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Potential of Briquette Produced with Torrefied Agroforestry Biomass to Generate Energy

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Abstract: Agroforestry industries, such as sugar-alcohol, food, and logging, produce large quantities of waste, used to generate energy from direct burning. The application of other processes, such as torrefaction and briquetting, can increase the profits from the use of agro-industrial waste for energy generation. Briquetting is an alternative for using these wastes, allowing the compaction of the biomass, generating a biofuel with high energy density, and which is more homogeneous and easier to store and transport. The objective of this study was to evaluate the physical and chemical properties of four biomass types (wastes from sawed eucalypt and pine wood, coffee pruning wastes, and sugarcane bagasse) torrefied at 300 °C and compacted (briquetting) at pressures of 6.21, 8.27, and 10.34 MPa. The torrefaction increased the fixed carbon content, ash, and calorific value, and reduced the volatile material content and hygroscopic equilibrium moisture of the biomasses. The volatile material content was lower and the fixed carbon higher in the coffee pruning waste, the ash content higher in the sugarcane bagasse, and the calorific value higher in the pine and eucalypt wood. The briquetting and the torrefaction processes increased the biomass bulk density, and the useful calorific value, respectively, and consequently the energy density of the briquettes produced with torrefied raw material under high pressure. The mechanical properties of the briquettes produced with all materials increased with the compaction pressure. Torrefaction and briquetting increased the energy potential of the biomasses evaluated to produce energy from clean technology.

Keywords: agroforestry wastes; biofuel; biomass residues; energy density; heat treatment

1. Introduction

Biomass from urban green wastes and agroforestry industries, such as sugar and ethanol, grass, food, and timber, are sources of renewable and sustainable energy [1–3]. Wastes of bark, straw, sawdust, sugarcane bagasse, and wood shavings are important in tropical countries such as Brazil, and with high commercial value and energy content [4,5]. The lignocellulosic wastes are used mainly for direct combustion, for heating and power generation in boilers [6]. New treatments and technologies, such as torrefaction [7–10] and briquetting improve the efficiency of these materials by reducing their negative aspects, such as size variation, low density, and high moisture content [4].

The briquetting compacts the lignocellulosic biomass wastes reducing their irregular granulometry to geometric solids with a high density and burning potential [11–13]. The briquette can be used to generate heat or steam, reducing the use of natural gas, charcoal and coal, firewood, or other fuels in industrial processes [13,14].

The application of high temperatures makes the use of biomass for energy more feasible [15]. Torrefaction is a partial pyrolysis of the biomass in an environment with oxygen restriction, temperatures from 200 to 300 °C, and atmospheric pressure for short periods, differing from the complete carbonization to produce charcoal [16–18]. Torrefied biomasses are dark brown and this process produces condensable gases rich in organics, and non-condensable ones as CO and CO_2 [19–21]. This increases the relative proportions of carbon and lignin [8–10] and the energy density, and decreases the biomass hygroscopicity and attractiveness to xylophagous organisms [10,22,23].

Biomasses torrefied and converted into briquettes and pellets can reduce the use of fossil fuels in thermal conversion processes such as gasification and energy cogeneration [16]. The torrefied biomass briquettes have a shorter heating time and better combustion, handling, and storage, and can replace coal [16]. In addition, the wastes are generated from industrial processes of other products; therefore, they are purchased at low prices, ensuring the competitiveness and viability of the torrefied briquettes [24].

Brazil is one of the largest producers of wood, coffee, and sugar cane in the world, and generates a large amount of waste, which can be burned or to produce briquettes to generate energy. However, the scarcity of studies reduces the production of torrefied briquettes.

Agro-industrial waste comes from raw materials with different characteristics and suitability for the torrefaction and briquetting process. The objective of this study was to evaluate the physical, chemical, and energetic properties of in natura and torrefied agro-industrial waste, and its use in the production of briquettes.

2. Materials and Methods

2.1. Materials

Wastes of *Eucalyptus* spp. and *Pinus* spp. from sawmill process, *Coffea arabica* pruning; and sugarcane bagasse, without residues of bark, leaves, or roots, were air-dried to a moisture content of, approximately, 20% (dry basis).

2.2. Biomasses Characterization

The biomass samples were ground in a Wiley knife mill with a 2 mm sieve opening, passed through the 40 and 60 mesh sieve, and the energy content of the material retained was evaluated. The granulometry of the sample particles ranged from 0.5 to 2 mm.

The content of volatiles, ash, and carbon fixed on a dry basis [25], and the higher calorific value of the particles [26] were determined in an adiabatic calorimeter pump, model IKA 300.

2.3. Torrefaction Process

The torrefaction process was adapted from previous studies [17–20]. One kilogram of each biomass was oven dried at 103 ± 2 °C until reaching 0% moisture content. Dry biomasses were torrefied in a cylindrical metallic container inside an electric oven (muffle) laboratory in an atmosphere with oxygen scarcity. The container was rotated to distribute the heat homogeneously between the particles during the torrefaction process. The heating rate increase was 1.67 °C per minute until it achieved the final temperature of 300 ± 10 °C, while the biomass remained at this temperature for ten minutes. The torrefication yield was calculated according to the equation: Ty = Mt/Mm, where, Ty = torrefication yield; Mt = mass of torrefied biomass produced; Mm = mass of fresh material used.

2.4. Briquette Production

Five briquettes were made with 17 g of each biomass in a laboratory briquette machine, at a temperature of 120 °C and compaction pressure of 6.21, 8.27, and 10.34 MPa (Figure 1). The pressing period was five minutes, followed by six minutes of cooling in the briquette machine. The process had no additives.

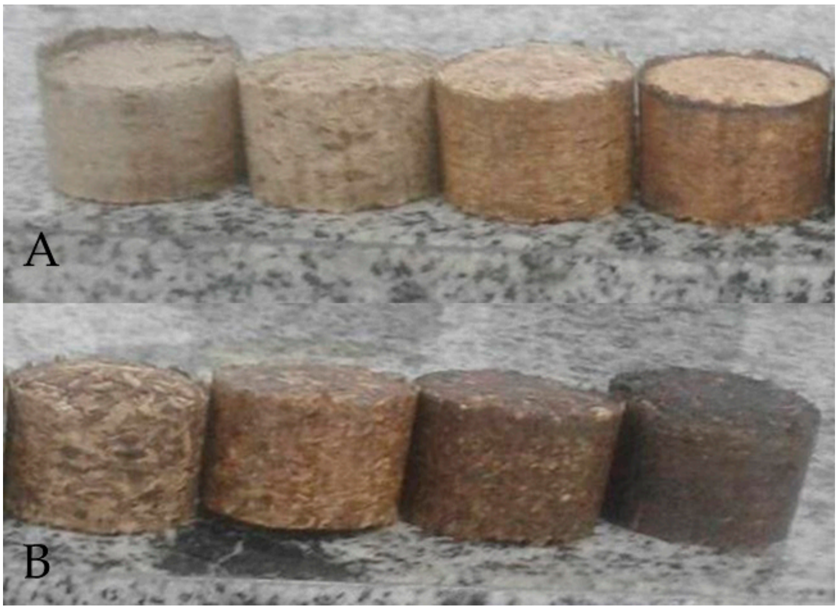

Figure 1. Briquettes produced at 10.34 MPa pressure. (**A**) = Briquettes produced from fresh biomass, left to right: bagasse, coffee, eucalyptus, and pine. (**B**) = Briquettes produced from torrefied biomass, from left to right: coffee, eucalyptus, pine, and sugarcane bagasse.

2.5. Physical and Mechanical Briquette Properties

Ashes and volatile matter were determined according EN 14,775 [27] and EN 15,148 [28], respectively, and the fixed carbon content calculated by subtracting the volatile matter and ash content from 100 (100%-Volatile Matter-Ash), and the calorific value according to EN 14,918 [29].

The moisture content of the briquette samples was calculated in a dry basis; the wood samples were placed in a climatic chamber at 20 °C and 65% relative humidity until a constant mass [30]. The calorific value of the biomass particles was determined with the following equations:

$$\text{UHV} = (\text{LHV} \times (1 - (0.01 \times \text{U}))) \times (600 \times 0.01 \times \%\ \text{moisture}) \quad (1)$$

and

$$\text{LHV} = \text{HHV} - (600 \times 0.09 \times \%\ \text{hydrogen}) \quad (2)$$

where:

HHV: higher calorific value, dry basis, (kcal/kg);
LHV: lower calorific value, dry basis, (kcal/kg);
UHV: useful calorific value, wet basis, (kcal/kg);
U: humidity of the sample on the wet basis (%);
H: hydrogen content considered as 5.99% for the in natura material, and 2.99% for the torrefied one.

Apparent density was determined by the ratio between the sample mass and its volume [31], and the energy density by multiplying the apparent density by the useful calorific value of the briquette.

The resistance to compression was performed in intact briquettes, without cracks, in a universal mechanical test machine, model Losenhausen, by continuously compressing the material at constant speed of 4 mm·min^{-1} until rupture. The briquettes' shape was cylindrical and, for this reason, the force was applied parallel to its longest axis. The data were obtained with the aid of Pavitest software coupled to the equipment.

2.6. Statistical Analysis

The experimental design was completely randomized with four biomasses (wastes of eucalypt and sawed pine logs, coffee, and sugarcane bagasse wastes), five replications, eight treatments, and 40 sample units. The data of the parameters measured were submitted to variance analysis (ANOVA) at the 95% probability by the F test and, when significant, to the Tukey test ($p \leq 0.05$) with the STATISTICA 8.0 software [32].

3. Results

The calorific value of the wastes with different heat treatments was calculated, and overall, the torrefaction process decreased the content of volatile materials in the wastes (Table 1). Torrefaction decreased the volatile materials of the bagasse sugarcane, coffee pruning, and pinus and eucalyptus sawdust wastes by 20.50, 16.06, 13.52, and 12.31%, respectively.

Table 1. Volatile materials, fixed carbon, ash content, calorific value, and torrefaction yield of the sugarcane (SC), *Coffea arabica* (CO), *Eucalyptus* spp. (EU) and *Pinus* spp. (PI) biomasses wastes with different heat treatments.

	Material	SC	CO	EU	PI
Volatile materials (%)	In natura	82.32 bA$^{(0.695)}$	78.07 aA$^{(1.342)}$	86.75 cA$^{(1.272)}$	86.32 cA$^{(1.002)}$
	Torrified	65.42 bB$^{(0.193)}$	65.53 bB$^{(1.168)}$	76.07 bB$^{(1.122)}$	74.65 bB$^{(1.454)}$
Fixed carbon (%)	In natura	12.73 bB$^{(0.705)}$	19.37 aB$^{(1.252)}$	12.93 bB$^{(1.152)}$	13.50 bB$^{(1.037)}$
	Torrified	25.75 bA$^{(0.234)}$	31.12 aA$^{(1.203)}$	23.45 bA$^{(1.457)}$	25.14 bA$^{(1.451)}$
Ash content (%)	In natura	4.95 aB$^{(0.334)}$	2.56 bB$^{(0.091)}$	0.32 cA$^{(0.169)}$	0.18 cA$^{(0.015)}$
	Torrified	8.83 aA$^{(0.409)}$	3.35 bA$^{(0.240)}$	0.48 aA$^{(0.409)}$	0.21 cA$^{(0.006)}$
Calorific value (kJ kg^{-1})	In natura	18,857 dB$^{(224.9)}$	19,799 cB$^{(74.01)}$	20,937 bB$^{(216.1)}$	21,556 aB$^{(59.21)}$
	Torrified	20,966 cA$^{(5.921)}$	20,560 dA$^{(76.97)}$	21,619 bA$^{(14.14)}$	22,033 aA$^{(21.21)}$
Torrefaction yield (%)	Average	80.41 b	76.96 c	87.7 a	87.7 a

Means followed by the same lowercase, per line, or capital, per column, letter do not differ by the Tukey test ($p > 0.05$). The values in parentheses represent the standard deviation.

The torrefaction increased the fixed carbon content of the sugarcane bagasse, coffee pruning waste, eucalyptus and pinus torrefied by 102, 60, 81, and 86%, respectively.

Torrefaction increased the ash content by 78.38, 30.85, 50.00, and 16.67% for sugarcane bagasse, coffee pruning, eucalyptus and pinus wastes, respectively. The ash content was highest in the torrefied sugarcane bagasse, followed by that of the coffee pruning waste, and with the lowest concentrations in the pine and eucalypt sawdust wastes.

The calorific value of all biomasses increased with the torrefaction process, by 11.18, 3.85, 3.25, and 2.21% for the sugarcane bagasse, coffee, eucalyptus and pinus wastes, respectively. The calorific value in the eucalyptus and pine sawdust wastes was highest.

Torrefaction decreased the gravimetric yield of bagasse (76.96%), coffee pruning (80.41%), eucalyptus (87.70%), and pine waste (87.70%). The gravimetric yield of the torrefaction process was directly proportional to the volatile material content.

The briquetting process increased the apparent density with increasing compaction pressure (Table 2). The apparent density of briquettes made with torrefied sugarcane bagasse and pruning coffee wastes were lower than those with pine and eucalyptus wastes. The differences between the apparent density of the briquettes in natura and torrefied of the other biomasses were lower at higher pressures, without interaction between them. The torrefaction process reduced the biomass moisture content to 5.12 and 6.66%, compared to 7.43 and 9.09% for the in natura ones.

The energy density and heat capacity of torrefied biomass briquettes was higher (17.3 to 23.2 MJ·m^{-3}) than that of the in natura ones (16.8 to 21.5 MJ·m^{-3}) (Table 2). The energy density of the briquettes increased with the compaction pressure, without relation to the apparent density (Table 2). The energy density of torrefied briquettes from pinus and eucalyptus residue was higher, regardless of the pressure. The parameter was highest for pinus briquettes produced with 10.34 MPa compaction pressure.

The resistance to compression was higher at a pressure of 10.34 MPa for all biomasses, with a higher value for the briquettes with pine in natura and torrefied. The resistance of the briquettes produced with sugarcane bagasse was lower, regardless of the compaction pressure.

Table 2. Apparent density (g.cm^{-3}), hygroscopic equilibrium moisture (%), useful calorific value (MJ·kg^{-1}), energy density (MJ·m^{-3}), and resistance to compression (N) as a function of pressure (MPa), and the heat treatment effect on briquettes made of sugarcane (SC), *Coffea arabica* (CO), *Eucalyptus* spp. (EU) and *Pinus* spp. (PI).

BI	**In Natura**			**Torrefied**		
	Compaction Pressure (MPa)					
	6.21	8.27	10.34	6.21	8.27	10.34
	Apparent density (g.cm^{-3})					
SC	1.09 bA$^{0.0138}$	1.15 aA$^{0.0052}$	1.15 aA$^{0.0218}$	* 0.99 bC$^{0.0026}$	* 1.03 aC$^{0.0127}$	* 1.06 aC$^{0.0191}$
CO	0.94 bC$^{(0.0161)}$	0.96 bD$^{(0.0106)}$	1.04 aC$^{(0.0262)}$	* 0.90 cD$^{(0.0111)}$	^{ns} 0.98 bD$^{(0.0105)}$	^{ns} 1.05 aC$^{(0.0219)}$
EU	1.03 cB$^{(0.0045)}$	1.06 bC$^{(0.0032)}$	1.11 aB$^{(0.0123)}$	* 1.05 bB$^{(0.0105)}$	^{ns} 1.07 abB$^{(0.0106)}$	^{ns} 1.09 aB$^{(0.0221)}$
PI	1.06 bA$^{(0.0224)}$	1.09 bB$^{(0.0075)}$	1.12 aB$^{(0.0234)}$	* 1.09 bA$^{(0.0059)}$	* 1.12 abA$^{(0.0193)}$	^{ns} 1.14 aA$^{(0.0062)}$
	Hygroscopic equilibrium moisture (%)					
SC	8.86 aA$^{(0.3527)}$	8.71 abA$^{(0.1650)}$	8.43 bB$^{(0.0283)}$	* 5.79 aA$^{(0.0451)}$	* 5,67 aA$^{(0.1320)}$	* 5,89 aA$^{(0.2762)}$
CO	7.69 aB$^{(0.0650)}$	7.43 aB$^{(0.2194)}$	7.43 aC$^{(0.5093)}$	* 5.22 aA$^{(0.1159)}$	* 5.35 aA$^{(0.1401)}$	* 5.21 aA$^{(0.1015)}$
EU	8.81 abA$^{(0.6451)}$	9.07 aA$^{(0.3568)}$	8.48 bB$^{(0.4234)}$	* 6.01 aB$^{(0.2858)}$	* 6.13 aB$^{(0.2686)}$	* 6.25 bB$^{(0.0945)}$
PI	8.99 aA$^{(0.1002)}$	9.04 aA$^{(0.1212)}$	9.09 aA$^{(0.0493)}$	* 6.54 aB$^{(0.0929)}$	* 6.34 bB$^{(0.1504)}$	* 6.66 aB$^{(0.0100)}$
	Briquettes useful calorific value (MJ·kg^{-1})					
SC	15.9 aA$^{(0.0162)}$	15.9 aA$^{(0.0089)}$	15.9 aA$^{(0.0107)}$	* 19.0 aA$^{(0.0032)}$	* 19.1 aA$^{(0.0031)}$	* 19.0 aA$^{(0.0012)}$
CO	16.9 aB$^{(0.0089)}$	16.9 aB$^{(0.0042)}$	16.9 aB$^{(0.0008)}$	* 18.8 aA$^{(0.0016)}$	* 18.7 aA$^{(0.0055)}$	* 18.8 aA$^{(0.0128)}$
EU	17.8 aC$^{(0.0011)}$	17.7 aC$^{(0.0033)}$	17.8 aC$^{(0.0069)}$	* 19.6 aB$^{(0.0029)}$	* 19.6 aB$^{(0.0035)}$	* 19.5 aB$^{(0.0026)}$
PI	18.3 aC$^{(0.0072)}$	18.3 aD$^{(0.0068)}$	18.3 aD$^{(0.0024)}$	* 19.9 aB$^{(0.0030)}$	* 19.9 aB$^{(0.0038)}$	* 19.8 aB$^{(0.0003)}$
	Energy density (MJ·m^{-3})					
SC	18.1 bC$^{(0.2486)}$	19.9 aB$^{(0.0912)}$	19.2 aC$^{(0.3768)}$	* 19.4 cC$^{(0.0508)}$	* 20.2 bC$^{(0.2594)}$	* 20.6 aC$^{(0.3808)}$
CO	17.1 bD$^{(0.2939)}$	16.8 bC$^{(0.1903)}$	17.9 aD$^{(0.4834)}$	* 17.3 cD$^{(0.2189)}$	* 18.7 bD$^{(0.2106)}$	* 20.2 aC$^{(0.4373)}$
EU	18.7 bB$^{(0.0707)}$	19.2 bB$^{(0.0701)}$	20.5 aB$^{(0.2406)}$	* 20.8 bB$^{(0.2174)}$	* 21.6 bB$^{(0.2268)}$	* 22.7 aB$^{(0.4603)}$
PI	19,3 bA$^{(0.4495)}$	20.4 bA$^{(0.1479)}$	21.5 aA$^{(0.4667)}$	* 22.9 bA$^{(0.1235)}$	* 22.4 abA$^{(0.4048)}$	* 23.2 aA$^{(0.1307)}$
	Resistance to compression (N)					
SC	758 aA$^{(147.09)}$	1032 bA$^{(50.869)}$	1245 cA$^{(13.687)}$	* 694 aA$^{(19.404)}$	* 934 bA$^{(60.435)}$	* 1099 cA$^{(44.176)}$
CO	1505 aC$^{(66.112)}$	1775 bC$^{(58.639)}$	2045 cC$^{(111.58)}$	* 1222 aB$^{(148.77)}$	* 1470 bB$^{(57.179)}$	* 1672 cB$^{(47.039)}$
EU	1077 aB$^{(191.44)}$	1300 bB$^{(21.005)}$	1417 cB$^{(168.56)}$	* 1387 aC$^{(117.58)}$	* 1544 bB$^{(9.7673)}$	* 1704 cB$^{(13.652)}$
PI	1699 aD$^{(85.536)}$	1894 bD$^{(27.392)}$	2282 cD$^{(130.08)}$	* 1680 aD$^{(193.26)}$	* 1948 bC$^{(51.842)}$	* 2260 cC$^{(51.676)}$

Means followed by the same capital letter per line, or lowercase letter, per column, do not differ by Tukey test ($p > 0.05$). * Significant and ^{ns} non-significant.

4. Discussion

The decrease in volatile materials of the pruning waste was related to chemical compounds with high oxygen content and weak chemical bonds, such as extractives and holocellulose, with a faster burning and release of large quantities of energy during combustion [17,33]. The hemicelluloses, cellulose, and polar extractives of these biomasses are rich in oxygen and degrade at temperatures lower than those of the lignin and lipophilic extractives [34]. The reduction of these volatile components causes the proportional concentration of fixed carbon, increasing the calorific value of the biomasses and the energetic properties of the briquettes [9,35,36].

The increase in the fixed carbon content of all torrefied biomasses was due to the proportional concentration of lignin during treatment [20,37,38]. Moreover, the lignin remains in the biomass in a larger proportion than the holocellulose and polar extractives, increasing the fixed carbon content, and the energy expenditure during combustion and the burning time [17,25]. The high proportion of fixed carbon in torrefied biomass is due to its proportion of lignin with high thermal stability [20,28]. Chemical changes in agro-industrial wastes improve their potential for bioenergy, while the quality of the raw material improves them for other purposes, such as biochar [39,40].

The increase of the ash content in all biomasses was, probably, due to the degradation of less stable molecules at low temperatures, such as polar extracts and holocellulose [20]. The higher ash content in the torrefied sugarcane bagasse was probably due to its high silicon dioxide content (83.70%) [41], which can reduce the energy generation and cause the wear of machinery [28]. The high ash content in the sugarcane bagasse agrees with that reported for the grasses *Dendrocalamus brandisii* and *Pennisetum purpureum,* with levels 9.1–11.6% and 10.5% [42] higher than those found in this paper for sugarcane bagasse (8.83%) [43] ash, respectively. The high ash content of the coffee pruning waste was, probably, due to the bark in this biomass, higher by 3.5% compared to the <0.3% in the wood, and may explain the ash content in the briquettes produced with this material [29,44]. The ash content of pine and eucalypt wastes agrees with reports that this parameter is, generally, lower than 1% in these materials [45].

The variable increase in the calorific value of the biomasses was due to their chemical composition, mainly lignin and extractive content, with greater aromatic ring content and, therefore, a greater number of carbon double bonds that released more energy during burning [20]. The greater calorific value of the eucalypt and pine wood is explained by their lower ash content, as each 1% of ash reduced the calorific value of the biomass of *Eucalyptus* spp. in 47.8 Kcal·Kg^{-1} [20].

Lower gravimetric yield of bagasse wastes and coffee pruning wastes was probably due to the greater surface area of their particles, improving contact between them, and distributing thermal energy evenly [8]. The gravimetric yield was directly proportional to the volatile material content of the biomass, and the lower yield of the torrefied biomass compared to in natura was due to the degradation of nitrogen and hydrogen based compounds, such as holocellulose and extracts [46].

The increase in the apparent density with the increase of the compaction pressures was due to the reduction of empty spaces during the compaction, improving the cohesion between the compacted particles [47]. The lower apparent density of coffee pruning wastes and sugarcane bagasse briquettes agreed with results from 0.96 to 1.03 g·cm^{-3} for those made with 26 years old coffee Arabica plant materials [36]. The reduction of the biomass apparent density by the torrefaction process facilitated the pressing [9]. The high density of the torrefied briquettes was due to the non-use of additives, and to the changes in the lignin structure of the biomass torrefied at 300 °C influencing the binding properties of this agent [48]. This is important because the durability and the density of briquettes are directly correlated [39,49].

The reduction of the biomass moisture content by the torrefaction was due to the destruction of hygroscopic components, such as hemicelluloses and cellulose, reducing water adsorption [50]. This reduction decreased the energy necessary to evaporate the water [12,51], which is desirable for energy purposes by increasing the useful calorific value. The torrefaction and briquetting of biomass reduces the transportation cost of briquettes due to the lower mass of water transported and the increase of their useful calorific value [39].

The higher energy density of the briquettes with torrefied biomass was mainly related to their useful calorific value [5,52]. The increase in this parameter was due to the degradation of components with low heating power, such as hemicelluloses, increasing the fixed carbon content and reducing the hygroscopicity [53]. The increase in the energy density of the briquettes with the compaction pressure, in relation to the apparent density, was due to the greater amount of biomass per unit of volume of the briquette [44]. The energy density, or heat quantity per unit volume (Gcal·m^{-3} or Gj·m^{-3}), are important because they allow the evaluation of the performance of the biomass as fuel, summating the physical and chemical characteristics between these parameters [5]. The highest apparent density and the calorific power of the briquettes produced with eucalypt and pine wood wastes explain the highest values of energy density of these biomasses.

The greater resistance to compression of the briquettes produced with a pressure of 10.34 Mpa was due to greater compaction, reducing voids and, consequently, increasing the cohesion between the particles, with an increase in the apparent density and resistance to compression [39]. The greater resistance to compression of in the natura and torrefied pine briquettes was due to their low density, as the particles are subjected to lower resistance during compaction, reducing empty spaces and consequently fissures that decrease the resistance to compression [54]. The lowest resistance values to compression for the briquettes produced with sugarcane bagasse was probably due to their higher ash content, which hindered the cohesion between the particles [55]. Briquettes produced with biomass with a higher lignin content were generally more durable and stable [46]. The maximum breaking load for compressive strength determines the resistance to storage, handling and transport, and is therefore important for the quality of the briquettes [39,56].

Torrefaction altered the chemical composition of the agro-industrial waste, improving its quality for power generation, with an emphasis on reducing hygroscopicity and increasing fixed carbon. The raw material represents the main cost to produce briquettes, therefore, the use of low cost waste from renewable sources generates economic and environmental gains. The briquetting of the torrefied material increased the energy density. These two processes combined are important to increase the economic viability of using agro industrial waste for energy generation.

5. Conclusions

Comparing materials without torrefaction, the *Coffea arabica* residue had a higher fixed carbon content, while the *Pinus* spp. residue had a higher calorific value; interesting characteristics for energy use. The non-torrefied briquettes produced with this latter material showed good compaction, resulting in high energy density and resistance to compression. The high fixed carbon and calorific values for the *Coffea arabica* and *Pinus* spp. residues, respectively, are desirable for energy production

The volatile material content was lower and the fixed carbon content higher for briquettes produced with the coffee pruning wastes, and the ash content higher for those with sugarcane bagasse. Torrefaction increased the calorific value and fixed carbon content, and the ash reduced the volatile material content of the biomasses, improving the quality of the raw material for energy generation. The process reduced the hygroscopicity and increased the calorific value of all biomasses. Therefore, torrefaction has potential as a pre-treatment for biomass fuel improvement.

The increase in the compression pressure increased the apparent density of the briquettes. The higher density of the biomass of pine and bagasse was due to their lower compaction resistance. The energy density of the torrefied and compressed briquettes at 10.34 MPa was higher for all biomasses, with higher values for those with *Pinus*. These results indicate its potential as a valuable raw material for biomass supply.

Briquetting and torrefaction are important for allowing the use of agro-industrial wastes to generate energy.

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