFIED BAMBOO AND EUCALYPTUS BIOMASS FOR PELLET PRODUCTION

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Resumo

Utilização da biomassa in natura *e torrificada de bambu e eucalipto para produção de* pellets. Os resíduos de origem florestal são uma importante fonte de biomassa para uso energético. Uma das formas de aproveitamento é a produção de *pellets*, na qual o material passa por um processo de densificação, a fim de melhorar as propriedades da biomassa. A torrefação da biomassa também pode contribuir para melhorar as propriedades dos *pellets*. O presente trabalho teve como objetivo avaliar as propriedades dos *pellets* produzidos a partir das biomassas *in natura* e torrificada de Bambu e Eucalipto. Para tanto, foram produzidos *pellets* da biomassa *in natura* e após torrificação a 220 ºC, os quais foram avaliados com base nos parâmetros das normas internacionais e de *pellets* comerciais de Pinus. Verificou-se que os *pellets* da biomassa de Bambu *in natura* apresentaram propriedades similares aos *pellets* comerciais de Pinus, no que tange as propriedades físico-químicas, diferente do Eucalipto, pois este não atendeu ao requisito mínimo referente ao teor de umidade. Os resultados demonstraram que as propriedades químicas e energéticas foram melhoradas com a biomassa torrificada, pois o processo aumentou os teores de carbono fixo e poder calorífico e também a degradação dos *pellets* em temperaturas maiores, melhorando a combustão. No entanto, as propriedades mecânicas foram afetadas negativamente, para ambas as espécies. Pode-se concluir que o bambu da espécie *Phyllostachys aurea* apresentou-se como promissora fonte de matéria-prima para produção de *pellets* a partir da torrefação da biomassa, quando comparada ao mesmo tratamento para a espécie de *Eucalyptus dunnii* e também comparado ao *Pinus taeda* na forma *in natura.*
Palavras-chave: resíduos; biocombustível; energia renovável; qualidade energética.

Abstract

Forest residues are an important source of biomass for energy purposes. One of the ways to utilize this biomass is through pellet production, , in which the material undergoes a densification process to improve its properties. Torrefaction of biomass can also contribute to improving the pellets characteristics. The present study aimed to evaluate the properties of pellets produced from raw and torrefied biomass of bamboo and eucalyptus. For this purpose, pellets were produced from raw biomass and after torrefaction at 220 °C, and their properties were evaluated based on the parameters of international standards and commercial Pinus pellets. It was observed that pellets made from raw Bamboo biomass exhibited properties similar to commercial Pinus pellets, in terms of physicochemical characteristics , whereas eucalyptus pellets did not meet the minimum requirement for moisture content. The results demonstrated that the chemical and energy properties were improved with the torrefied biomass, since the process increased the fixed carbon content and calorific value, as well as the degradation of the pellets at higher temperatures, enhancing combustion. However, the mechanical properties were negatively affected for both species. It can be concluded that the bamboo species *Phyllostachys aurea* represents a promising raw material source for pellet production through biomasstorrefaction, when compared to the same treatment applied to *Eucalyptus dunnii* and also with raw *Pinus taeda* pellets.
Keywords: residues; biofuel; renewable energy; energy quality.

INTRODUCTION

Forest, agroforestry, and industrial residue biomass is considered an abundant source that can be used for the production of solid biofuels, such os pellets. Two potential biomass sources in the country are the lignocellulosic materials eucalyptus and bamboo. Eucalyptus species account for approximately 76% of the planted area in Brazil, being the most widely cultivated species in reforestation programs (IBÁ, 2023). Bamboo, on the other hand, has around 22,000 hectares planted in the state of Maranhão for biomass production (GONÇALVES, 2018), and its cultivation has been expanding over the years due to its high productivity (VECHI e MAGALHES JUNIOR, 2018).

Raw biomass presents limitations for use, such as large volumes, which complicate storage, handling, and transportation, as well as high moisture content that requires energy for drying, and low energy density compared to mineral coal (FOELKEL, 2016). To mitigate the negative effects of these biomass characteristics, the use of thermal modification techniques, such as torrefaction, involving controlled conversion treatments at temperatures between 150 and 300 ºC, has emerged as a potential alternative (BASU, 2018).

It is hypothesized that the combined use of two processes commonly employed to improve biomass properties as fuel pelletization and torrefaction may contribute to increasing the efficiency of biomass utilization from eucalyptus and bamboo species as solid fuels. It is necessary to verify how the pelletization and torrefaction conditions interact and influence pellet properties. Therefore, the objective of this study was to evaluate the quality of pellets produced from raw and torrefied biomass of *Phyllostachys aurea* A. C. Rivière (bamboo) and *Eucalyptus dunnii* Maiden (eucalyptus), according to the standards established by EN Plus, based on ISO 17225-2.

Eucalyptus is widely used in the timber industry, generating large amounts of by-products, especially from the pulp and paper sector. Bamboo is distributed throughout the country and is easily propagated. The comparison was made with commercial pellets from *Pinus taeda*, the most commonly used species for this purpose in Brazil.

MATERIAL AND METHODS

Biomass Collection and Preparation

The biomass used as raw material consisted of *Phyllostachys aurea* (bamboo) and *Eucalyptus dunnii* (eucalyptus). The bamboo was sourced from a plantation located in the municipality of São Mateus do Sul, Paraná, where harvesting was carried out using a saw and machete. The eucalyptus biomass originated from a veneer and plywood company, as a by-product of the lamination process, located in the municipality of Três Barras, Santa Catarina.

Bamboo samples were initially size-reduced using a disc-type forest chipper, brand Lippel, attached to the hydraulic system of an agricultural tractor, transforming the material into wood chips. The bamboo chips were then sun-dried for three days. After drying, they were ground using a hammer mill, brand Trapp, to obtain smaller particles. Eucalyptus samples were collected as chips and underwent the same particle size reduction process applied to the bamboo. Sieve analysis was used to characterize the particle size distribution. For comparison purposes, commercial pellets of *Pinus taeda* L. were obtained from a producer located in the municipality of Quedas do Iguaçu, Paraná.

Biomass Characterization

The characterization of the raw biomass, after collection and particle preparation, was carried out through the determination of moisture content and bulk density. These determinations were performed following the parameters established by the standards NBR 14660 (ABNT, 2004) and EN 17828 (EN, 2015).

Biomass Torrefaction

After sieving, the biomass samples retained in 10-mesh sieves (1.70 mm opening) were dried in a forced-air circulation oven at 100 ± 5 ºC to determine moisture content and to homogenize the samples.

Subsequently, 300 g samples were separated for each torrefaction run, totaling seven torrefaction trials for both eucalyptus and bamboo. Each torrefaction trial was conducted at 220 ºC with a residence time of 15 minutes (YILMAZ *et al.*, 2022) in a laboratory-scale fixed horizontal tubular reactor, as shown in Figure 1, at the School of Engineering of Lorena, São Paulo. The equipment was started at an ambient temperature of approximately 25 ºC, with a heating rate between 3 and 6 ºC min^{-1}.

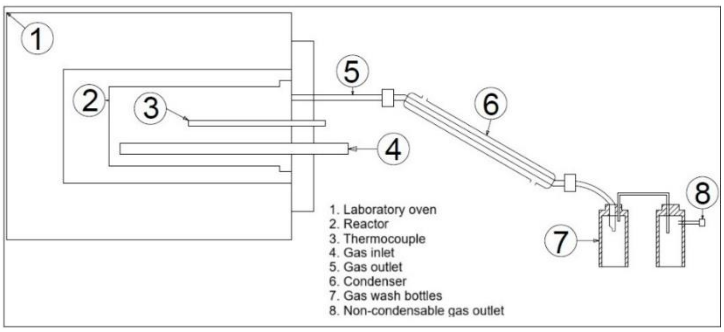

Figure 1. Diagram of the fixed horizontal tubular reactor used for torrefaction of the studied biomasses. Source: Romão *et al.* (2021).

Figura 1. Esquema do reator tubular horizontal fixo utilizado para torrefação das biomassas estudadas. Fonte: Romão *et al.* (2021).

Each raw wood sample was loaded into the reactor and continuously purged with nitrogen at a flow rate of 2 L min^{-1} to prevent undesired reactions and ensure controlled conditions in an inert atmosphere throughout the reaction time. After the reaction, the reactor was cooled to ambient temperature. The samples were then removed and weighed.

Pellet production

Pellets were produced using biomass from *Phyllostachys aurea* (bamboo) and *Eucalyptus dunnii* (eucalyptus). After sieving to obtain particles of the ideal size for production, 1.40 mm (12 mesh), both raw and torrefied biomass were dried in an oven until reaching a moisture content between 10 and 15% before pelletization.

For pellet production, a laboratory pellet press with a flat die, Amandus Kahl brand, model 14-175, with a 6 mm diameter, 3.0 kW power, and a production capacity of 30 kg h^{-1}, was used at the Bio3 Laboratory, State University of Central-West, Irati campus, Paraná. During the process, the pelletization temperature ranged from 80 to 90 ºC, and the roller rotation speed was 1,400 rpm. Water was added during the process, resulting in a moisture content between 10 and 20%. Moisture content determinations were performed following the parameters established by standards NBR 14660 (ABNT, 2004). All trials were conducted in triplicate for each biomass type.

Pellet quality evaluation

For the evaluation of the final pellet quality, the parameters established by the EN Plus standard (2015) were used, which is based on ISO 17225-2 (2014). This standard sets the minimum requirements for residential, commercial, and industrial use.

Physicomechanical properties

For the determination of equilibrium moisture content, the parameters established by the BS EN ISO 18134-2 standard (ISO, 2017) were followed. The pellets were placed in a climatic chamber at 20 ºC and 65% relative humidity to obtain the final equilibrium mass on a wet basis. Moisture content was determined from the difference between the sample at equilibrium moisture and after drying in an oven at 105 ± 2 ºC, using a semi-analytical balance.

To determine the individual pellet density, the diameter and length of each pellet were measured according to the parameters established by the BS EN ISO 17829 standard (ISO, 2015) using a digital caliper. Samples of 50 pellets were selected for analysis. After measuring the volume and weighing on an analytical balance, the density was calculated as the ratio of mass to volume.

The determination of bulk density was performed following the BS EN ISO 17828 standard (ISO, 2015). A beaker of known volume was filled with pellets up to the brim. The filled beaker was then weighed on an analytical balance with 0.1 g precision to obtain the mass, allowing for variations of up to 2%.

Mechanical durability, to evaluate pellet resistance, was determined according to the BS EN ISO 17831-1 standard (ISO, 2015). A 500 g pellet sample was sieved to separate smaller from larger particles before testing.

The fines content of the samples was determined according to the BS EN ISO 18846:2016 standard (ISO, 2016), in order to quantify the amount of material passing through a 400 mm sieve with round holes of 3.15 mm diameter. With an adaptation, a Tyler series 6 sieve (3.327 mm) with a 200 mm diameter was used, and the sample was sieved by manual agitation using horizontal movements.

Chemical properties, calorific value, and thermogravimetry

The proximate chemical analysis was performed in triplicate, following the parameters established by the ASTM D 1762-84 standard (ASTM, 2021). For the determination of volatile matter content, porcelain crucibles were first preheated at the outer edge of the muffle furnace door (lid) for 2 minutes (T = 300 ºC) and for an additional 3 minutes at the inner edge of the door (T = 500 ºC). The samples were then placed inside the muffle furnace, with the initial temperature set to 950 ºC, remaining with the lid closed for 6 minutes. After this period, the samples were cooled in a desiccator and weighed.

For the determination of ash content, the crucibles were placed inside the muffle furnace at 750 ºC for 6 hours, then cooled and weighed. The fixed carbon content was subsequently determined by difference, discounting the volatile matter and ash contents.

The higher heating value (HHV) of the samples was determined at 0% moisture using a digital calorimetric bomb IKA WORKS, model C 5000, following the ASTM D 5865 standard (ASTM, 2019). The system, operating in dynamic mode, was pressurized with oxygen (99.95%) at 3.43 × 10^6 Pa.

Thermogravimetric analysis (TGA) of the samples was carried out using a LABSYS EVO DTA/DSC/Setaram Instrumentation apparatus. The parameters were a constant gas flow of 50 ml min^-1 of argon and air for biomass pellets, and only air for torrefied biomass pellets. The heating rate was 15 ºC min^-1, maintained for all samples. The temperature range of the analysis varied from ambient (25 ºC) to 600 ºC.

Data acquisition was performed using the equipment software, Calisto Data Acquisition. The thermogravimetric (TG) curves of the material were processed in Excel to identify their thermal characteristics, followed by their derivatives (DTG), which allow better visualization of the different stages of thermal decomposition.

Experimental Design

The experiment was conducted using a completely randomized design (CRD), with the independent variables being the two types of biomass, *Phyllostachys aurea* (Bamboo) and *Eucalyptus dunnii* (Eucalyptus), used both in natura and torrefied for pellet production. Additionally, properties of *Pinus taeda* pellets acquired from a commercial company were determined and used as a reference (control).

Initially, the treatment variances were assessed for homogeneity using Bartlett's test. Variables with homogeneous variances had the treatment effects evaluated through the F-test in an analysis of variance (ANOVA). When statistical differences between means were observed, Tukey's multiple comparison test was applied at a 95% significance level. Data treatment and analysis were performed using the Assistat software.

RESULTS

Characterization of *in natura* biomass

Analyses of moisture content and bulk density revealed significant differences between the biomasses of *Phyllostachys aurea* (Bamboo) and *Eucalyptus dunnii* (Eucalyptus). The moisture content of bamboo was 8.51%, while that of eucalyptus was 9.92%. Bulk density also differed, being higher for bamboo (262.47 kg m^{-3}) compared to eucalyptus (239.40 kg m^{-3}). These differences can be attributed to the intrinsic characteristics of each biomass.

Characteristics of torrefied biomass

Torrefaction at 220°C for 15 minutes resulted in visual changes in the biomasses, such as darkening and size reduction. The gravimetric yield was 89.66% for bamboo and 94.15% for eucalyptus. These differences indicate that torrefaction of bamboo led to a greater mass loss.

Pellet quality assessment

The quality assessment of the pellets was carried out after their production from the studied biomasses, as shown in Figure 2, together with industrially produced Pinus pellets.

By observing the photos of the in natura and torrefied pellets at 220°C with a residence time of 15 minutes, the main change identified was in color, due to chemical composition alterations, resulting in a darker appearance. This led to the designation of the torrefied pellets as "black pellets" (SULISTIO *et al.*, 2020). This phenomenon is supported by the study of Rubiyanti *et al.* (2019).

Figure 2. Pellets produced from raw and torrefied biomass.
Caption: A = *Phyllostachys aurea* raw pellets; B = *Eucalyptus dunnii* raw pellets; C = *Pinus taeda* commercial pellets; D = *Phyllostachys aurea* pellets from torrefied biomass; E = *Eucalyptus dunnii* pellets from torrefied biomass.

Figura 2. *Pellets* produzidos a partir das biomassas *in natura* e torrificadas.
Legenda: A = *pellets* de *Phyllostachys aurea in natura*; B = *pellets* de *Eucalyptus dunnii in natura*; C = *pellets* comerciais de *Pinus taeda*; D = *pellets* de *Phyllostachys aurea* de biomassa torrificada; E = *pellets* de *Eucalyptus dunnii* de biomassa torrificada.

Physicomechanical properties

The physicomechanical properties of pellets produced from in natura and torrefied biomass, as well as commercial Pinus pellets, are presented in Table 1, where statistical differences can be observed among the five types of pellets evaluated.

The in natura and torrefied bamboo pellets showed diameters within the standards of ISO 17225-2 (6 mm), whereas the eucalyptus pellets exhibited higher moisture content (13.49% in natura and 15.69% torrefied) compared to the allowed limit (10%). Regarding length, all produced pellets were within the minimum required range (3.15 to 40 mm), with bamboo pellets showing higher average values than the commercial pellets.

The unit density of the pellets, a parameter not defined by ISO 17225-2, ranged from 1,139.70 to 1,292.38 kg m⁻³, with no statistically significant differences observed. Values above 900 kg m⁻³ classify the biofuels as highly densified. Bulk density ranged from 568.15 kg m⁻³ (torrefied eucalyptus) to 725.37 kg m⁻³ (in natura bamboo). Mechanical durability exceeded 97.5% for all pellets, except for torrefied bamboo (94.42%). The fines content was higher in torrefied eucalyptus pellets (0.68%), while in natura bamboo pellets showed lower values (0.02%).

Table 1. Average values for the physical-mechanical properties of the pellets.
Tabela 1. Valores médios para as propriedades físico-mecânicas dos *pellets*.

Pellets	**D (mm)**	**C (mm)**	**Mc (%)**	**Ud (kg m^{-3})**	**Bd (kg m^{-3})**	**Md (%)**	**Fc (%)**
PAR	5.94 b	26.17 a	9.43 cd	1292.38 a	725.37 a	98.80	0.02 b
EDR	5.89 c	22.97 c	13.49 b	1139.70 a	601.21 c	99.40	0.71 a
PTR	6.04 a	24.44 b	8.96 d	1220.16 a	717.95 a	98.40	0.10 b
PA220	6.00 a	24.40 a	11.22 c	1183.44 a	628.88 b	94.42	0.49 a
ED220	6.02 a	24.25 a	15.69 a	1140.93 a	568.15 d	97.60	0.68 a

Legend: PAR = in natura Phyllostachys aurea pellets; EDR = in natura Eucalyptus dunnii pellets; PIR = in natura Pinus taeda pellets; PA220 = Phyllostachys aurea biomass pellets torrefied at 220°C for 15 min; ED220 = Eucalyptus dunnii biomass pellets torrefied at 220°C for 15 min; D = diameter; C = length; Mc = moisture content; Ud = unit density; Bd = bulk density; Md = mechanical durability; Fc = fines content. Means followed by the same lowercase letter do not differ significantly according to Tukey's test at 5% probability.

Chemical properties and calorific value

The chemical properties and calorific value of pellets produced from in natura and torrefied biomass were analyzed, and the mean values obtained are presented in Table 2, in which statistical differences were observed between the pellets from in natura and torrefied biomass

The torrefied pellets showed improvements in higher heating value (HHV) and lower heating value (LHV) compared to the in natura pellets. The HHV of torrefied bamboo was 20.05 MJ kg⁻¹, while that of torrefied eucalyptus was 20.30 MJ kg⁻¹. The fixed carbon content was higher in torrefied bamboo pellets (22.30%) compared to eucalyptus pellets (18,78%).

Table 2. Average values for the chemical properties and calorific value of pellets.
Tabela 2. Valores médios para as propriedades químicas e poder calorífico dos *pellets*.

Pellets	**VM (%)**	**TA (%)**	**FC (%)**	**HHV(MJ kg^{-1})**	**LHV (MJ kg^{-1})**
PAR	76.59 b	1.62 a	21.78 a	19.32 d	16.09 d
EDR	81.57 a	0.64 b	17.78 c	18.14 e	14.90 e
PTR	80.36 a	0.39 c	19.24 b	19.56 c	16.32 c
PA220	75.93 b	1.76 a	22.30 a	20.05 b	16.81 b
ED220	80.80 a	0.42 bc	18.78 bc	20.30 a	17.06 a

Legend: PAR = pellets of Phyllostachys aurea in natura; EDR = pellets of Eucalyptus dunnii in natura; PTR = pellets of Pinus taeda in natura; PA220 = pellets of biomass torrefied at 220°C with 15 min residence time of Phyllostachys aurea; ED220 = pellets of biomass torrefied at 220°C with 15 min residence time of Eucalyptus dunnii;VM = volatile matter; TA = ash content; FC = fixed carbon; HHV = higher heating value; LHV = lower heating value. Means followed by the same letter do not differ from each other according to Tukey's test at 5% probability.

Thermogravimetric analysis (TGA)

The thermogravimetric analysis of the pellets from the evaluated biomasses and their respective derivatives (DTG) are shown in Figures 3 and 4, where significant differences related to the atmosphere used can be observed. Under oxidative conditions, the curves were more complex, with mass losses occurring in three stages, unlike the argon atmosphere, which showed two stages. In summary, the first analysis was conducted to simulate thermal treatment under controlled conditions, while the second aimed to assess the combustion behavior of the biomass. Bamboo exhibited a higher thermal degradation rate than eucalyptus, both in inert and oxidative atmosphere.

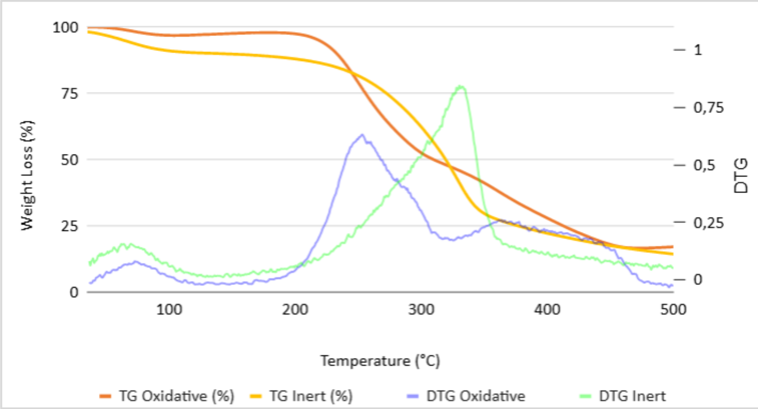

Figure 3. Mass loss curves and their respective derivative for *Phyllostachys aurea* (Bamboo) biomass pellets, under an oxidative and inert atmosphere.
Figura 3. Curvas de perda de massa e sua respectiva derivada para os *pellets* da biomassa de *Phyllostachys aurea* (Bambu), sob atmosfera oxidativa e inerte.

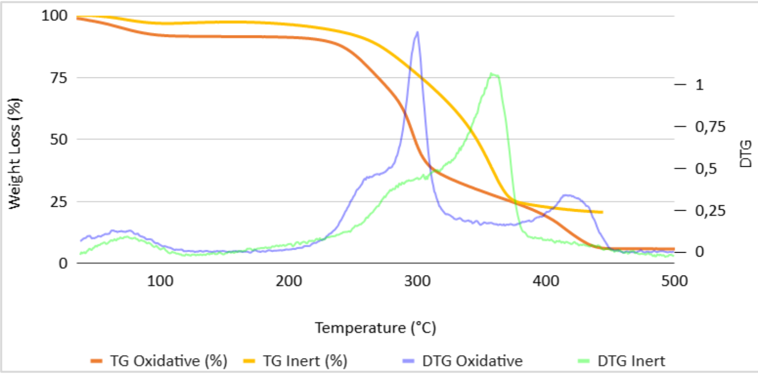

Figure 4. Mass loss curves and their respective derivatives for *Eucalyptus dunnii* (Eucalyptus) biomass pellets, under an oxidative and inert atmosphere.
Figura 4. Curvas de perda de massa e sua respectiva derivada para os *pellets* da biomassa de *Eucalyptus dunnii* (Eucalipto), sob atmosfera oxidativa e inerte.

Figures 5 and 6 show the TGA curves under oxidative atmosphere for the pellets produced from in natura and torrefied biomass for each species, aiming to compare the differences in the degradation profiles of torrefied biomass pellets relative to those from in natura biomass. Differences are less noticeable in the TG curves but become more evident in the DTG curves. The TGA analysis indicated that the torrefied pellets exhibited higher thermal stability, with degradation occurring at higher temperatures (above 220°C) compared to the *in natura* pellets.

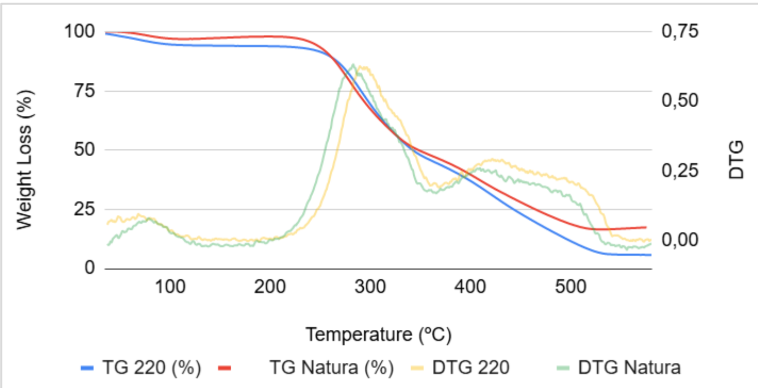

Figure 5. Thermogravimetric analysis and its derivative for Phylloscatchys aurea (Bamboo) pellets in natura and biomass pellets torrefied at 220°C.
Figura 5. Análise termogravimétrica e sua derivada para os *pellets* de *Phylloscatchys aurea* (Bambu) *in natura* e *pellets* de biomassa torrificada a 220°C.

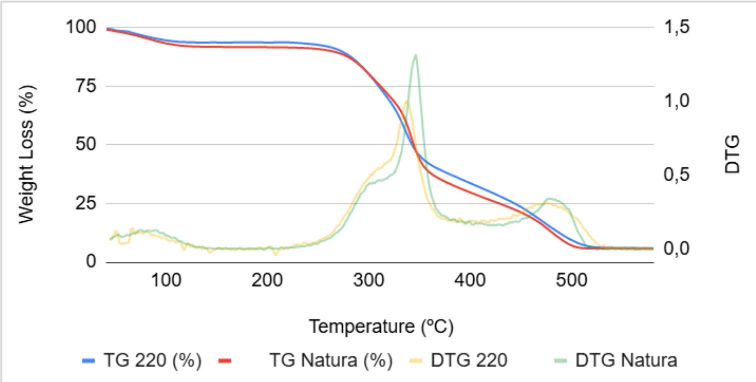

Figure 6. Thermogravimetric analysis and its derivative for Eucalyptus dunnii (Eucalyptus) pellets in natura and biomass pellets torrefied at 220°C.

Figura 6. Análise termogravimétrica e sua derivada para os *pellets* de *Eucalyptus dunnii* (Eucalipto) *in natura* e *pellets* de biomassa torrificada a 220°C.

DISCUSSION

The results obtained demonstrate that biomass torrefaction can significantly improve some energetic properties of pellets but can also negatively impact essential mechanical characteristics for storage and transportation. The increase in fixed carbon content and calorific value aligns with previous studies indicating that torrefaction contributes to the removal of volatile compounds and the energetic enrichment of biomass (DO VALE and CHAVES, 2021).

However, torrefaction also resulted in a reduction in bulk density and mechanical durability of the pellets, especially for bamboo. This can be explained by the partial degradation of lignin, which plays a fundamental role in particle cohesion during pellet compaction (KALIYAN and MOREY, 2010). The increased friability of torrefied pellets may compromise their resistance to transport and storage, leading to higher fines generation, which can reduce combustion efficiency in industrial equipment.

Comparison with commercial pellets revealed that in natura bamboo pellets exhibited physicochemical properties similar to those of Pinus, suggesting that this biomass could be a viable alternative for solid biofuel production. However, eucalyptus pellets did not meet the minimum moisture requirement, indicating the need for adjustments in the production process to optimize their performance.

Thermogravimetric analyses showed that torrefied biomass pellets exhibited higher thermal resistance, which may enhance their performance in energy applications. This improvement is a positive factor for controlled combustion, reducing particulate emissions and optimizing energy recovery (TUMULURU, 2011).

Based on these results, it can be concluded that torrefied Phyllostachys aurea (bamboo) biomass represents a promising alternative for producing high-energy-quality pellets, comparable to Pinus. However, the torrefaction of eucalyptus pellets requires improvements, particularly in controlling moisture content and bulk density, to make them commercially viable.

Nonetheless, the applicability of these findings should consider advancements in torrefaction methods that minimize these drawbacks, through future research focusing on innovative and interdisciplinary approaches combining materials science, engineering, and sustainability. Coupled with the development of new pelletization/torrefaction techniques and the investigation of sustainable forest management practices, these efforts can not only improve the quality of produced pellets but also ensure the conservation and better utilization of the studied species. Therefore, the path forward should include collaboration among researchers, industries, and policymakers to promote the efficient and sustainable use of biomass as a renewable energy source.

CONCLUSIONS

Based on the analysis of the results of this study, it can be concluded that:

- It was possible to produce pellets from Phyllostachys aurea (bamboo) and Eucalyptus dunnii (eucalyptus) using torrefied biomass under the same conditions as in natura biomass, without the need for binding agents.
- *Phyllostachys aurea* (bamboo) pellets, both in natura and torrefied, met the normative parameters for residential use regarding physical-mechanical properties, except for the moisture content and mechanical durability of the torrefied pellets.

- Eucalyptus dunnii (eucalyptus) pellets, both in natura and torrefied, met the normative parameters for residential use regarding physical-mechanical properties, except for the moisture content and bulk density of the torrefied pellets.
- Biomass torrefaction had a negative effect on the bulk density of the pellets and a positive effect on the fines content and calorific value.
- The contents of volatiles, ash, and fixed carbon were not affected by biomass torrefaction for either species.
- In the TGA curves under oxidative atmosphere, it was observed that torrefaction at 220 ºC improved the thermal behavior for all species.
- In general, biomass pellets after torrefaction pre-treatment can be an alternative to enhance the final quality of the pellets.

REFERENCES

ABNT – Associação Brasileira de Normas Técnicas. **NBR 14660:** Madeira – Amostragem e preparação. Rio de Janeiro, 2004.

AMERICAN SOCIETY FOR TESTING AND MATERIALS. **D1762-84**: Standard Test Method for Chemical Analysis of Wood Charcoal: ASTM International, West Conshohocken, 2021. 2 p.

AMERICAN SOCIETY FOR TESTING AND MATERIALS. **D5865**: Standard Test Method for Gross Calorific Value of Coal and Coke: ASTM International, West Conshohocken, 2019. 6 p.

BASU, P. 2018. **Biomass Gasification, Pyrolysis and Torrefaction: Practical Design and Theory.** Book. Academic Press. London. 530p.

DO VALE, A. T.; CHAVES, B. S. Bambu como combustível sólido. **Pesquisas agrárias e ambientais**, Nova Xavantina, MT, v. 7, p. 7, 2021. https://doi.org/10.46420/9786581460044 Acesso em: 10 mar. 2024.

EN 17828 Solid biofuels – Determination of bulk density –European Standard, 2015, Pilsen.

INDÚSTRIA BRASILEIRA DE ÁRVORES. Anuário estatístico do IBÁ. Ano-base 2022. Indústria Brasileira de Árvores. Associação Brasileira de Árvores, São Pulo, SP, 2020. https://iba.org/datafiles/publicacoes/relatorios/relatorio-anual-iba2023-r.pdf Acesso em: 14 mar. 2024.

ISO 17225-2 Solid biofuels – Fuel specifications and classes – Part 2: Graded wood pellets, ISO – International Standard, 2014, International Organization for Standardization, Geneva.

ISO 18134-2 Solid biofuels – Determination of moisture content – Part 2: Simplified method, ISO – International Standard, 2017, International Organization for Standardization, Geneva.

ISO 17829 Solid biofuels – Determination of length and diameter of pellets, ISO – International Standard, 2015, International Organization for Standardization, Geneva.

ISO 17828 Solid biofuels – Determination of bulk density, ISO – International Standard, 2015, International Organization for Standardization, Geneva.

ISO 17831-1 Solid biofuels – Determination of mechanical durability of pellets and briquettes – Part 1: Pellets, ISO – International Standard, 2015, International Organization for Standardization, Geneva.

ISO/CD 18846-1 Solid biofuels – Determination of mechanical durability of pellets and briquettes – Part 1: Pellets, ISO – International Standard, 2016, International Organization for Standardization, Geneva.

FOELKEL, C. Utilização da biomassa do Eucalipto para produção de Calor, Vapor e Eletricidade. In: FOELKEL, C. *Eucalyptus Online Book*. 1. ed. 2016. v. 1, cap. 44, p. 05-264. [online]. Disponível em: <https://www.eucalyptus.com.br/eucaliptos/PT44_Geracao_Calor_Vapor_Eletricidade.pdf>. Acesso em: 04 jun. 2024.

GONÇALVES, D. **Bambu é alternativa de renda na produção familiar.** Rio Branco, AC: Embrapa Acre, 2018. Disponível em: <https://www.embrapa.br/busca-de-noticias/-/noticia/34230725/bambu-e-alternativa-de-renda-na-producao-familiar>. Acesso em: 23 ago. 2024.

KALIYAN, N.; MOREY, R. V. Natural binders and solid bridge type binding mechanisms in briquettes and pellets made from corn stover and switchgrass. **Bioresource Technology**, Amsterdam, v. 101, n. 3, p. 1082 - 1090, 2010. https://doi.org/10.1016/j.biortech.2009.08.064. Acesso em: 04 jul. 2024.

ROMAO, E. L.; CONTE, R. A. Energy gains of Eucalyptus by torrefaction process. **Maderas, Ciencia y Tecnologia**, Concepción, v. 23, n.3, p. 1-6, 2021. https://doi.org/10.4067/s0718-221x2021000100403 Acesso em: 24 ago. 2022.

RUBIYANTI, T.; HIDAYAT, W.; FEBRYANO, I. G.; BAKRI, S. Karakterisasi pelet kayu karet (Hevea brasiliensis) hasil torefaksi dengan menggunakan reaktor Counter-Flow Multi Baffle (COMB). **Jurnal Sylva Lestari,** Bandar Lampung, v. 7, n. 3, p. 321–331, 2019. https://doi.org/10.23960/jsl37321-331 Acesso em: 10 jan. 2023.

SULISTIO, Y.; FEBRYANO, I.G.; HASANUDIN, U.; YOO, J.; KIM, S.; LEE, S.; HIDAYAT, W. Pengaruh torefaksi dengan reaktor Counter-Flow Multi Baffle (COMB) dan electric furnace terhadap pelet kayu jabon (Anthocephalus cadamba). **Jurnal Sylva Lestari**, Bandar Lampung, v. 8, n. 1, p. 65–76, 2020. https://doi.org/10.23960/jsl1865-76 Acesso em: 10 fev. 2023.

TUMULURU, J. S. A review on biomass torrefaction process and product properties for energy applications. **Industrial Biotechnology,** New Rochelle, NY, v. 7, n. 5, p. 384-401, 2011.https://doi.org/10.1089/ind.2011.0013. Acesso em: 27 mar. 2024.

VECHI, A; MAGALHÃES JÚNIOR, C. A. O. Aspectos positivos e negativos da cultura do eucalipto e os efeitos ambientais do seu cultivo. **Revista Valore**, Volta Redonda, v. 3, n. 1, p. 495-507, 2018. https://doi.org/10.22408/reva312018101495-507 Acesso em: 24 jun. 2023.

YILMAZ, H.; TOPAKCI, M.; VAROL, M.; KARAYEL, D.; ÇANAKCI, M. Effect of Torrefaction Conditions on Physical and Thermal Properties of High- and Low- Quality Palm Pruning Residue Pellets. **Bioenergy Research**, New York, v. 15, p. 530–543, 2022. https://doi.org/10.1007/s12155-021-10339-4 Acesso em: 22 jul. 2024.