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Solid Biofuel from the Amazon: A Circular Economy Approach to Briquette Production from Wood Waste

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Abstract: The Amazon region contains numerous areas dedicated to sustainable timber extraction. This operation has low yields and generates a large amount of waste. However, this waste can be repurposed for energy generation, providing income for locals and reducing reliance on non-renewable energy sources prevalent in the region. This study aimed to assess the impact of torrefaction on various wood residues for briquette production. Wood residues from *Mimosa scabrella* Benth (Bracatinga), *Dipteryx odorata* (Aubl.) Willd. (Cumaru), and *Aspidosperma populifolium* A.DC. (Peroba mica) were torrefied at temperatures ranging from 180 to 220 °C for sixty minutes under a nitrogen atmosphere. Briquettes were produced using laboratory equipment with loading pressures between 7 and 14 MPa. Torrefied particle properties were evaluated based on proximate composition and calorific value tests, while briquette quality was assessed for physical and mechanical properties. The results demonstrated the briquetting potential of different wood species before and after torrefaction, with optimal outcomes achieved by torrefaction at 220 °C due to its enhancement of energy density. Briquettes showed optimal characteristics at compression pressures of 14 MPa, resulting in increased density (between 1.10 and 1.24 g·cm^{-3}) and compression strength (between 7.20 and 21.02 MPa). The ash values were low and met the requirements. The utilization of waste for briquette production offers a significant alternative for energy generation in economically disadvantaged communities, while also enabling the replacement of non-renewable energy sources.

Keywords: bioenergy; biomass; heating value; sustainability; torrefaction; wood waste management

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1. Introduction

Population growth has increased energy demand, and the global energy matrix needs to change, as it predominantly relies on non-renewable energy sources that emit greenhouse gases [1,2]. In this context, it is necessary to increase the use of renewable energies, such as solar, wind, and biomass [3].

The advantages of utilizing biomass for energy make it an excellent choice as a sustainable energy source. Energy can be produced using various raw materials, such as wood sawdust, sugarcane bagasse, and coffee and rice husks, among others [4–6]. This process exhibits low greenhouse gas emissions while simultaneously generating employment opportunities and income for local populations.

In Brazil, there have been few studies on the production of energy from waste generated by native forest management activities. Brazil stands as one of the largest producers of tropical roundwood, annually harvesting 81 million m^3 of logs [7,8]. The processing of wood derived from sustainable management plans for native forests yields less than 50%, resulting in large quantities of sawdust that can be used for energy generation [9].

However, the low energy density of the residues generated in wood processing limits their transportation and utilization for bioenergy [10–12]. To overcome these issues, it is possible to torrefy and compact biomass. The briquette production process involves pressing biomass at 120 °C and 80 kgf·cm^{-2}, forming blocks of defined volume with a greater particle size homogeneity, lower moisture content, and higher density compared to the raw material [13,14]. Torrefaction for briquette production shows potential for widely used species cultivated on large plantations in Brazil, such as sugarcane, coffee, and eucalyptus [11–13]. However, studies on the use of residues from species derived from native forest management plans have not kept up with demand.

Torrefaction is a thermal process that involves heating biomass to temperatures up to 300 °C in an oxygen-free environment. This process removes moisture and volatile compounds, resulting in a dry, energy-dense, and hydrophobic material that is easier to store, transport, and grind compared to untreated biomass. Torrefied biomass has a higher calorific value and improved combustion properties, making it an attractive alternative to coal in power generation [15,16]. Additionally, it reduces the challenges associated with biomass variability and enhances the efficiency and reliability of biomass energy systems [17]. By converting raw biomass into a more uniform and stable form, torrefaction contributes to the optimization of biomass as a renewable energy source, facilitating its integration into existing energy infrastructures. Torrefaction for 1.2 h at 260 °C increased the calorific value of oak wood by 20% [15], while torrefaction of spruce wood and grass and rice husks at 300 °C increased their calorific values by 22.35 and 13%, respectively [17].

The objective of this study was to evaluate the physical, chemical, and energetic properties of torrefied wood residues of *Mimosa scabrella* Benth (Bracatinga), *Aspidosperma populifolium* (Aubl.) Willd. (Peroba Mica), and *Dipteryx odorata* A.DC. (Cumaru) and their use in briquette production.

2. Materials and Methods

2.1. Biomass Characterization

Untreated wood residues of *Mimosa scabrella* (Bracatinga), *Dipteryx odorata* (Cumaru), and *Aspidosperma populifolium* (Peroba Mica) with dimensions of 60 cm × 7.5 cm × 2 cm (length × width × thickness) that originated from wood sawing processes were supplied by Indusparquet, a hardwood-floor manufacturing company located in Tietê City, São Paulo State, Brazil (23°06′07″ S, 47°42′53″ W). The wood moisture content was reduced to 12%–15% over a period of three months in a climatic chamber.

The torrefaction process was conducted using a Marconi vacuum oven (Model MA-027). This oven allows for precise control of temperature, pressure, and atmospheric conditions (either air or nitrogen). Once the oven reached the predetermined temperature, the samples were placed inside and torrefied for one hour.

Three temperatures were tested: 180 °C, 200 °C, and 220 °C. To create an inert atmosphere within the oven chamber, the pressure was reduced close to zero using a vacuum pump. Subsequently, nitrogen was introduced until atmospheric pressure was reached. The pressure was then kept constant throughout the temperature increase by utilizing a relief valve.

The samples were conditioned at 20 °C and 65% relative humidity, and a Marconi climatic chamber (Model MA-835/450UR; Marconi Laboratory Industry, São Paulo, Brazil) was used to measure the equilibrium moisture content. After stabilizing the sample mass, it was subjected to oven drying at 103 °C for 24 h and then weighed again. The equilibrium moisture content was calculated according to Equation (1).

$$EMC = \frac{(Wm - DM) \times 100}{Dm} \quad (1)$$

where

EMC = equilibrium moisture content (%);
Wm = wet mass (g);
Dm = Dry mass of the sample (g).

Then, the samples were ground in a Wiley knife mill with a 2 mm sieve opening, and the fraction of material retained between the 40- and 60-mesh sieves was used to evaluate the proximate analysis (fixed carbon, volatile material, and ash) with a higher heating value in an adiabatic calorimeter pump (Model IKA 300).

2.2. Briquette Properties

For briquette production, heat-treated wood was cut and ground using a Thomas Wiley Model 4 hammer mill and then sieved. The fraction that passed through a 40-mesh (0.42 mm) sieve was utilized in the production of briquettes.

Briquettes 32.5 mm in diameter and 17.08 mm in length were produced with 17 g of wood particles using laboratory equipment (Lippel, Model LB-32, Lippel Laboratory Industry, Santa Catarina, Brazil) set at 120 °C for 7 min of pressing time and 6 min of cooling time. Three pressures were tested: 7, 10, and 14 MPa. These pressure and cooling-time conditions were defined based on preliminary tests to avoid the production of briquettes with cracks or fissures. Ten briquettes were produced per treatment. The briquetting mass loss was calculated gravimetrically.

Briquette dimensions were measured with a caliper ruler with 0.01 mm accuracy. After stabilization at 200 °C and 65% relative humidity (using the Marconi climatic chamber, Model MA-835/450UR) the length, diameter, and mass were redetermined. The dimensional variations were presented as percentages of the original briquettes. Moisture absorption was obtained gravimetrically by determining the values before and after conditioning in the climatic chamber.

The apparent density was determined as the ratio between the mass of the briquette and the volume displaced when immersed in mercury, according to Equation (2).

$$Da = \frac{M}{V} \tag{2}$$

where

Da = apparent density (kg/m^3);
M = mass of the briquette (kg);
V = volume (m^3).

The diameters and masses of the briquettes were measured after their production and cooling. Subsequently, they were conditioned at 20 °C and 65% relative humidity using a Marconi climatic chamber (Model MA-835/450UR; São Paulo, Brazil) to measure the equilibrium moisture content according to Equation (1).

The diameter return rate was determined according to Equation (3).

$$DRR = \frac{(D2 - D1)}{D1} \tag{3}$$

where

DRR = diameter return rate (%);
D1 = initial diameter (mm);
D2 = final diameter (mm).

A Universal Testing Machine (Model Losenhausen) was utilized to determine the compression strength, during which the briquettes were compressed at a continuous rate of 3.5 mm/min until failure. The maximum load of the briquettes until rupture was determined according to ISO 11093-9. Ten replicates were used to determine each test property.

2.3. Statistical Analysis

The data were submitted to tests for homogeneity of variance (the Bartlett test, 5% significance) and normality (the Shapiro–Wilk test, 5% significance) prior to variance analysis. The contrast between the means of the parameters evaluated was determined by the Tukey test at a 5% significance level.

3. Results

3.1. Biomass Characterization

The torrefaction process reduced the equilibrium moisture content and the volatile matter content, while it increased the fixed carbon content and higher heating value (Table 1).

Table 1. *Mimosa scabrella* Benth (bracatinga), *Aspidosperma populifolium* A.DC. (Peroba mica), and *Dipteryx odorata* (Aubl.) Willd. (Cumaru) wood untreated and heat-treated at 180, 200, and 220 °C.

Species	Temperature (°C)	E.M.C. (%)	Volatile Matter (%)	Ash Content (%)	Fixed Carbon (%)	Higher Heating Value (MJ kg^{-1})
Mimosa scabrella	Untreated	$13.4^{4.5}$ a	$85.5^{3.4}$ a	$0.5^{15.5}$ a	$14.0^{5.6}$ a	$20.1^{3.4}$ a
	180	$10.2^{3.6}$ b	$84.8^{4.3}$ a	$0.7^{18.6}$ a	$14.6^{4.3}$ b	$19.6^{4.7}$ a
	200	$9.8^{2.5}$ b	$84.8^{5.3}$ a	$0.5^{20.5}$ a	$14.8^{4.3}$ b	$20.1^{5.1}$ a
	220	$9.8^{4.1}$ b	$83.3^{4.8}$ b	$0.6^{14.6}$ a	$16.2^{5.4}$ c	$20.5^{4.5}$ a
Aspidosperma populifolium	Untreated	$10.9^{3.2}$ a	$86.8^{5.7}$ a	$0.7^{17.8}$ a	$12.6^{6.1}$ a	$21.4^{3.1}$ a
	180	$10.0^{3.1}$ ab	$85.3^{5.9}$ b	$0.6^{18.6}$ a	$14.1^{3.4}$ b	$21.4^{5.3}$ a
	200	$10.1^{3.5}$ ab	$84.7^{4.8}$ b	$0.8^{19.7}$ a	$14.6^{4.6}$ b	$21.7^{5.2}$ a
	220	$9.5^{3.6}$ b	$83.6^{6.1}$ c	$0.6^{22.1}$ a	$15.8^{4.7}$ c	$22.7^{4.2}$ b
Dipteryx odorata	Untreated	$11.2^{3.8}$ a	$84.0^{5.7}$ a	$0.6^{20.5}$ a	$15.5^{5.4}$ a	$21.4^{3.8}$ a
	180	$9.9^{2.6}$ b	$81.0^{4.5}$ b	$0.5^{18.6}$ a	$18.5^{5.7}$ b	$20.9^{4.2}$ a
	200	$9.7^{3.4}$ b	$79.8^{5.1}$ c	$0.6^{17.4}$ a	$19.6^{7.2}$ c	$21.8^{5.2}$ a
	220	$8.9^{4.4}$ c	$79.8^{4.3}$ c	$0.5^{19.4}$ a	$19.7^{5.3}$ c	$21.8^{5.1}$ a

Means in the vertical followed by the same letter do not differ from each other by the Tukey test at 5% probability. Values in superscript represent the coefficients of variation.

3.2. Briquette Properties

The quality of the briquettes varied according to wood species, heat treatment, and compaction pressure (Table 2). The results highlight how briquette quality was a result of a combination of factors inherent in the wood and the production process. Therefore, the choice of wood species and process variables should be carefully selected according to the final objective of the briquettes.

Table 2. Briquette density (g·cm^{-3}), compression resistance, weight loss (%), length expansion (%), diameter return rate, water absorption (%), and equilibrium moisture content (%) produced with untreated and heat-treated wood particles at 180, 200, and 220 °C, with three compression pressures (7, 10, and 14 MPa), using *Mimosa scabrella* Benth (Bragatinga) (1), *Aspidosperma populifolium* A.DC. (Peroba Mica) (2), and *Dipterix odorata* (Aubl.) Willd. (Cumaru) (3).

Species	Temp. (°C)	Pressure (Mpa)	Briquette Density (kg·m^{-3})	Compression Strength (MPa)	Diameter Return Rate (%)	Expansion (%)	Equiv. Moisture Content (%)	Water Absorption (%)
1	Unt.	7	$1050^{4.6}$ a	$6.31^{6.1}$ a	$0.93^{7.2}$ a	$12.51^{8.7}$ a	$10.74^{3.3}$ a	$3.57^{5.3}$ a
	180	7	$1040^{5.7}$ a	$8.52^{5.2}$ b	$0.87^{7.8}$ a	$7.88^{8.4}$ bc	$10.10^{3.5}$ a	$4.00^{5.5}$ a
	200	7	$1050^{6.7}$ a	$7.67^{5.5}$ ab	$1.12^{8.2}$ a	$7.27^{8.9}$ c	$8.99^{5.3}$ b	$1.78^{5.8}$ b
	220	7	$1130^{5.3}$ a	$9.94^{5.2}$ c	$0.91^{9.1}$ a	$5.52^{9.2}$ d	$8.98^{4.6}$ b	$1.84^{5.6}$ b
1	Unt.	10	$1060^{4.4}$ a	$6.48^{4.8}$ a	$0.80^{7.8}$ a	$12.39^{8.2}$ a	$11.06^{4.8}$ a	$3.75^{5.4}$ a
	180	10	$1120^{4.8}$ a	$8.88^{5.5}$ b	$0.99^{9.0}$ a	$9.79^{7.8}$ b	$10.96^{4.7}$ a	$2.11^{5.7}$ b
	200	10	$1100^{4.1}$ a	$9.31^{6.2}$ c	$0.80^{8.5}$ a	$8.46^{8.8}$ b	$8.89^{4.6}$ b	$2.02^{5.3}$ b
	220	10	$1060^{5.0}$ a	$8.54^{6.3}$ b	$1.06^{8.3}$ a	$8.78^{7.9}$ b	$8.25^{4.9}$ b	$2.08^{5.1}$ b

Table 2. *Cont.*

Species	Temp. (°C)	Pressure (Mpa)	Briquette Density (kg·m^{-3})	Compression Strength (MPa)	Diameter Return Rate (%)	Expansion (%)	Equiv. Moisture Content (%)	Water Absorption (%)
1	Unt.	14	$1100^{4.2}$ a	$7.20^{4.1}$ ab	$0.85^{7.3}$ a	$11.43^{8.4}$ a	$10.05^{5.7}$ a	$3.37^{5.9}$ a
	180	14	$1110^{3.8}$ a	$9.74^{4.5}$ c	$0.94^{8.0}$ a	$9.80^{10.4}$ b	$10.56^{4.3}$ a	$3.92^{4.2}$ a
	200	14	$1220^{5.3}$ b	$9.85^{5.0}$ c	$0.81^{7.3}$ a	$8.04^{6.7}$ b	$8.90^{4.6}$ b	$1.67^{4.7}$ b
	220	14	$1240^{5.9}$ b	$9.28^{4.2}$ c	$0.93^{7.8}$ a	$8.32^{8.6}$ b	$8.84^{4.4}$ b	$2.30^{4.6}$ b
2	Unt.	7	$1040^{6.1}$ a	$17.16^{5.5}$ d	$0.68^{10.1}$ b	$12.51^{8.9}$ a	$10.14^{4.4}$ a	$4.11^{4.2}$ a
	180	7	$1070^{5.2}$ a	$17.87^{5.1}$ d	$0.68^{9.3}$ b	$8.88^{9.9}$ b	$10.10^{4.9}$ a	$4.00^{4.9}$ a
	200	7	$1080^{5.8}$ a	$16.61^{4.8}$ d	$0.74^{9.8}$ b	$8.27^{8.8}$ b	$8.82^{4.6}$ b	$3.85^{5.1}$ a
	220	7	$1050^{6.7}$ a	$17.29^{4.5}$ d	$0.74^{9.2}$ b	$5.52^{7.3}$ d	$8.59^{4.5}$ b	$2.17^{6.1}$ b
2	Unt.	10	$1090^{5.2}$ a	$19.97^{5.1}$ e	$0.68^{9.1}$ b	$12.39^{7.6}$ a	$10.66^{4.1}$ a	$4.75^{4.7}$ a
	180	10	$1120^{5.1}$ a	$19.41^{5.2}$ e	$0.69^{9.0}$ b	$9.79^{7.8}$ b	$10.96^{4.3}$ a	$3.47^{4.9}$ a
	200	10	$1130^{4.5}$ a	$19.35^{5.3}$ e	$0.65^{9.2}$ b	$7.46^{8.9}$ c	$8.24^{5.0}$ b	$2.02^{3.8}$ b
	220	10	$1070^{4.0}$ a	$19.36^{5.0}$ e	$0.70^{10.5}$ b	$8.78^{7.5}$ b	$8.40^{4.6}$ b	$1.98^{3.6}$ b
2	Unt.	14	$1100^{3.8}$ a	$19.26^{4.5}$ e	$0.70^{8.9}$ b	$12.43^{8.4}$ a	$10.41^{4.9}$ a	$3.37^{3.1}$ a
	180	14	$1230^{4.5}$ b	$19.92^{4.4}$ e	$0.69^{8.1}$ b	$9.80^{8.5}$ b	$10.26^{4.3}$ a	$3.29^{4.7}$ a
	200	14	$1230^{4.1}$ b	$19.27^{4.1}$ e	$0.72^{8.5}$ b	$7.04^{5.6}$ c	$8.34^{4.2}$ b	$2.26^{3.8}$ b
	220	14	$1210^{4.0}$ b	$21.02^{4.3}$ f	$0.74^{8.3}$ b	$8.32^{7.8}$ bc	$8.94^{4.7}$ b	$2.24^{3.6}$ b
3	Unt.	7	$1080^{6.9}$ a	$7.49^{5.1}$ b	$0.65^{6.4}$ b	$9.02^{8.7}$ b	$10.63^{4.8}$ a	$3.83^{4.4}$ a
	180	7	$1120^{7.5}$ a	$8.68^{5.3}$ bc	$0.56^{8.1}$ b	$5.17^{7.6}$ d	$10.95^{4.6}$ a	$3.76^{4.3}$ a
	200	7	$1100^{7.3}$ a	$9.13^{5.6}$ c	$0.55^{8.2}$ b	$5.93^{7.8}$ d	$8.97^{4.5}$ b	$1.62^{4.7}$ b
	220	7	$1120^{8.0}$ a	$9.59^{4.4}$ c	$0.62^{5.2}$ b	$5.74^{7.4}$ d	$6.50^{3.2}$ c	$2.01^{4.5}$ b
3	Unt.	10	$1180^{6.1}$ a	$7.98^{4.3}$ b	$0.57^{6.4}$ b	$12.85^{8.5}$ d	$10.97^{3.8}$ a	$3.17^{4.3}$ a
	180	10	$1080^{6.2}$ a	$9.8^{4.5}$ c	$0.70^{7.3}$ b	$4.14^{8.7}$ e	$10.57^{3.6}$ a	$2.39^{4.6}$ b
	200	10	$1110^{6.3}$ a	$9.75^{5.0}$ c	$0.31^{8.6}$ c	$3.47^{8.3}$ e	$8.85^{3.2}$ b	$1.80^{4.3}$ b
	220	10	$1140^{6.2}$ a	$9.93^{4.1}$ c	$0.43^{9.2}$ c	$3.81^{7.1}$ e	$9.04^{3.5}$ b	$1.91^{4.8}$ b
3	Unt.	14	$1100^{4.5}$ a	$7.91^{5.9}$ b	$0.68^{5.3}$ b	$9.80^{9.3}$ b	$10.33^{3.9}$ a	$3.33^{4.6}$ a
	180	14	$1160^{4.6}$ ab	$9.92^{6.1}$ c	$0.69^{7.7}$ b	$9.21^{9.4}$ b	$10.26^{3.9}$ a	$3.29^{4.3}$ a
	200	14	$1200^{3.9}$ b	$8.65^{6.3}$ bc	$0.31^{8.7}$ c	$3.14^{6.7}$ e	$8.37^{3.1}$ b	$2.36^{4.9}$ b
	220	14	$1240^{4.6}$ b	$9.48^{6.9}$ c	$0.54^{6.9}$ c	$4.24^{7.3}$ e	$6.19^{3.6}$ c	$2.03^{4.1}$ b

Means in the vertical followed by the same letter do not differ from each other by the Tukey test at 5% probability. Values in superscript represent the coefficients of variation.

4. Discussion

4.1. Biomass Characterization

The decrease in equilibrium moisture content following heat treatment is primarily attributable to the degradation of hemicelluloses between 200 °C and 330 °C [18,19]. The degradation decreases the quantity of hydroxyl groups and the affinity with water, resulting in lower moisture adsorption from the atmosphere [20,21]. This reduction is beneficial for energy purposes, as it minimizes the energy loss required to evaporate water from biomass [22].

Increasing temperature decreased the volatile matter content, increased the fixed carbon content, and did not alter the ash content in the material of the three analyzed species. Temperature increase initially degrades polar extractives and hemicelluloses; these compounds are highly branched and unstable at high temperatures, burning in the form of gas and are classed as volatile materials [19,23]. The removal of these compounds increases the proportion of material that burns in solid form, characterized as fixed carbon [24]. These compounds are mainly derived from lignins, which have high thermal stability due to the strong bonds that unite their monomers [25]. Therefore, the thermal treatment reduced the volatile material content by 2.5% to 5% and increased the fixed carbon content by 15% to 27%. Reductions in volatile material content and increases in fixed carbon contents are desirable for energy generation, as they result in uniform and prolonged combustion, improving the quality of materials intended for this purpose.

Ashes consist of non-combustible wood minerals and therefore do not contribute to energy generation [26,27]. Additionally, they wear out equipment and increase the generation of waste. The low ash contents found in the three evaluated species—all of which were below 1%—demonstrate the materials' quality for energy generation. Ash contents increase with temperature in the case of woods subjected to thermal treatment, torrefaction, and carbonization [28,29]. However, in the evaluated species, these values were not altered due to the representativeness of the wood ashes and the low temperatures used.

The higher heating value increased by 1.8% to 6% in the analyzed species, with a greater increase observed for *Aspidosperma populifolium* (Peroba mica) and *Dipteryx odorata* (Cumaru) under thermal treatment at 220 °C. In these species, the thermal treatment resulted in a more significant reduction in their volatile material contents and a higher increase in their fixed carbon contents. A rise in heating value due to an increase in fixed carbon contents and a reduction in volatile material contents has also been reported for *Populus nigra* (poplar), *Fagus sylvatica* (beech), *Pinus sylvestris* (pine), and *Abies pectinata* (fir), indicating that this phenomenon occurs in softwood and hardwood [30].

4.2. Briquette Properties

The density of the materials was not affected by the quality of the raw materials and increased with pressure. Higher densities were observed for the material treated at 200 °C for *Aspidosperma populifolium* (Peroba Mica) and 220 °C for *Mimosa scabrella* (Bragatinga) and *Dipterix odorata* (Cumaru). The degradation of wood components due to temperature reduces the resistance of the raw material, allowing for greater compaction under pressure, reduced void spaces, increased cohesion among particles, and, consequently, higher density [31]. The increased density of briquettes enhances the materials' energy efficiency and durability while reducing transportation costs, making it desirable in the production process [32].

The pressure of 14 MPa increased the density of the briquettes produced with torrefied raw material. An increase in pressure during the production process reduces the volume of briquettes, increasing their density [33]. In materials that do not undergo torrefaction, the particles exhibit higher resistance to compression; thus, an increase in pressure does not manage to increase the density of the briquettes produced [34]. In treated wood, thermal degradation reduces the material's resistance to compression, allowing for high-density values even with a low compaction pressure [35].

The increase in compaction pressure during the production process enhanced the briquettes' compression resistance and reduced the return rate, as this process minimized the number of void spaces and increased interaction between sawdust particles [36,37]. *Mimosa scabrella* wood (Bragatinga) exhibited the lowest compression resistance values and the highest return rate, which can be attributed to poorer material compaction, as evidenced by the lower density of the produced briquettes. The most significant increases in compression resistance with the rise in compaction pressure were observed for *Dipterix odorata* wood (Cumaru), while briquettes made from *Aspidosperma populifolium* wood (Peroba Mica) demonstrated higher compression resistance, irrespective of the thermal treatment temperature and applied pressure.

The expansion of briquettes produced at a pressure of 7 MPa was higher; the low pressure applied hindered material compaction, reducing the interaction between particles, resulting in increased volumes in the final products [38]. This phenomenon is undesirable, as it leads to a higher generation of fines after the process, making the material susceptible to breakage during loading and transportation to the end consumer, thereby reducing its market value or even making its commercialization unfeasible.

The compaction of the material also affected the equilibrium moisture and water adsorption. The use of high pressures resulted in greater material density and a higher amount of dry matter per unit volume. Consequently, the number of hydrophilic sites increased, allowing for greater water adsorption and resulting in higher equilibrium moisture contents in the briquettes [39]. This was confirmed by the lower equilibrium moisture and moisture contents in the briquettes produced from *Mimosa scabrella* wood (Bragatinga), which exhibited lower density values across all levels of thermal treatment and compaction pressure.

5. Conclusions

The species *Mimosa scabrella* (Bragatinga), *Aspidosperma populifolium* (Peroba mica), and *Dipterix odorata* (Cumaru) showed potential for briquette production. The biomasses' torrefaction before the briquette production process improved their quality, reducing their equilibrium moisture contents by 12.8% to 26.8% and increasing their calorific values and fixed carbon contents by 1.8% to 6% and 15% to 27%, respectively, when a temperature of 220 °C was applied. The compaction pressure affected briquette quality; an increase in compaction pressure resulted in a higher density, compressive strength, equilibrium moisture content, and water adsorption, while it reduced the expansion and diameter return rate. The choice of species and production process should be made together, considering the eventual briquettes' final use. Based on the density and strength of the briquettes, we recommend producing briquettes with 14 MPa pressure and torrefaction at 200 °C for *Aspidosperma populifolium* (Peroba Mica) and *Dipteryx odorata* (Cumaru). For *Mimosa scabrella* (Bragatinga), we recommend using the material without torrefaction and pressing it at 14 MPa. The production of briquettes from these species is an important alternative for generating renewable energy through the processing of residues derived from sustainable management plans for tropical forests.

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References

1. Jeffry, L.; Ong, M.Y.; Nomanbhay, S.; Mofijur, M.; Mubashir, M.; Show, P.L. Greenhouse Gases Utilization: A Review. *Fuel* **2021**, *301*, 121017. [CrossRef]
2. Romero, J.P.; Gramkow, C. Economic Complexity and Greenhouse Gas Emissions. *World Dev.* **2021**, *139*, 105317. [CrossRef]
3. Olabi, A.G.; Abdelkareem, M.A. Renewable Energy and Climate Change. *Renew. Sustain. Energy Rev.* **2022**, *158*, 112111. [CrossRef]
4. Cutz, L.; Haro, P.; Santana, D.; Johnsson, F. Assessment of Biomass Energy Sources and Technologies: The Case of Central America. *Renew. Sustain. Energy Rev.* **2016**, *58*, 1411–1431. [CrossRef]
5. Tun, M.M.; Juchelkova, D.; Win, M.M.; Thu, A.M.; Puchor, T. Biomass Energy: An Overview of Biomass Sources, Energy Potential, and Management in Southeast Asian Countries. *Resources* **2019**, *8*, 81. [CrossRef]
6. Nunes, L.J.R.; Causer, T.P.; Ciolkosz, D. Biomass for Energy: A Review on Supply Chain Management Models. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109658. [CrossRef]
7. Ferreira da Silva, E.; Fernandes da Silva, G.; Orfanó Figueiredo, E.; Ribeiro de Mendonça, A.; Junio de Oliveira Santana, C.; César Fiedler, N.; Pereira Martins Silva, J.; Otone Aguiar, M.; Silva Santos, J. Optimized Forest Planning: Allocation of Log Storage Yards in the Amazonian Sustainable Forest Management Area. *For. Ecol. Manag.* **2020**, *472*, 118231. [CrossRef]
8. Cardoso, R.M.; Miguel, E.P.; de Souza, H.J.; de Souza, Á.N.; Nascimento, R.G.M. Wood Volume Is Overestimated in the Brazilian Amazon: Why Not Use Generic Volume Prediction Methods in Tropical Forest Management? *J. Environ. Manag.* **2024**, *350*, 119593. [CrossRef]

9. da Silva Luz, E.; Soares, Á.A.V.; Goulart, S.L.; Carvalho, A.G.; Monteiro, T.C.; de Paula Protásio, T. Challenges of the Lumber Production in the Amazon Region: Relation between Sustainability of Sawmills, Process Yield and Logs Quality. *Environ. Dev. Sustain.* **2021**, *23*, 4924–4948. [CrossRef]
10. Seguin, R.; Flax, V.L.; Jagger, P. Barriers and Facilitators to Adoption and Use of Fuel Pellets and Improved Cookstoves in Urban Rwanda. *PLoS ONE* **2019**, *13*, e0203775. [CrossRef]
11. Costa, E.V.S.; Pereira, M.P.d.C.F.; da Silva, C.M.S.; Pereira, B.L.C.; Rocha, M.F.V.; Carneiro, A. de C.O. Torrefied Briquettes of Sugar Cane Bagasse and Eucalyptus. *Rev. Arvore* **2019**, *43*, e430101. [CrossRef]
12. Alizadeh, P.; Tabil, L.G.; Adapa, P.K.; Cree, D.; Mupondwa, E.; Emadi, B. Torrefaction and Densification of Wood Sawdust for Bioenergy Applications. *Fuels* **2022**, *3*, 152–175. [CrossRef]
13. Portilho, G.R.; de Castro, V.R.; Carneiro, A.d.C.O.; Zanuncio, J.C.; Zanuncio, A.J.V.; Surdi, P.G.; Gominho, J.; Araújo, S. de O. Potential of Briquette Produced with Torrefied Agroforestry Biomass to Generate Energy. *Forests* **2020**, *11*, 1272. [CrossRef]
14. Rashedi, A.; Gul, N.; Hussain, M.; Hadi, R.; Khan, N.; Nadeem, S.G.; Khanam, T.; Asyraf, M.R.M.; Kumar, V. Life Cycle Environmental Sustainability and Cumulative Energy Assessment of Biomass Pellets Biofuel Derived from Agroforest Residues. *PLoS ONE* **2022**, *17*, e0275005. [CrossRef]
15. Simonic, M.; Goricanec, D.; Urbancl, D. Impact of Torrefaction on Biomass Properties Depending on Temperature and Operation Time. *Sci. Total Environ.* **2020**, *740*, 140086. [CrossRef]
16. Yang, X.; Zhao, Z.; Zhao, Y.; Xu, L.; Feng, S.; Wang, Z.; Zhang, L.; Shen, B. Effects of Torrefaction Pretreatment on Fuel Quality and Combustion Characteristics of Biomass: A Review. *Fuel* **2024**, *358*, 130314. [CrossRef]
17. Grycova, B.; Pryszcz, A.; Krzack, S.; Klinger, M.; Lestinsky, P. Torrefaction of Biomass Pellets Using the Thermogravimetric Analyser. *Biomass-Convers. Biorefinery* **2020**, *11*, 2837–2842. [CrossRef]
18. Werner, K.; Pommer, L.; Broström, M. Thermal Decomposition of Hemicelluloses. *J. Anal. Appl. Pyrolysis* **2014**, *110*, 130–137. [CrossRef]
19. Ivanovski, M.; Petrovic, A.; Ban, I.; Goricanec, D.; Urbancl, D. Determination of the Kinetics and Thermodynamic Parameters of Lignocellulosic Biomass Subjected to the Torrefaction Process. *Materials* **2021**, *14*, 7877. [CrossRef]
20. Mori, Y.; Suzuki, R.; Yamashita, K.; Katayama, Y.; Kiguchi, M. Influence of Hydrothermal Treatment on Hemicellulose Structure in *Cryptomeria japonica*. *Bioresources* **2023**, *18*, 3254–3266. [CrossRef]
21. Yue, K.; Qian, J.; Wu, P.; Jiao, X.; Lu, D.; Song, X. Experimental Analysis of Thermally-Treated Chinese Poplar Wood with Focus on Structural Application. *Ind. Crops Prod.* **2023**, *197*, 116612. [CrossRef]
22. Rahman, A.; Marufuzzaman, M.; Street, J.; Wooten, J.; Gude, V.G.; Buchanan, R.; Wang, H. A Comprehensive Review on Wood Chip Moisture Content Assessment and Prediction. *Renew. Sustain. Energy Rev.* **2024**, *189*, 113843. [CrossRef]
23. Mészáros, E.; Jakab, E.; Várhegyi, G. TG/MS, Py-GC/MS and THM-GC/MS Study of the Composition and Thermal Behavior of Extractive Components of *Robinia pseudoacacia*. *J. Anal. Appl. Pyrolysis* **2007**, *79*, 61–70. [CrossRef]
24. Kizuka, R.; Ishii, K.; Ochiai, S.; Sato, M.; Yamada, A.; Nishimiya, K. Improvement of Biomass Fuel Properties for Rice Straw Pellets Using Torrefaction and Mixing with Wood Chips. *Waste Biomass Valorization* **2021**, *12*, 3417–3429. [CrossRef]
25. Apaydın Varol, E.; Mutlu, Ü. TGA-FTIR Analysis of Biomass Samples Based on the Thermal Decomposition Behavior of Hemicellulose, Cellulose, and Lignin. *Energies* **2023**, *16*, 3674. [CrossRef]
26. Carnaje, N.P.; Talagon, R.B.; Peralta, J.P.; Shah, K.; Paz-Ferreiro, J. Development and Characterisation of Charcoal Briquettes from Water Hyacinth (Eichhornia Crassipes)-Molasses Blend. *PLoS ONE* **2018**, *13*, e0207135. [CrossRef] [PubMed]
27. Vieira, T.A.S.; Trugilho, P.F.; Carabineiro, S.A.C.; Zanuncio, A.J.V.; Carvalho, A.G.; Branco-Vieira, M. Impact of Chemical Composition on *Eucalyptus* Wood Clones for Sustainable Energy Production. *Forests* **2023**, *14*, 2240. [CrossRef]
28. Shapchenkova, O.; Loskutov, S.; Aniskina, A.; Börcsök, Z.; Pásztory, Z. Thermal Characterization of Wood of Nine European Tree Species: Thermogravimetry and Differential Scanning Calorimetry in an Air Atmosphere. *Eur. J. Wood Wood Prod.* **2022**, *80*, 409–417. [CrossRef]
29. Xu, X.; Pan, R.; Chen, R. Combustion Characteristics, Kinetics, and Thermodynamics of Pine Wood Through Thermogravimetric Analysis. *Appl. Biochem. Biotechnol.* **2021**, *193*, 1427–1446. [CrossRef]
30. Lin, Y.Y.; Chen, W.H.; Colin, B.; Pétrissans, A.; Lopes Quirino, R.; Pétrissans, M. Thermodegradation Characterization of Hardwoods and Softwoods in Torrefaction and Transition Zone between Torrefaction and Pyrolysis. *Fuel* **2022**, *310*, 122281. [CrossRef]
31. Siyal, A.A.; Liu, Y.; Mao, X.; Ali, B.; Husaain, S.; Dai, J.; Zhang, T.; Fu, J.; Liu, G. Characterization and Quality Analysis of Wood Pellets: Effect of Pelletization and Torrefaction Process Variables on Quality of Pellets. *Biomass-Convers. Biorefinery* **2021**, *11*, 2201–2217. [CrossRef]
32. Ibitoye, S.E.; Jen, T.C.; Mahamood, R.M.; Akinlabi, E.T. Densification of Agro-Residues for Sustainable Energy Generation: An Overview. *Bioresour. Bioprocess.* **2021**, *8*, 75. [CrossRef]
33. Li, W.; Wang, M.; Meng, F.; Zhang, Y.; Zhang, B. A Review on the Effects of Pretreatment and Process Parameters on Properties of Pellets. *Energies* **2022**, *15*, 7303. [CrossRef]
34. Waheed, M.A.; Akogun, O.A.; Enweremadu, C.C. An Overview of Torrefied Bioresource Briquettes: Quality-Influencing Parameters, Enhancement through Torrefaction and Applications. *Bioresour. Bioprocess.* **2022**, *9*, 122. [CrossRef] [PubMed]

35. Raju, C.H.A.I.; Prem, K.; Sunil, K.; Srikanth Bhimareddy, K.; Ramya, C. Studies on Densification and Conversion of Wastes as Fuel Briquettes for Power Generation. In Proceedings of the Materials Today: Proceedings; Elsevier Ltd.: Amsterdam, The Netherlands, 2021; Volume 44, pp. 1090–1107.
36. Khlifi, S.; Lajili, M.; Belghith, S.; Mezlini, S.; Tabet, F.; Jeguirim, M. Briquettes Production from Olive Mill Waste under Optimal Temperature and Pressure Conditions: Physico-Chemical and Mechanical Characterizations. *Energies* **2020**, *13*, 1214. [CrossRef]
37. Granado, M.P.P.; Suhogusoff, Y.V.M.; Santos, L.R.O.; Yamaji, F.M.; De Conti, A.C. Effects of Pressure Densification on Strength and Properties of Cassava Waste Briquettes. *Renew. Energy* **2021**, *167*, 306–312. [CrossRef]
38. De Oliveira, P.R.S.; Trugilho, P.F.; De Oliveira, T.J.P. Briquettes of Acai Seeds: Characterization of the Biomass and Influence of the Parameters of Production Temperature and Pressure in the Physical-Mechanical and Energy Quality. *Environ. Sci. Pollut. Res.* **2022**, *29*, 8549–8558. [CrossRef]
39. Obi, O.F.; Pecenka, R. Briquetting of Poplar Wood from Short Rotation Coppice—The Effects of Moisture Content and Hammer Mill Screen Size. *Energies* **2023**, *16*, 1454. [CrossRef]