TORREFACTION OF WOOD CONSTRUCTION WASTE AND EUCALYPTUS BLENDS FOR BIOFUEL WITH ENHANCED ENERGY DENSITY AND LOW ASH CONTENT

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ABSTRACT: Civil construction is one of the most important economic and social development areas. In this sector, many natural resources are used, generating significant waste. It is estimated that 98% of Brazil's civil construction waste could be recycled, but only 21% has a correct destination. Wood construction waste (WCW) (15% of all construction waste) is a prominent biomass source with potential energy use. Further, lignocellulosic biomass is considered a carbon-neutral biofuel. However, biomass has some limitations for energy use; it has a high moisture content, low calorific value, and low density, among other barriers. In addition, WCW contains contamination, such as cement traces, which include elements that increase the ash content. Therefore, the formation of blends is a possible solution to take advantage of the residue. In addition, torrefaction treatment provides a solid product with higher energy density and better properties for further valuation on thermochemical routes. In this context, this study aims to perform the thermal upgrade of biomass blends by applying torrefaction pre-treatment. First, blends were established by mixing 50:50 of WCW and Eucalyptus. Then, torrefaction treatment was performed under inert conditions at 200, 250, and 300 °C at 50 min (isotherm). Finally, the torrefied product was assessed by investigating solid yield evolution, ash content, higher heating value, and energy yield.B250 possesses 1.24% of ash content (less than 1.48% of WCW) and an HHV increment of 5%, presenting 20.76 MJ kg^{-1}, being, for instance, the suitable treatment for reducing ash content while upgrading HHV.

Keywords: torrefaction, waste, wood, blends biofuel

1 INTRODUCTION

Using energy resources is one of the main factors directly affecting the environment[1]. With the growing consumption of fossil fuels, there has been a significant increase in the concentration of carbon dioxide in the atmosphere, causing substantial impacts on the environment and the well-being of the population[2,3].

Biomass is an abundant energy resource that covers a large part of the Earth's surface and has a short life cycle, thus being an alternative to replace mineral coal partially or entirely [4]. In addition, lignocellulosic biomass has enormous potential for sustainable production of second-generation biofuels[5].On the other hand, the growth of the civil construction industry is of great importance for maintaining and supporting the Brazilian economy[6]. It uses large amounts of natural resources, which generate a significant volume of waste, commonly deposited improperly, without traceability [7]. The gravimetric composition of waste exhibits variations due to the type of construction, construction phase, economic region where the construction is located, regional differences within the country, and the traceability capacity of the generated waste, among other relevant factors[8].

In Brazil, the recycling potential of construction waste (CW) is 98%, but only 21% of these wastes are effectively recycled [9]. Brazilian company Eco Response, dedicatedto environmental protection products, estimates the composition of waste generated from construction and renovations. According to their data, approximately 40% of these wastes consist of concrete, stones, and mortar, 30% are ceramic materials, 15% are wood, 7% are metals, and 8% are categorized as other materials.

Civil construction waste can be reused or recycled. Wood residue, specifically, is a biomass source that has applications of economic value and can be added to the market for energy use[10–12]. However, despite the sustainability qualities, some factors hinder the use of biomass as fuel. For example, some factors such as low density, low specific heat, high moisture and oxygen content, hygroscopicity and heterogeneity make biofuel generated from biomass unattractive[4,13]. In addition to the limitations of biomass for energy use, wood construction waste (WCW) is contaminated by other elements such as cement, mortar, paint, metal, and nails. These elements can increase the ash content, which is problematic to combustion systems, causing corrosion and slag in the equipment (reactor, turbines, among others), reducing their useful life and efficiency.

Waste-to-energy conversion via a thermochemical process is one of the most promising alternative methods in waste management strategies[13]. Therefore, torrefaction, pyrolysis, and gasification have gained prominence in the search for possibilities to improve biomass characteristics for biofuels[14–16]. Furthermore, torrefaction has attracted attention as it can effectively upgrade solid biomass and produce coal-like fuel, having a lower global warming potential [4,13].

One of the bottlenecks for implementing wood residues in the energy matrix in large urban centers is the continuous availability of raw materials to meet the energy demand. Thus, a possible solution to have a constant supply volume is the combination of different biomass sources, composing a mixture[3]. In this context, the present study aims to assess the blend composed of WCW and Eucalyptus as a solid renewable biofuel, seeking the energy recovery of this biomass. Furthermore, the investigation seeks alternatives to reduce the ash content while increasing energy density by applying torrefaction pre-treatment.

2 MATERIAL AND METHODS

2.1 Feedstock and Chemical Analysis

The Framework of the present investigation is shown in Fig.1. The construction company Tejo Engenharialocated in Brasília, Brazil (15°47′38″ S, 47°52′58″ W), provided the WCW for investigation. First, all the nails from the boards were removed and then sawn into pieces up to 5 cm wide. Next, these pieces were ground in a hammer mill and deposited in a plastic bag. Before analysis and blend formation, the waste wood was mechanically shaken, and the samples were collected at different sections (bottom, center, and surface of the package) to obtain a more homogeneous sample.

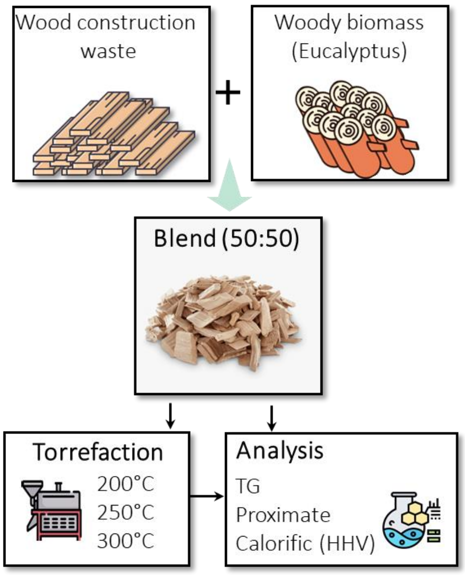


Figure 1: Framework of the presented investigation

The Brazilian Forest Service Laboratory, Brazil, provided *Eucalyptus sp*. samples. Separately, the biomasses were placed in a Willey knife mill and subjected to sieving in a sieve with a 60 mesh (0.25 mm), following the ISO 18123:2015 standard. Before experiments and analysis, blends were established by mixing 50:50 WCW and Eucalyptus, then oven-dried at 105±2 °C.

The proximate analysis was conducted to determine the volatile matter, ash, and fixed carbon content, following the ISO standards 18123-2015 and 18122-2015, respectively.The calorific analysis was conducted with a PARR 6400 bomb calorimeter following ISO 18125:2017, solid biofuels - Determination of Calorific Value. The dry basis was considered for all analyses. The morphology of raw biomass was evaluated by scanning electron microscopy with dispersive energy spectroscopy (SEM–EDX). The sample images were captured with a TM-4000Plus from Hitachi, Japan (400X and 1000X magnification and 15 kV voltage).

2.2 Torrefaction

The torrefaction treatment was operated in duplicate. The tests were performed for samples of 1.2±0.05g in alumina crucibles with a thermogravimetric analyzer (Macro-TG Analyzer *Navas Instruments*, TGA-2000-A).

The TG experimental error was controlled below 0.5%. A linear heating rate of 20 °C min^{-1} was imposed from room temperature to 105 °C and maintained isothermally for 30 min to ensure dry conditions. The treatment was carried out in an inert atmosphere with a constant flow rate (3 L min^{-1}) of nitrogen gas (99.2%) and a heating rate of 7 °C min^{-1}. The blends were torrefied at 200, 250, and 300 °C (50 min isotherm).

The torrefaction performance was assessed by thesolid yield ($S_Y^{(T)}$), the energy yield ($EY^{(T)}$) and the energy-mass-coefficient-index (EMCI), defined byEqs. (01-03), respectively.

$$S_Y^{(T)} = \frac{m_i(t)}{m_0} \times 100 \tag{1}$$

$$EY^{(T)} = S_Y^{(T)} \times EF \tag{2}$$

$$EMCI = EY^{(T)} - SY^{(T)} \tag{3}$$

Here m_i is the constantly measured mass throughout the treatment; $m_0$is the dried mass before torrefaction; t is the holding time (min), and T the reaction temperature (°C). The Enhancement Factor (EF) was determined by Eq. (04)

$$EF = \frac{HHV_{torrefied}}{HHV_{raw}} \tag{4}$$

Pursuing alternatives for WCW utilization relies on finding alternatives to reduce ash content while upgrading the energetic properties of the biofuel.Thus, the present work proposes blending WCW(Pinus with impurities) with biomass with low ash content and similar properties for blend homogeneity. Eucalyptusis a fast-growing tree that presents low ash content. Moreover, Brazil’s central region possesses energetic eucalyptus forests for biofuel. Therefore, eucalyptus was selected as a blend component with a 50%.

3 RESULTS AND DISCUSSIONS

3.1 Blend formation and properties

Table I presents the feedstock properties. In addition, the SEM images of Fig. 2(a) WCW and (b)Pinus allowed the identification of the impurities in WCW.

Table I: Proximate (volatile matter (VM), fixed carbon (FC), and ash content in %, dry basis), ultimate (CHON in %), and calorific (HHV in MJ kg^{-1}) analysis of wood construction waste (WCW) and Eucalyptus sp. (EUC) and their blend (B50:50).

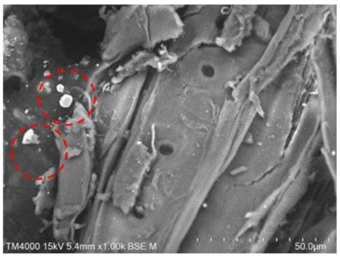
	WCW	**EUC**	**B50:50**
Proximate (%)			
Ash	1.48±0.05	0.67±0.03	1.08 ±0.03
VM	82.48±0.18	85.27±0.79	83.88±0.01
FC	16.04±0.18	14.06±0.79	15.05±0.05
Calorific (MJ.kg^{-1})			
HHV	20.10±0.03	19.42±0.03	19.76± 0.03

The proximate analysis of the WCW revealed 1.48% for ash content, 16.12% for FC, 82.40% for VM, and an HHVof 20.10 MJ kg^{-1}. Upon analyzing the proximate properties and higher heating value, no divergence was observed between the WCW and uncontaminated biomass (Pinus), except for the ash content, which exhibited a 1% increase.

Dionizio et al. (2019) analyzed wood waste from the construction industry and obtained an ash content of 2.45%, FC of 17.51%, VM of 80.06%, and anHHV of 19.31 MJ kg^{-1}[17]. Additionally, Iroba, Baik, and Tabil (2017) reported an ash content of 1.83% for demolition and construction wood waste [18].

Eucalyptus sp. wood chips analyses revealed average values of 14.06% for FC, 85.27% for VM, 0.67% for ash content, and an HHV of 19.41 MJ kg^{-1}. Another study conducted by Costa et al. (2015) reported values for the same *Eucalyptus sp*. species of 13.39% for FC, 86.50% for VM, 0.12% for ash content, and anHHV of 19.51 MJ kg^{-1} [19]. Moreover, Bersch et al. (2018) [20] evaluated the energetic characterization of wood from three different genetic materials of *Eucalyptus sp*., resulting in FC ranging between 13.27–6.23%, VM between 83.17–86.16%, and ash content 0.57–0.60%, in line with results.

(a) WCW



(b) Eucalyptus

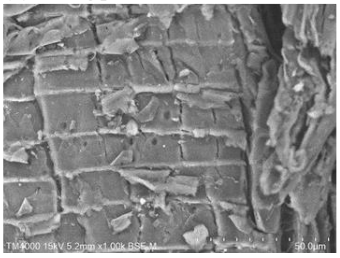


Figure 2:SEM images with 400 and 1000X for raw WCW (a) and Eucalyptus (b). Red circles indicated the cement contamination on WCW.

The blend of a 50:50 ratio of each biomass was also characterized, and the results were within the values of each biomass (Table I). Mixing the biomass resulted in a reduction of ash content from 1.48 to 1.08%, as expected.

To improve the HHV of the obtained blend, torrefaction was performed, and the results are discussed in the next section.

3.2 Experimental wood torrefaction

Torrefaction results are presented in Fig. 2. The solid yield evolution is presented in Fig. 2(a), allowing to assess the thermal degradation dynamics throughout torrefaction [21]. As previously stated, prior research indicated that wood thermo-degradation occurs when the treatment temperature exceeds 180 °C [22–24]. Therefore, Fig. 2(a) presents the normalized solid yield normalized after 160 °C for better visualization.

The increase in torrefactionseverity (temperature or time) promotes the release of volatiles through moisture loss and the decomposition of low-molecular-weight compounds, primarily hemicelluloses, in the biomass.

This devolatilization, in turn, leads to a decrease in the SY [25].Considering the 50 min treatment, the SY reduces when the torrefaction severity increases, resulting in 98.44, 86.88, and 62.93% for the 200, 250, and 300 °C treatments, respectively. As can be seen, light torrefaction presented a marginal effect (1.56%) on the SY. However, as the torrefaction temperature increases, the SY reduces to 37.7%.

Previous work evaluated the torrefaction of *Eucalyptus grandis*[26]. The reported SY for 210, 230, 250, and 270 °C torrefaction treatment during 60min were 96.61, 90.45, 83.43, and 75.55%. Another study conducted by Batista et al. 2015 [27] evaluated the torrefaction of *Pinus Elliottii* at temperatures of 220, 250, and 300 °C, obtaining yields of 99.47, 95.67, and 67.10% for 30 min and 95.46, 84.31, and 45.49%, for 60 min, respectively. In addition, Arteaga-Pérez et al. (2015) [28] evaluated a combined experimental and modeling approach of *Pinus radiata* and *Eucalyptus globulus.* Torrefaction was carried out for mild (250 °C) and severe (280 °C) conditions. For 30 min of treatment, the SY was pinus 79.43 and 58.14%, higher than eucalyptus, which stated 79 and 56%, respectively. The present work's feedstock comprises 50% of WCW (Pinus contaminated with cement and construction impurities) and 50% of eucalyptus. Thus, the obtained SYs for the proposed blend are consistent with eucalyptus and pinus literature.

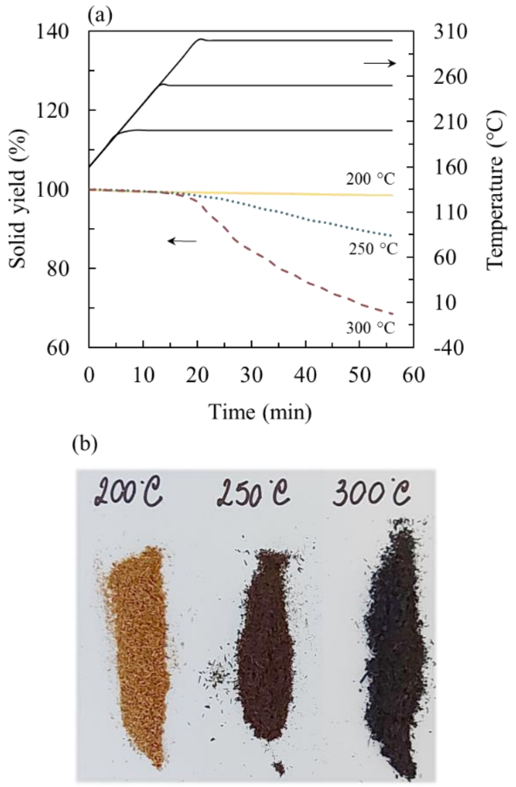


Figure 3:(a) Solid yield (SY) dynamics, (b) physical aspect of torrefied blends, B200, B250 and B300.

The torrefaction of biomass is accompanied by a significant change in color, an essential physical indicator [29,30]. Regarding Fig. 2(b), the color change of B200 was less pronounced, and the mass reduction was below 2%. Conversely, B250 and B300 exhibited more significant mass reduction and evident color modification, suggesting the effectiveness of the torrefaction process.

During torrefaction, distinct reaction mechanisms (decarboxylation, dehydration, and demethylation) occurred for each lignocellulosic component[2]. As the torrefaction severity increases, the dehydration process of biomass releases moisture and light volatiles more rapidly and extensively, decreasing its volatile matter (VM).Conversely, this process leads to an increase in the fixed carbon (FC), which is intrinsically related to the HHV and EY of the biofuel. Fig. 4 shows the ternary diagram of the raw blend (B) and its torrefied products (B200, B250 and B300).

Considering 200, 250 and 300 °C treatments, FC ranged between 15.04–44.42%, proportional to an increase of 1.8, 47.81 and 192.28%, compared to raw blend (B). Meanwhile, VM varied between 83.88–53.81, showing a reduction of 0.3, 8.82 and 35.85%.

As evidenced by the slight SY reduction and color change promoted by the 200 °C treatment (Fig. 3), the raw blend and the B200 present an almost identical position on the ternary diagram, with a slight displacement of B200 forward higher FC. As indicated in the diagram, as the torrefaction severity increases, the torrefied biomass moves toward the high corner of the diagram, indicating an increase in FC and a reduction in VM. B300 showed a pronounced displacement within the diagram, in line with the high mass loss (lower SY) shown in Fig. 3(a).

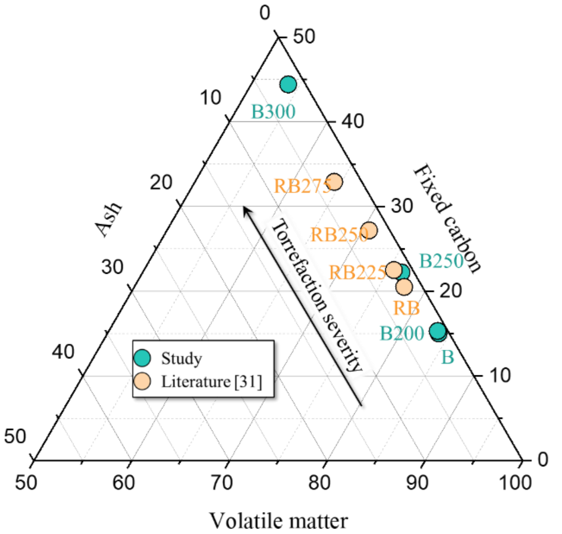


Figure 4: Ternary diagram of proximate analysis for the raw blend (B) and its torrefied product (B200, B250, and B300). Data for comparison: urban forest waste (raw, 225, 250, and 275 °C [31]).

The ash content proportion is much lower than FC and VM within biomass samples, and its modification is not evidenced in the ternary diagram. The experimental characterization of the torrefied product revealed the ash content ranging from 1.05–1.77%, progressing with torrefaction temperature.

Batista et al. 2015 [27] investigated the torrefaction of pinus biomass and reported VM and FC ranging between 81.74–67.18% and 18.02–32.55%, for torrefaction temperatures between 200–300 °C and 30min treatment time, in line with the present study.

Figs. 5(a) and (b) show the EY, the HHV and the EMCI. The energy parameters value are also displayed in Table II. The raw biomass comprehends structures formed by polar carboxyl, carbonyl, and hydroxyl groups, contributing to its low HHV (Table I). As mentioned earlier, the reduction of VM and increase of FC is related to the dehydration of hydroxyls and the dissociation of O-acetyls in hemicelluloses, anhydrosugar in cellulose, and phenols in lignin throughout torrefaction [32]. The release of the associated volatiles decreases H/C and O/C ratios,promoting the thermal upgrade of the material [32].

As expected, the HHV increases as the torrefaction temperature grows, ranging between 19.98–24.10 MJ kg^{-1} for B200, B250 andB300, respectively. The treatment severity is highlighted by the EF of HHV, presenting an increase of 1, 5 and 22% compared to raw biomass, respectively (Fig. 5(a) and Table II). Results are in line with Arteaga-Pérez et al. (2015) [28], that reported an HHV of 20.6 and 21 MJ kg^{-1} for Pine and Eucalyptus torrefaction at 280 °C with a holding time of 30 min. The result from Batista et al. 2015 [27], which reported an HHV of 23.9 MJ kg^{-1} for 30 min torrefaction at 300 °C, also corroborates the obtained HHV. The EMCI can be used as a performance indicator of optimum operating conditions for biomass torrefaction [33]. Figure 5(b) and Table II show an EMCI of 1.11, 4.38 and 13.83, showing the energy densification promoted by torrefaction.

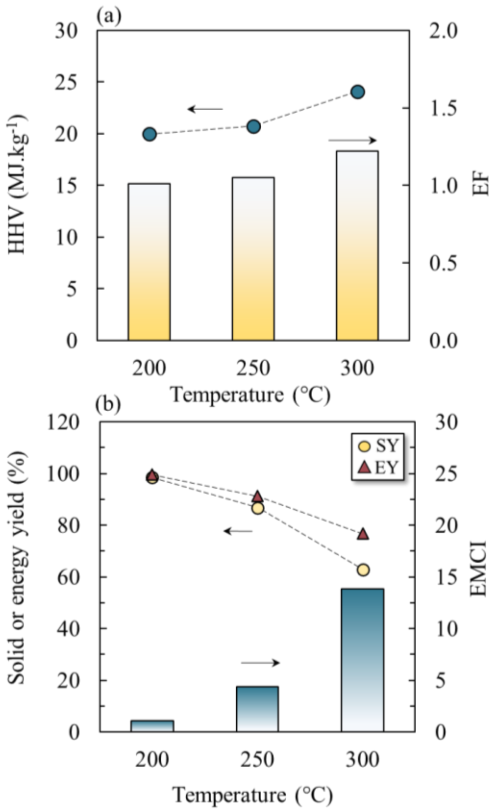


Figure 5: (a)HHV and enhancement factor (EF), and (b) SY, energy yield (EY) and the Energy-mass-coefficient-index (EMCI) for 200, 250, and 300 °C torrefaction.

The present work aims to evaluate the ash reduction promoted by mixing the raw materials (WCW and eucalyptus) and the energy upgrade promoted by torrefaction. Regarding energetic properties and ash content in Table II, it can be inferred that B200 presents practically the same ash content as raw material with an increment on HHV of 1%, which was unsuitable for upgrading the blended material.

Table II. Solid yield (%), higher heating value (MJ.kg^{-1}), enhancement factor (dimensionless), energy yield (%) and ash content (%) for50:50%blends (WCW and EUC) considering raw (B) torrefied products (B200, B250 and B275).

	B (raw)	**B200**	**B250**	**B300**
$S_Y^{(T)}$ (%)	100	98.44	86.88	62.93
HHV (MJ kg^{-1})	19.76	19.98	20.76	24.10
EF^{a}	-	1.01	1.05	1.22
$EY^{(T)}$ (%)	-	99.55	91.25	76.76
EMCI[a]	1	1.11	4.38	13.83
Ash (%)	1.08	1.05	1.24	1.77

[a] dimensionless

On the other hand, B300 has an exciting upgrade on HHV with a 22% increase (a consequence of enhanced FC), but the ash content % was higher than the raw WCW, presenting 1.77%. Finally, B250 possesses 1.24% of ash content (less than 1.48% of WCW) and an HHV increment of 5%, presenting 20.76 MJ kg^{-1}, being, for instance, the suitable treatment for reducing ash content while upgrading HHV.

4 CONCLUSIONS

The present investigation presents results on the thermal upgrading of biomass as biofuel aiming to reduce ash content and upgrade calorific power by performing torrefaction treatment on a WCW/eucalyptus blend.

Torrefaction severity and properties modification were evaluated, corroborating obtained data with literature and providing insights on how torrefaction treatment influences the proposed blend regardingthe proximate and calorific data. B250 possesses 1.24% of ash content (less than 1.48% of WCW) and an HHV increment of 5%, presenting 20.76 MJ kg^{-1}, for instance, the suitable treatment for reducing ash content while upgrading HHV.

For a proper optimization of biomass as biofuel, numerical and statistical models can help to select proper operational conditions and blend proportions. Moreover, choosing the appropriate biomass as biofuel concerns knowing the restrictions of the energy conversion system. In addition, selecting specific operational conditions and blend proportions evaluating the biofuel properties relies on a multicriteria decision problem. Therefore future research will be conducted on optimization tools (response surface methodology and artificial neural networks [34,35]), blend and operational conditions definition (multicriteria decision analysis[31,33,36]) and analysis of combustion behavior and related emissions[37–39].

Further investigation on life cycle assessment[40] is also recommended since the impacts ofWCW deposition on landfills must be evaluated (CH_4-related flows [41]) within system boundaries to account for the actual environmental impact reduction.

5 REFERENCES

[1] E.A. Silveira, A. Caldeira-Pires, S.M. Luz, C.M. Silveira, Mass and energy allocation method analysis for an oil refinery characterization using multi-scale modeling, Int. J. Life Cycle Assess. 22 (2017) 1815–1822. https://doi.org/DOI 10.1007/s11367-017-1369-9.

[2] G.C. Lamas, B. S. Chaves, P.P. Oliveira, T. Barbosa, T. da S. Gonzales, G.F. Ghesti, P. Rousset, E.A. Silveira, Effect of torrefaction on steam-enhanced co-gasification of an urban forest and landfill waste blend: H2 production and CO2 emissions mitigation, Int. J. Hydrogen Energy. (2023). https://doi.org/https://doi.org/10.1016/j.ijhydene.2023.03.367.

[3] A. Javanmard, M. Fazly, A. Patah, A. Zulhelmi, W. Mohd, A. Wan, A comprehensive overview of the continuous torrefaction method : Operational characteristics , applications , and challenges, J. Energy Inst. 108 (2023) 101199. https://doi.org/10.1016/j.joei.2023.101199.

[4] W.-H. Chen, B.-J. Lin, Y.-Y. Lin, Y. Chu, A.T. Ubando, P.L. Show, H.C. Ong, J. Chang, S. Ho, A.B. Culaba, A. Pétrissans, M. Pétrissans, P. Loke, H. Chyuan, J. Chang, S. Ho, A.B. Culaba, A. Pétrissans, M. Pétrissans, Progress in biomass torrefaction: Principles, applications and challenges, Prog. Energy Combust. Sci. 82 (2021) 100887. https://doi.org/10.1016/j.pecs.2020.100887.

[5] J.A. Okolie, S. Nanda, A.K. Dalai, J.A. Kozinski, Chemistry and Specialty Industrial Applications of Lignocellulosic Biomass, Waste and Biomass Valorization. 12 (2021) 2145–2169. https://doi.org/10.1007/s12649-020-01123-0.

[6] F. de A. Oliveira, L.M.F. Maués, C.C.N. Rosa, D.G. Santos, R. de M. Seixas, Previsão da geração de resíduos na construção civil por meio da modelagem BIM, Ambient. Construído. 20 (2020) 157–176. https://doi.org/10.1590/s1678-86212020000400465.

[7] W.M. Cavalcanti, E.J. Alves, Aplicação De Resíduos Da Construção Civil Como Aglomerado De Compósitos De Madeira Péletes / Briquetes : Um Estudo Bibliográfico E Documental, Congr. Sul Am. Resíduos Sólidos e Sustentabilidade. (2018) 1–8.

[8] S.C. Angulo, C.E. Teixeira, A.L. de Castro, T.P. Nogueira, Resíduos de construção e demolição: Avaliação de métodos de quantificação, Eng. Sanit. e Ambient. 16 (2011) 299–306. https://doi.org/10.1590/S1413-41522011000300013.

[9] S.P. Mendes, D.P. Lima, Logística reversa de resíduos sólidos na construção civil, Eng. Sci. 9 (2022) 12–21. https://doi.org/10.6008/cbpc2318-3055.2021.003.0002.

[10] Y.H.M. Ribeiro, G.C. Lamas, R.C.F. Mendes, M.S. Santanna, A. Caldeira-Pires, E.A. Silveira, ENERGY RECOVERY FROM MUNICIPAL SOLID WASTE COMBUSTION AND AGROPASTORAL BIO- DIGESTION: ANALYSIS OF THE TECHNICAL FEASIBILITY IN BRAZIL'CAPITAL, in: 30th Eur. Biomass Conf. Exhib., 2022: pp. 228–234.

https://doi.org/10.5071/30thEUBCE2022-1CV.2.7.

[11] E.A. Silveira, M.S. Santanna, N.P. Barbosa Souto, G.C. Lamas, L.G.O. Galvão, S.M. Luz, A. Caldeira-Pires, Urban lignocellulosic waste as biofuel: thermal improvement and torrefaction kinetics, J. Therm. Anal. Calorim. 148 (2023) 197–212. https://doi.org/10.1007/s10973-022-11515-0.

[12] Í.M.L. Mendes, M.S.B. Fialho, R.M. Leão, E.A. Silveira, S.M. da Luz, Processing Biodegradable Blends of Hemicellulose with Polyhydroxybutyrate and Poly (Lactic Acid), Mater. Res. 26 (2023). https://doi.org/10.1590/1980-5373-mr-2022-0390.

[13] S.K. Thengane, K.S. Kung, A. Gomez-Barea, A.F. Ghoniem, Advances in biomass torrefaction: Parameters, models, reactors, applications, deployment, and market, Prog. Energy Combust. Sci. 93 (2022) 101040. https://doi.org/10.1016/j.pecs.2022.101040.

[14] E.A. Silveira, L.A. Macedo, P. Rousset, K. Candelier, L.G.O. Galvão, B.S. Chaves, J.-M. Commandré, A potassium responsive numerical path to model catalytic torrefaction kinetics, Energy. 239 (2022) 122208. https://doi.org/10.1016/j.energy.2021.122208.

[15] L.A. Macedo, E.A. Silveira, P. Rousset, J. Valette, J.-M. Commandré, Synergistic effect of biomass potassium content and oxidative atmosphere: Impact on torrefaction severity and released condensables, Energy. 254 (2022) 124472. https://doi.org/10.1016/j.energy.2022.124472.

[16] E.A. Silveira, L.A. Macedo, K. Candelier, P. Rousset, J.-M. Commandré, Assessment of catalytic torrefaction promoted by biomass potassium impregnation through performance indexes, Fuel. 304 (2021) 121353. https://doi.org/10.1016/j.fuel.2021.121353.

[17] A. Faleiro Dionizio, A. Teixeira do Vale, A. Cézar de Oliveira Moreira, L. Gustavo Oliveira Galvão, B. Sant, A. Chaves, M. de Almeida Costa, Agregação de valor a resíduos agroindustriais para fins energéticos Adding value to agro-industrial waste for energy purposes, Rev. Ciências Agrárias. 42 (2019) 528–538. https://doi.org/10.19084/rca.15129.

[18] K.L. Iroba, O.D. Baik, L.G. Tabil, Torrefaction of biomass from municipal solid waste fractions I: Temperature profiles, moisture content, energy consumption, mass yield, and thermochemical properties, Biomass and Bioenergy. 105 (2017) 320–330. https://doi.org/10.1016/j.biombioe.2017.07.009.

[19] E.V.S. COSTA, M.F.V. ROCHA, A. de Cássia, O. CARNEIRO, C.M.S. da SILVA, B.L.C. PEREIRA, M.P. de C.F. PEREIRA, D.N. SORATTO, J.J. BIACHE, INFLUÊNCIA DA TORREFAÇÃO NAS PROPRIEDADES DOS BRIQUETES PRODUZIDOS COM MADEIRA DE Eucalyptus sp, in: 2015.

[20] A.P. Bersch, E.J. Brun, F.A. Pereira, D.A. Silva, Y.R. De Barba, J.R. Dorini Junior, CARACTERIZAÇÃO ENERGÉTICA DA MADEIRA DE TRÊS MATERIAIS GENÉTICOS DE Eucalyptus sp., FLORESTA. 48 (2018) 87. https://doi.org/10.5380/rf.v48i1.51673.

[21] E.A. Silveira, L.G.O. Galvão, I.A. Sá, B.F. Silva, L. Macedo, P. Rousset, A. Caldeira-Pires, Effect of torrefaction on thermal behavior and fuel properties of Eucalyptus grandis macro-particulates, J. Therm. Anal. Calorim. 138 (2019) 3645–3652. https://doi.org/10.1007/s10973-018-07999-4.

[22] E.A. Silveira, B.J. Lin, B. Colin, M. Chaouch, A. Pétrissans, P. Rousset, W.H. Chen, M. Pétrissans, Heat treatment kinetics using three-stage approach for sustainable wood material production, Ind. Crops Prod. 124 (2018) 563–571. https://doi.org/10.1016/j.indcrop.2018.07.045.

[23] B.-J. Lin, E.A. Silveira, B. Colin, W.-H. Chen, Y.-Y. Lin, F. Leconte, A. Pétrissans, P. Rousset, M. Pétrissans, Modeling and prediction of devolatilization and elemental composition of wood during mild pyrolysis in a pilot-scale reactor, Ind. Crops Prod. 131 (2019) 357–370. https://doi.org/10.1016/j.indcrop.2019.01.065.

[24] B.-J. Lin, E.A. Silveira, B. Colin, W.-H. Chen, A. Pétrissans, P. Rousset, M. Pétrissans, Prediction of higher heating values (HHVs) and energy yield during torrefaction via kinetics, Energy Procedia. 158 (2019) 111–116. https://doi.org/10.1016/j.egypro.2019.01.054.

[25] W.-H.H. Chen, C. Fong Eng, Y.-Y.Y. Lin, Q.-V.V. Bach, V. Ashokkumar, P.-L.L. Show, Two-step thermodegradation kinetics of cellulose, hemicelluloses, and lignin under isothermal torrefaction analyzed by particle swarm optimization, Energy Convers. Manag. 238 (2021) 114116. https://doi.org/10.1016/j.enconman.2021.114116.

[26] E.A. Silveira, S.M. Luz, R.M. Leão, P. Rousset, A. Caldeira-Pires, Numerical modeling and experimental assessment of sustainable woody biomass torrefaction via coupled TG-FTIR, Biomass and Bioenergy. 146 (2021) 105981. https://doi.org/10.1016/j.biombioe.2021.105981.

[27] J.A.N. BATISTA, Torrefação do Pinus elliottii para fins energéticos, Unessp, 2015. http://hdl.handle.net/11449/155613.

[28] L.E. Arteaga-Pérez, C. Segura, D. Espinoza, L.R. Radovic, R. Jiménez, Torrefaction of Pinus radiata and Eucalyptus globulus: A combined experimental and modeling approach to process synthesis, Energy Sustain. Dev. 29 (2015) 13–23. https://doi.org/10.1016/j.esd.2015.08.004.

[29] W.H. Chen, B.J. Lin, B. Colin, J.S. Chang, A. Pétrissans, X. Bi, M. Pétrissans, Hygroscopic transformation of woody biomass torrefaction for carbon storage, Appl. Energy. 231 (2018) 768–776. https://doi.org/10.1016/j.apenergy.2018.09.135.

[30] K. Cheol, J. Kim, S. Yong, S. Jun, L. Hoon, C. Geon, J. Roh, D. Hyun, Development and validation of torrefaction optimization model applied element content prediction of biomass, Energy. 214 (2021) 119027. https://doi.org/10.1016/j.energy.2020.119027.

[31] E.A. Silveira, B. Santanna Chaves, L. Macedo, G.F. Ghesti, R.B.W. Evaristo, G. Cruz Lamas, S.M. Luz, T. de P. Protásio, P. Rousset, A hybrid optimization approach towards energy recovery from torrefied waste blends, Renew. Energy. (2023). https://doi.org/10.1016/j.renene.2023.05.053.

[32] H.C. Ong, K.L. Yu, W.-H.H. Chen, M.K. Pillejera, X. Bi, K.-Q.Q. Tran, A. Pétrissans, M. Pétrissans, Variation of lignocellulosic biomass structure from torrefaction: A critical review, Renew. Sustain.

Energy Rev. 152 (2021) 111698. https://doi.org/10.1016/j.rser.2021.111698.

[33] R.B.W. Evaristo, R. Ferreira, J. Petrocchi Rodrigues, J. Sabino Rodrigues, G.F. Ghesti, E.A. Silveira, M. Costa, Multiparameter-analysis of CO2/Steam-enhanced gasification and pyrolysis for syngas and biochar production from low-cost feedstock, Energy Convers. Manag. X. 12 (2021) 100138. https://doi.org/10.1016/j.ecmx.2021.100138.

[34] D.K. Singh, J. V. Tirkey, Modeling and multi-objective optimization of variable air gasification performance parameters using Syzygium cumini biomass by integrating ASPEN Plus with Response surface methodology (RSM), Int. J. Hydrogen Energy. 46 (2021) 18816–18831. https://doi.org/10.1016/j.ijhydene.2021.03.054.

[35] H.O. Kargbo, J. Zhang, A.N. Phan, Optimisation of two-stage biomass gasification for hydrogen production via artificial neural network, Appl. Energy. 302 (2021) 117567. https://doi.org/10.1016/j.apenergy.2021.117567.

[36] G.F. Ghesti, E.A. Silveira, M.G. Guimarães, R.B.W.W. Evaristo, M. Costa, Towards a sustainable waste-to-energy pathway to pequi biomass residues: Biochar, syngas, and biodiesel analysis, Waste Manag. 143 (2022) 144–156. https://doi.org/10.1016/j.wasman.2022.02.022.

[37] J.L.F. Alves, J.C.G. da Silva, G.D. Mumbach, M. Di Domenico, V.F. da Silva Filho, R.F. de Sena, R.A.F. Machado, C. Marangoni, Insights into the bioenergy potential of jackfruit wastes considering their physicochemical properties, bioenergy indicators, combustion behaviors, and emission characteristics, Renew. Energy. 155 (2020) 1328–1338. https://doi.org/10.1016/j.renene.2020.04.025.

[38] G. Maj, Emission factors and energy properties of agro and forest biomass in aspect of sustainability of energy sector, Energies. 11 (2018). https://doi.org/10.3390/en11061516.

[39] J. Luiz, F. Alves, J. Constantino, S. Noeli, S. Flávio, D.B. Prá, C. Sapelini, O. Souza, C. Marangoni, Upgrading of banana leaf waste to produce solid biofuel by torrefaction : physicochemical properties , combustion behaviors , and potential emissions, Environ. Sci. Pollut. Res. (2022) 25733–25747. https://doi.org/10.1007/s11356-021-17381-x.

[40] L. Deutsch, G.C. Lamas, T.S. Pereira, E.A. Silveira, A. Caldeira-Pires, Life cycle and risk assessment of vinasse storage dams: A Brazilian sugar-energy refinery analysis, Sustain. Futur. 4 (2022) 100083. https://doi.org/10.1016/j.sftr.2022.100083.

[41] M.C. Rodrigues, E.A. Silveira, A.C.P.B. Junior, On the correlation between thermal imagery and fugitive CH 4 emissions from MSW landfills, Waste Manag. 166 (2023) 163–170. https://doi.org/10.1016/j.wasman.2023.05.005.

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