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Understanding the impacts of pyrolysis temperature on the energy performance of eucalyptus charcoal†

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Abstract: This study aimed to investigate the influence of two pyrolysis temperatures (300 °C e 450 °C), an essential variable in the energy quality of the charcoal, on a mix of commercial eucalypt woods. For this, pyrolysis was carried out at a heating rate of 3.33 °C.min^{-1}, 3 h of duration The apparent density, bulk density, immediate analysis, high heating value, energy density, and combustibility index of the charcoal were measured. Under the conditions analyzed, pyrolysis performed at a final temperature of 450 °C results in better energy performance of charcoal than at 300 °C.

Keywords: bioenergy; charcoal quality; energetic forests

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1. Introduction

Primary energy resources, such as wood energy, are sources of energy and supplies obtained from nature [1,2]. Since the beginning of history, human been uses energy derived from biomass. This fuel type has been widely used for heat production, converting wood energy for cooking and/or heating [1–3]. Even today, developing countries still have residences whose biomass is the only fuel source available for domestic use. It is currently still the most important renewable energy source, accounting for about 6 percent of the total primary energy supply [1]. The search for energy efficiency makes charcoal an important wood product, contemplating several applications over the centuries.

There are several commercial processes available for pyrolyzing biomass and turning it into charcoal. Historically, kilns have been used with intensive labor and labor and require a high degree of control to produce good quality and high charcoal yields [4]. The charcoal production is considered rudimentary nowadays, even though it lasts centuries of practice [5,6]. Its specific properties are dictated by the control over the process variables and the homogenization of the raw material, constituting significant challenges for obtaining a high-quality product. Thus, understanding the influence of different pyrolysis temperatures becomes of importance since the temperature is an essential variable in the energy quality of the charcoal [7,8].

Although much research has been carried out with a focus on wood quality of eucalyptus species and the pyrolysis variables [8–10], it is necessary to improve the studies to have more and more technical information that allows us to take assertive decisions regarding the charcoal production. This study investigated the effect of two pyrolysis temperatures of a eucalypt wood mix in the charcoal energetic variables.

2. Materials and Methods

2.1 Material sample wood

To perform this study a commercial *Eucalyptus* plantation area were selected in the southwest region of Bahia State, Brazil. The location is characterized by flat to slightly undulating relief, climate classified as Cwb (tropical altitude), according to the Köppen classification, with an average temperature of 21 °C and annual precipitation of 700 mm [11]. From the collected trees, discs were obtained in different positions of the trunk, at 0%, 50%, and 100% of the commercial height (minimum diameter = 8 cm) and transformed into a smaller samples for the charcoal process.

The wood used had average basic density of 500 kg/m^3, 29% of lignin and 5% of extractives.

2.2 Charcoal

Wood samples measuring approximately 3 cm x 3 cm x 6 cm were dried in an oven at 103 ± 2 °C and placed in a metallic reactor whose volume was 1.34 dm^3. Pyrolysis was carried out at a heating rate of 3.33 °C/min^{-1}, with a duration of 3 h and two final temperatures (300 °C and 450 °C) an electric muffle furnace with water-cooled condenser and condensable gases collector (Figure 1).

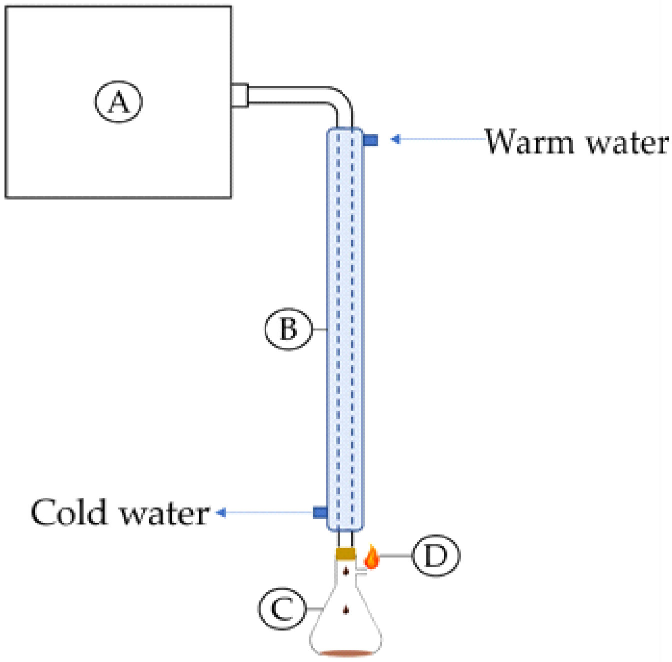

Figure 1. Schematic procedure of pyrolysis carried out in a muffle furnace, where A: Muffle furnace; B: Condenser; C: Collector of pyroligneous acid; D: Burning of non-condensable gases. Source: the authors (2021).

To evaluate the charcoal samples, the following analyzes were performed:

- Immediate analysis (volatile materials, ash, fixed carbon, %) - D-1762-84 [12];
- Apparent density (kg/m^3) - NBR 11941 [13];
- Bulk density (kg/m^3) - NBR 6922 [14];
- High Heating Value, Useful Calorific Value (MJ/kg) [15];
- Combustion test - ICOM [16].

The energy density (GJ/m^3) of charcoal was obtained through the maximum amount of energy per unit volume of charcoal, determined by the product between the bulk density and the useful calorific value. To determine the combustibility index, 149 ± 1.22 g of dry charcoal in homogeneous particle size of 16 mm were used [17]. Ignition was carried out using 4.5 g of anhydrous alcohol 96° INPM. The temperature reached and the mass consumed throughout the test were recorded every 3 minutes. The beginning of the test was considered from the alcohol volatilization in the system and the end was determined when the material completed the combustion, i.e., after the system did not show mass among the five consecutive readings.

2.3 Data Analysis

The data obtained were submitted to Student's t test, after checking the normality and homoscedasticity of the residuals at 5% significance, using the Shapiro-Wilk and Bartlett tests, respectively.

3. Results

Table 1 shows the results obtained from the charcoal characterization.

TPR (°C)	VM (%)	AS (%)	FC (%)	AD (kg m^{-3})	BD (kg m^{-3})	ED (GJ m^{-3})	HHV (MJ kg^{-}1)
300	33.23* (1.26)	1.07 (0.01)	65.70 (1.25)	299.74 (21.48)	133.86* (2.33)	3.58* (0.01)	28.25 (0.06)
450	15.92 (1.65)	1.11 (0.03)	82.98* (1.68)	320.90 (15.27)	105.36 (0.02)	3.22 (0.02)	32.00* (0.21)

*Where: Mean followed by standard error. TPR = temperature; VM = volatile matter; AS = ash; FC = fixed carbon; AD = apparent density; BD = bulk density; ED = energy density; HHV = high heating value;. *Significant at the 5% using the t test.*

The apparent density and ash were the same for both pyrolysis temperatures. The charcoal pyrolyzed at 450 °C provides the higher value of fixed carbon content (82.98%), lower volatile matter content (15.92%), and higher heating value (32 MJ/kg). In the other hand, the charcoal produced at 300 °C showed the higher energy density (3.58 GJ/m^3) and the higher bulk density (133.86 kg/m^3). The charcoal produced at a temperature of 450 °C showed combustion index of 0.135 and the charcoal produced at a temperature of 300 °C showed combustion index of 0.058.

The Figure 2 provides the variation of temperature (A) and mass consumption (B) during the pyrolysis process.

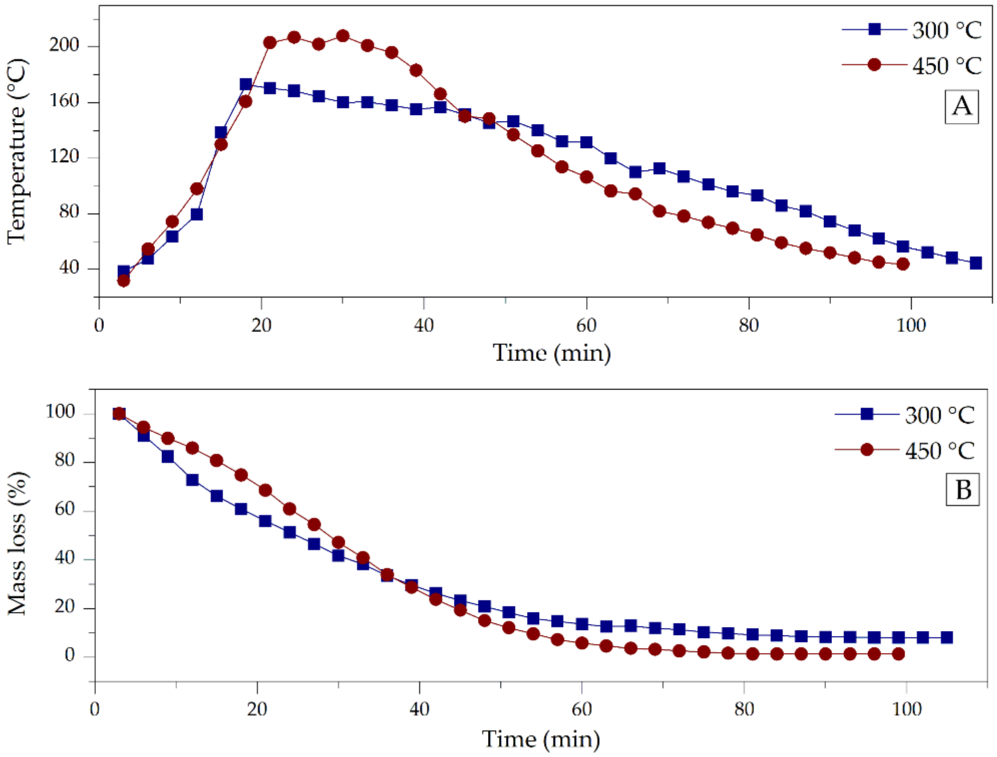

Figure 2. Variation of temperature (A) and mass consumption (B) during the combustion test**.**

4. Discussion

Increasing the temperature causes the degradation of cellulose, hemicellulose, and lignin, concentrating the carbon and increasing the calorific value of charcoal. However, degradation of the wood components leads a marked loss of mass with a low loss of volume, making the material less dense [18]. As the peaks of wood degradation during the pyrolysis process occur at different temperatures, depending on its chemical and elemental composition, this loss of mass and reduction in the charcoal density occurred differently for the two evaluated samples. While the degradation of hemicellulose and cellulose occurs at lower temperature ranges (220–315 °C and 315–400 °C, respectively), lignin has greater thermal stability and, despite initiating degradation at lower temperatures, mass loss is slow and occurs even at higher temperatures (160-900 °C) [19]. The samples carbonized at 300 °C, despite losing part of the components due to thermal degradation, still concentrate a higher percentage of lignin and cellulose in their composition when compared to the samples carbonized at 450 °C. This higher concentration reflects directly the high content of volatile matter and, consequently, the lower fixed carbon content of charcoal.

A high fixed carbon content (> 73%), accompanied by a low volatile matter content (< 25%) and a low ash content (< 1,5%) are desirable characteristics for charcoal to be used for energy, both for the steel industry and the barbecue charcoal sector [9,18,20]. According to the data collected in this work, only charcoal produced at 450 °C reached the levels required by the two sectors. In addition to these properties, another one that is considered essential to define the energy quality of charcoal is its calorific value. Although the calorific value is intrinsic to the material being used, the pyrolysis parameters can influence the content of other properties, such as fixed carbon. High fixed carbon contents are related to the high calorific values of charcoal. Confirming this trend, charcoal with a higher fixed carbon content (produced at 450 °C) also had a higher heating value when compared to other rated charcoal.

Regarding the inorganic part, the ash content is also a property that must be taken into account when evaluating the energy efficiency of solid fuel. However, the ash content of the material is not changed by the process, as the mineral composition is intrinsic to the wood. High contents of ash, which are related to the mineral fraction of charcoal, can compromise the use of solid fuel in some types of boiler [18]. Therefore, it is interesting that strategies are devised to reduce the ash content in waste reused for energy generation. As *Eucalyptus* has a low ash content, eucalypt wood blends can be the solution to reduce ash and improve the energy properties of other biomasses used as fuel [21].

Beside all these energy properties evaluated reflect on the combustion efficiency of this material the Combustion Index (ICOM) evaluates the amount of energy released in relation to the amount of mass consumed during the combustion process [21]. That is, the larger the ICOM, the greater the heat generation in the same amount of mass [21]. The final carbonization temperature influenced the ICOM of the studied materials, providing an increase of about 42.3% in the ICOM. Investigating the influence of carbonization temperature on the energy quality of charcoal is essential to increase knowledge about the thermal behavior of biomass when exposed to heat. However, other pyrolysis parameters can influence the physical, mechanical, chemical, and energetic properties of charcoal, and they must be studied in a complementary way.

5. Conclusions

Under the conditions analyzed, pyrolysis performed at a final temperature of 450 ° C resulted in better charcoal energy performance than 300 °C. This study can serve as a basis for new researches assessing the influence of other pyrolysis parameters on the energy quality of different charcoal produced from diverse eucalypt wood mixes. Future studies are indicated to assess the practical application of charcoal from the eucalypt wood mix, as an example, to improve production and operational efficiency for the use of charcoal in the steel industry or food barbecue.

Author Contributions: A.K.S.P conducted and performed lab experiments, collected and analyzed data, and prepared the manuscript; A.S.M., E.C.S., F.M.D. provided a strong contribution to the writing and review; A.K.S.P and D.L.J designed the study; A.F.D.J supervised the analyses at all stages and provided review of the manuscript; B.P.R. provided critical feedbacks, review and editing of the manuscript. All authors have read and agreed to the published version of the manuscript.

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References

1. FAO, F. and A.O. Wood Energy Available online: http://www.fao.org/forestry/energy/en/ (accessed on Jun 22, 2021).
2. Tvaronavičienė, M.; Baublys, J.; Raudeliūnienė, J.; Jatautaitė, D. *Global energy consumption peculiarities and energy sources: Role of renewables*; 2020; ISBN 9780128176887.
3. El Bassam, N. *Energy resources, global contribution, and applications*; Elsevier Inc., 2021; Vol. 2; ISBN 9780128216057.
4. Norgate, T.; Haque, N.; Somerville, M.; Jahanshahi, S. Biomass as a source of renewable carbon for iron and steelmaking. *ISIJ International* **2012**, *52*, 1472–1481, doi:10.2355/isijinternational.52.1472.
5. FAO, F.A.A.O.O.T.U.N.- *The charcoal transition*; 2017; ISBN 9789251096802.
6. Iiyama, M.; Chenevoy, A.; Otieno, E.; Kinyanjui, T.; Ndegwa, G.; Vandenabeele, J.; Njenga, M.; Johnson, O. Achieving sustainable charcoal in Kenya: harnessing the opportunities for cross-sectoral integration. *Technical Brief. Nairobi, World Agroforestry Centre (ICRAF) & Stockholm Environment Institute.* **2014**, 2–5.
7. Jahirul, M.I.; Rasul, M.G.; Chowdhury, A.A.; Ashwath, N. Biofuels production through biomass pyrolysis- A technological

review. *Energies* **2012**, *5*, 4952–5001, doi:10.3390/en5124952.

8. Solar, J.; de Marco, I.; Caballero, B.M.; Lopez-Urionabarrenechea, A.; Rodriguez, N.; Agirre, I.; Adrados, A. Influence of temperature and residence time in the pyrolysis of woody biomass waste in a continuous screw reactor. *Biomass and Bioenergy* **2016**, *95*, 416–423, doi:10.1016/j.biombioe.2016.07.004.
9. Assis, M.R.; Brancheriau, L.; Napoli, A.; Trugilho, P.F. Factors affecting the mechanics of carbonized wood: literature review. *Wood Science and Technology* **2016**, *50*, 519–536, doi:10.1007/s00226-016-0812-6.
10. Kan, T.; Strezov, V.; Evans, T.J. Lignocellulosic biomass pyrolysis: A review of product properties and effects of pyrolysis parameters. *Renewable and Sustainable Energy Reviews* **2016**, *57*, 1126–1140, doi:10.1016/j.rser.2015.12.185.
11. Oliveira, A.M. de; Anjos Bittencourt Barreto-Garcia, P.; José Rodrigues Alves, B.; Conceição Júnior, V.; Forestieri Gama-Rodrigues, E.; Citar, C.; Júnior, C. Efeito de rotações sucessivas de eucalipto na mineralização de nitrogênio e carbono do solo e suprimento de nitrogênio, no Sudoeste da Bahia, Brasil. *Scientia Forestalis* **2020**, *48*, doi:10.18671/scifor.v48n126.15.
12. ASTM D 1762-84: Standard Test Method for Chemical Analysis of Wood Charcoal 2007, *84*, 1–2.
13. ABNT, A.B. de N.T. NBR 11941: Madeira - determinação da densidade básica 2003.
14. ABNT, A.B. de N.T. NBR 6922: Carvão vegetal - Ensaios físicos determinação da massa específica (densidade à granel) 1981.
15. DIN Deutsches Institut Für Normung EN 51900-1: Testing of solid and liquid fuels – Determination of the gross calorific value by the bomb calorimeter and calculation of net calorific value - Part 1. Principles, apparatus, methods. 2000.
16. Quirino, W.F.; Brito, J.O. *Características e índice de combustão de briquetes de carvão vegetal*; 1991;
17. Dias Júnior, A.F.; Brito, J.O.; Andrade, C.R. Granulometric influence on the combustion of charcoal for barbecue. *Revista Árvore* **2015**, *39*, 1127–1133.
18. Dias Junior, A.F.; Esteves, R.P.; da Silva, Á.M.; Sousa Júnior, A.D.; Oliveira, M.P.; Brito, J.O.; Napoli, A.; Braga, B.M. Investigating the pyrolysis temperature to define the use of charcoal. *European Journal of Wood and Wood Products* **2020**, *78*, 193–204, doi:10.1007/s00107-019-01489-6.
19. Yang, H.; Yan, R.; Chen, H.; Lee, D.H.; Zheng, C. Characteristics of hemicellulose, cellulose and lignin pyrolysis. *Fuel* **2007**, *86*, 1781–1788, doi:10.1016/j.fuel.2006.12.013.
20. São Paulo *Resolução SAA - 40, de 14 de Dezembro da Secretaria de Agricultura e Abastecimento. Dispõe de padrões mínimos de qualidade de carvão vegetal*; 2015; pp. 1–11;.
21. Dias Júnior, A.F.; Anuto, R.B.; Andrade, C.R.; De Souza, N.D.; Takeshita, S.; Brito, J.O.; Nolasco, A.M. INFLUENCE OF Eucalyptus WOOD ADDITION TO URBAN WOOD WASTE DURING COMBUSTION. *Cerne* **2017**, *23*, 455–464, doi:10.1590/01047760201723042337.