

ORIGINAL ARTICLE

Investigating waste generated from logging in the Amazon for energy use

Investigando os resíduos gerados da exploração madeireira na Amazônia para o uso energético

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Abstract

Wood residues can go to waste due to a lack of knowledge of their properties. In order to contribute to the use of materials, the objective was to individually assess the physical and chemical characteristics of Amazonian wood waste. Due to the lack of information about most Amazonian tree species, *Eucalyptus grandis* was defined as a control treatment. The following tests carried out were: granule size, moisture, wood basic density, residuals bulk density, pH, total extractives, lignin, holocellulose, volatile matter, ash, fixed carbon, high and lower heating values and liquid energy density. The evaluated species presented different characteristics for the physical, chemical, and energetic tests of wood residues. In general, the Amazonian species showed superior characteristics in comparison to *Eucalyptus grandis* for energy production. *Qualea paraenses*, *Cedrela* sp., *Dinizia excelsa*, *Ocotea cinerea* and *Buchenavia grandis* need to be further investigated for energy purpose due to the low pH. Based on the data obtained, it would be recommended to adopt pre-treatments as a way to increase the energy performance of biomass.

Keywords: Wood residues destination; Timber waste; Amazonian species; Sawmills.

Resumo

Os resíduos madeireiros podem se tornar rejeitos, devido ao desconhecimento de suas características. Como forma de contribuir para a utilização destes materiais, objetivou-se avaliar individualmente as características físicas e químicas dos resíduos amazônicos. Devido à ausência de informações de grande parte das espécies amazônicas foi definido o *Eucalyptus grandis* como tratamento controle. Os ensaios realizados foram: granulometria, umidade base úmida, densidade básica da madeira, densidade à granel, pH, extrativos totais, lignina, holocelulose, materiais voláteis, cinza, carbono fixo, poder calorífico superior e útil e densidade energética líquida. As espécies avaliadas apresentaram características distintas para os ensaios físicos, químicos e energéticos dos resíduos madeireiros. De maneira geral, as espécies amazônicas apresentaram características superiores em relação ao *Eucalyptus grandis* para produção energética. As espécies *Qualea paraenses*, *Cedrela* sp., *Dinizia excelsa*, *Ocotea cinerea* e *Buchenavia grandis*, devem ser melhor estudadas para a produção energética, devido ao baixo pH. Com base nos dados obtidos, se recomenda a adoção de pré-tratamento, como forma de elevar o desempenho energético da biomassa.

Palavras-chave: Destinação de resíduos madeireiros; Resíduos de madeira; Espécies amazônicas; Serrarias.

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INTRODUCTION

The Brazilian Amazon region is known as one of the main production areas for tropical native wood worldwide (Melo et al., 2019). However, the efficiency and use of sawmill logs located in the Brazilian Amazon are considered low, mainly due to the use of outdated technologies, inadequate machinery operating conditions, and low labor qualification, which are factors that contribute to the greater generation of wood waste (Paixão et al., 2014). There are also factors inherent to the forest, for example: the use of a varied number of log and species diameters, without any adaptation in the sawing process, the ease of obtaining the raw material and the presence of defects in the logs (Melo et al., 2019; Ramos et al., 2018). Therefore, it is essential to ask how science can contribute to the best possible use of wood waste.

Despite all the productive potential, the wood producing areas of the Amazon region face difficulties in determining the proper end use and valorization of the residues generated during the log breakdown and sawing process (Soares et al., 2018). According to the DOF (document of forest origin) report by IBAMA (Brazilian Institute of Environment and Natural Resources) in 2017, approximately 92000 m³ of wood residues were produced in Roraima (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis, 2021). Due to the lack of viable alternatives for Amazon region waste, the environmental licensing processes of sawmills have become time consuming, which contributes to their illegal exploitation (Crivelli et al., 2017). In addition, the energy issue in the Amazon region is the greatest challenge for industrial development (Coelho et al., 2010). In this context, the high availability of wood waste combined with its use for energy production can mitigate the recurrent energy problems in the Amazon regions that produce lumber.

The lack of information on possible uses and the intrinsic difficulties in the utilization of wood residues in the Amazon result in improper storage or open burning. Therefore, Law N°. 12305 was created on August 2, 2010, known as the National Solid Waste Policy (Brasil, 2010), and Normative Instruction N°. 002/2016 of the State Foundation for the Environment and Water Resources (FEMARH) (Boa Vista, 2016). These prohibit the inadequate storage and burning of wood residues in the open, “even if this practice is part of the environmental studies that guided environmental licensing”. In this sense, wood residues have become hurdles for businessmen in the wood sector, due to licensing restrictions, notices, and fines from environmental agencies.

Thus, there is a context of legal obligations for the use of wood waste and, consequently, an abundance of opportunities for studies for the characterization of the material. The objective was to conduct studies of wood waste characterization from Amazonian species with the prospect of energy generation as a first and important technical step to be taken in relation to the theme.

MATERIAL AND METHODS

Waste collections were carried out during primary and secondary log splitting (diameter > 50 cm and length of 6 m) at sawmills at the Rorainópolis wood pole, Roraima, Brazil, located at 0°56'44" N and 60°25'6" W. The residues were collected from eight different sawmills that used similar types of machinery. All sawmills were made up of a single band saw for the primary split and multiple and simple circular saws (cutters) for the secondary split in order to establish the width and length of the boards, respectively.

The wood residue collection for each species was carried out using three different tree logs. Throughout the log sawing process, the residues were collected separately by log and species (Table 1) in polypropylene bags directly from the conveyors, that is, without contact with the ground. The set made up of wood shavings, sawdust, and dust in this study is called the Fine Residues of Log Breakdown by Sawing Processes (FRLBS).

Table 1. Amazonian species with their respective vernacular names and collection locations.

Species	Vernacular names	Collection locations
<i>Manilkara huberi</i> (Ducke) A. Chev	maçaranduba	Sawmill 1
<i>Bagassa guianensis</i> Aubl.	tatajuba	Sawmill 1
<i>Andira inermis</i> (W.Wright) DC.	andira	Sawmill 1
<i>Cedrela</i> sp.	cedro – doce	Sawmill 2
<i>Caryocar villosum</i> (Abul.) Pers.	pequiá	Sawmill 2
<i>Hymenaea</i> sp.	jatobá	Sawmill 2
<i>Handroanthus</i> sp.	ipê amarelo	Sawmill 2
<i>Cariniana micrantha</i> Ducke	cachimbeiro	Sawmill 3
<i>Ocotea cinerea</i> van der Werff	louro preto	Sawmill 3
<i>Buchenavia grandis</i> Ducke	tanibuca	Sawmill 4
<i>Qualea paraensis</i> Ducke	rabo de arraia	Sawmill 4
<i>Dinizia excelsa</i> Ducke	angelim – ferro	Sawmill 5
<i>Vatairea guianensis</i> Aubl.	amargoso	Sawmill 6
<i>Iryanthera</i> sp.	ucuúba	Sawmill 7
<i>Hymenolobium excelsum</i> Ducke	angelim – pedra	Sawmill 8

Three logs were sampled by species, homogenized individually using a concrete mixer, of which three samples of 200 grams were stored separately, taken prior to drying for the first analysis of the wood. The rest of the FRLBS was dried in an oven at a temperature of $103 \pm 3^\circ\text{C}$ until constant weight. The purpose was to reduce the risk of microbial contamination, and this was an essential condition for the transport of the material to the University of São Paulo, Piracicaba, SP, Brazil, where the analyses were carried out. In addition to this material, 20 samples were collected at the sawmills; 10 in the radial direction and 10 longitudinally from the split logs, in order to estimate the wood basic density.

Eucalyptus grandis Hill ex Maiden was used as a reference sample and comparative standard, due to the vast studies and thorough research conducted across the world. The *Eucalyptus grandis* wood came from commercial plantations of three trees, aged seven years, located in the municipality of Barra do Chápeu, SP, at coordinates $24^\circ 30' 57.2''$ S and $48^\circ 59' 59.2''$ W.

The granule size analysis of the FRLBS was performed by the screening method, according to the standard NBR 7217 (Associação Brasileira de Normas Técnicas, 1987), using different mesh sieves, 4 mm, 0.600 mm, 0.425 mm, 0.250 mm, and <0.250 mm (base), respectively. The determination of the wet base moisture of the FRLBS was performed using the gravimetric method NBR 7190 (Associação Brasileira de Normas Técnicas, 1997).

The determination of the wood basic density was performed by the hydrostatic balance method, according to the standard NBR 11941 (Associação Brasileira de Normas Técnicas, 2003). For classification of basic wood densities by species, the mean from the pieces of logs was considered, applying the following scale (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis, 2021): low (0.310 g.cm^{-3} to 0.500 g.cm^{-3}), medium (0.501 g.cm^{-3} to 0.720 g.cm^{-3}), and high (above 0.721 g.cm^{-3}). For the determination of wood residue bulk densities, a 100 mL beaker was slowly filled with FRLBS at equilibrium moisture up to the edge of the beaker, and then a scale was used to remove excess. The use of the beaker was an adaptation of the standard NBR 6922 (Associação Brasileira de Normas Técnicas, 1981).

To determine the wood pH, the equivalent of 1 gram of absolutely dry FRLBS was placed in a 200 mL Erlenmeyer filled with 100 mL of distilled water. The mixture was heated in a water bath at 100°C for 60 minutes. After natural cooling, the pH meter was read, and the result was classified as: strongly acidic (0.00 to 3.50); weakly acidic (3.51 to 6.50); neutral (6.51 to 7.50), weakly alkaline (7.51 to 10.50) and strongly alkaline (10.51 to 14.00), according to the international pH scale.

The procedures used to quantify the total extractives and lignin were TAPPI T 204 cm-97 and TAPPI 222 os-74, respectively; and holocellulose was calculated by the total sum of the percentages of lignin and total extractives from 100% (Technical Association of the Pulp and Paper Industry, 2006, 2007). The immediate chemical analysis of waste *in natura* was carried out according to the standard NBR 8112 (Associação Brasileira de Normas Técnicas, 1984a).

The high heating value (HHV) was determined in a calorimeter (PARR 1201, Parr Instrument Company, Moline, IL, USA), according to the standard NBR 8633 (Associação Brasileira de Normas Técnicas, 1984b). The lower heating value (LHV) of the wood was calculated according to equation 1 (Ferreira et al., 2014). The net energy density was calculated by multiplying the bulk density and lower heating value.

$$LHV = (HHV - 324) - (1 - (\%moisture * 0.01)) \times (6 \times \%moisture) \quad (\text{Equation 1})$$

Where: LHV= lower heating value, also known as net calorific value (MJ.kg⁻¹). HHV = high heating value (MJ.kg⁻¹).

The data obtained were processed and analyzed using a database constructed in the program Excel®. A completely randomized design of sixteen species was used (15 Amazonian species + *Eucalyptus grandis*), constituting the dependent variables, and triplicates for each investigated variable. It is noteworthy that the averages presented in the last row of each Table 2 and 3 do not consider the values obtained from *Eucalyptus grandis*.

RESULTS AND DISCUSSION

The granule analysis (Table 2) presented low percentage of granules in the upper fraction (> 4.000 mm), and this result can be attributed to the absence of sawmill processing units. In other words, the processing units are attained by wood machining, a process subsequent to the splitting. This is carried out by planers and thickening machines, which produce residues larger than 2.5 mm, called shavings, and consequently, these result in an increase in the percentage of granules in the higher fractions.

Table 2. Average particle size distribution of wood waste produced by sawmills in the Amazon Area.

SPECIES	percentage retained on the sieve				
	> 4.000 mm	4.000 mm - 0.600 mm	0.600 mm - 0.425 mm	0.425 mm - 0.250 mm	< 0.250 mm
<i>Manilkara huberi</i>	1.7 (1.7)	17.5 (4.7)	29.6 (8.1)	29.6 (6.5)	21.6 (5.5)
<i>Bagassa guianensis</i>	0.1 (0.1)	44.3 (2.6)	25.9 (0.9)	18.9 (0.3)	10.7 (3.1)
<i>Andira inermis</i>	0.6 (0.1)	48.6 (6.4)	30.0 (2.8)	16.3 (1.9)	5.0 (2.3)
<i>Cedrela</i> sp.	0.3 (0.2)	69.1 (6.6)	16.2 (3.3)	8.9 (2.3)	5.5 (1.0)
<i>Caryocar villosum</i>	0.1 (0.1)	50.7 (10.8)	23.5 (4.9)	15.7 (5.0)	9.9 (1.0)
<i>Hymenaea</i> sp.	1.3 (0.7)	43.6 (11.1)	19.8 (4.8)	15.0 (5.2)	20.3 (0.5)
<i>Handroanthus</i> sp.	1.5 (1.6)	25.4 (9.7)	27.9 (2.6)	24.9 (8.1)	20.4 (3.4)
<i>Cariniana micrantha</i>	1.0 (0.4)	54.4 (3.4)	16.5 (1.5)	17.6 (1.7)	10.4 (2.7)
<i>Ocotea cinerea</i>	0.5 (0.4)	62.7 (8.7)	18.0 (3.9)	10.9 (3.5)	7.8 (1.1)
<i>Buchenavia grandis</i>	1.7 (0.1)	39.7 (7.0)	23.1 (0.8)	20.2 (3.7)	15.3 (2.8)
<i>Qualea paraensis</i>	0.3 (0.1)	43.8 (24.6)	31.9 (12.6)	13.3 (9.4)	10.7 (3.4)
<i>Dinizia excelsa</i>	0.2 (0.1)	26.1 (4.7)	25.5 (0.1)	26.4 (2.7)	21.8 (2.1)
<i>Vatairea guianensis</i>	2.1 (0.2)	66.0 (1.0)	21.4 (1.5)	8.4 (0.4)	2.1 (0.1)
<i>Iryanthera</i> sp.	0.4 (0.2)	78.6 (11.2)	14.1 (7.0)	5.2 (2.7)	1.7 (1.4)
<i>Hymenolobium excelsum</i>	0.3 (0.2)	21.0 (2.6)	39.1 (2.6)	33.1 (2.8)	6.4 (2.1)
\bar{X}	0.8	46.1	24.2	17.6	11.3

\bar{X} : General average of tests for Amazonian species.

The largest amounts of dust were produced by *Dinizia excelsa*, *Manilkara huberi* e *Handroanthus* sp., 21.8%, 21.6% and 20.4% respectively. Compared to softer woods, it is known that species considered hard, of high density, have greater resistance to penetration to the saw teeth, and consequently, produce a greater proportion of dust lower than 0.250 mm (Cassilha et al., 2004), when compared to softwoods. *Dinizia excelsa*, *Manilkara huberi* and *Handroanthus* sp. offered resistance to penetration of 14,318 N (Instituto de Pesquisas Tecnológicas, 2017a) and 9,611 N (Instituto de Pesquisas Tecnológicas, 2017b) e 10,807 N (Instituto de Pesquisas Tecnológicas, 2017c), respectively, and they are classified as hardwoods (> 8,006 N), according to the classification suggested by Tom & Peter Flooring Inc (2021). *Vatairea guianensis* presented a value of 6,816 N (Instituto de Pesquisas Tecnológicas, 2017d), had a medium hardness wood (5,338 N to 8,006 N), and the highest concentration of granules in the upper fractions. According to the wood residues classification suggested by Cassilha et al. (2004), the predominance of fractions less than 4.000 mm up to 0.600 mm and less than 0.600 mm up to 0.425 mm is noted. These comprised approximately 70% of the total value, and they mostly represent sawdust (2.500 mm to 0.500 mm). It is worth mentioning that the granule size of the residues affects the conversion rate during the burning. In smaller fractions, there is a reduction of empty spaces for oxygen penetration, due to the compaction in the combustion chamber, which reduces the energy conversion efficiency, but the reverse occurs for the larger fractions (Haberle et al., 2018).

The lowest moisture contents (Table 3) were below 30%, obtained from *Handroanthus* sp., *Manilkara huberi* and *Cariniana micrantha*. The reason for the lower moisture observed for the *Handroanthus* sp. and *Manilkara huberi* species is related to the log storage time in the yard. Normally, species with high economic value are sold in large lots, requiring the storage of the logs. In addition, it is noted that the collections were carried out in November, a month of low rainfall in the municipality of Rorainópolis.

Table 3. Moisture content on wet weight base e pH and rating of residues of Amazonian species and *Eucalyptus grandis*.

SPECIES	MCW (%)	pH	pH rating
<i>Manilkara huberi</i>	28.31 (3.93)	5.26 (0.07)	Weakly acid
<i>Bagassa guianensis</i>	38.16 (5.54)	6.45 (0.23)	Weakly acid
<i>Andira inermis</i>	49.12 (1.01)	6.74 (0.04)	Neutral
<i>Cedrela</i> sp.	34.98 (0.83)	4.71 (0.13)	Weakly acid
<i>Caryocar villosum</i>	43.75 (1.45)	6.15 (0.06)	Weakly acid
<i>Hymenaea</i> sp.	34.07 (2.70)	5.37 (0.13)	Weakly acid
<i>Handroanthus</i> sp.	18.90 (2.39)	5.47 (0.19)	Weakly acid
<i>Cariniana micrantha</i>	29.97 (2.82)	5.67 (0.09)	Weakly acid
<i>Ocotea cinerea</i>	50.05 (1.04)	4.48 (0.13)	Weakly acid
<i>Buchenavia grandis</i>	32.15 (2.53)	4.31 (0.06)	Weakly acid
<i>Qualea paraensis</i>	39.20 (2.54)	4.72 (0.18)	Weakly acid
<i>Dinizia excelsa</i>	32.15 (6.48)	4.66 (0.06)	Weakly acid
<i>Vatairea guianensis</i>	44.38 (5.47)	5.08 (0.03)	Weakly acid
<i>Iryanthera</i> sp.	49.51 (3.23)	5.73 (0.09)	Weakly acid
<i>Hymenolobium excelsum</i>	48.18 (0.58)	6.77 (0.04)	Neutral
<i>Eucalyptus grandis</i>	34.93 (0.72)	5.28 (0.02)	Weakly acid
\bar{X}	38.19	5.44	

\bar{X} : General average of tests for Amazonian species. MCW: Moisture content on wet weight base. pH: Hydrogen potential.

As for energy, it can be observed that all species should be subjected to drying in order to increase the energy conversion efficiency of waste. This can be achieved through solar drying with a cover (rainy season in the region) or by longer storage of residues in the dry season. Moisture content causes a reduction in energy conversion, due to the loss of energy to evaporate the water contained in the wood. In addition, it is known that high moisture content values reduce both the temperature of the gases generated and the pressure at the combustion chamber exit, which consequently favors the formation of soot crusts inside the combustion chamber and in the chimneys (Dzurenda & Banski, 2017). These problems can impair the equipment performance during biomass combustion for energy purposes.

In Table 3, the pH ranged from 4.31 (*Buchenavia grandis*) to 6.77 (*Hymenolobium excelsum*), considered to be of low acidity and neutral, respectively. The species considered neutral were *Hymenolobium excelsum* (6.77) and *Andira inermis* (6.74), and the other species were considered of low acidity, including *Eucalyptus grandis*. Iwakiri et al. (2015) claimed that the wood pH is between 3.00 and 5.50; however, values above the reported range were observed. The difference between the intervals obtained and the literature can be explained by the lack of standardization and, consequently, the adoption of different methods.

Measuring the pH and the amount of contaminants present in the biomass are important for energy production, due to their influence on boiler corrosion processes (Cotton, 2000). During operation, the boiler tubes form protective layers to resist corrosion, consisting mainly of magnetite (Namduri & Nasrazadani, 2008). However, magnetite at 310°C becomes unstable and soluble at pH below 5 and above 12, making the tubes vulnerable to corrosion (American Society for Metals, 1990). According to Table 3, *Qualea paraenses*, *Cedrela* sp., *Dinizia excelsa*, *Ocotea cinerea* and *Buchenavia grandis* species have lower pH than recommended, however it is worth analyzing the pH of the gases generated by the combustion of these species residues.

The highest averages for wood basic density were observed in the *Dinizia excelsa* (877.2 g.cm⁻³) and *Hymenaea* sp. (856.2 g.cm⁻³) species, both classified as high density. The lowest basic densities were measured for *Cedrela* sp. (407.3 g.cm⁻³) and *Eucalyptus grandis* (452.6 g.cm⁻³), classified as being of low density (Figure 1). In the literature, the wood basic density for *Dinizia excelsa*, *Hymenaea* sp. and *Cedrela* sp. varied between 830.0 g.cm⁻³ to 880.0 g.cm⁻³ and 380.0 g.cm⁻³ to 431.0 g.cm⁻³, respectively (Nascimento et al., 2016; Quirino et al., 2004; Araújo 2007; Valério et al., 2009). It is observed that the mentioned intervals include the values observed in this study.

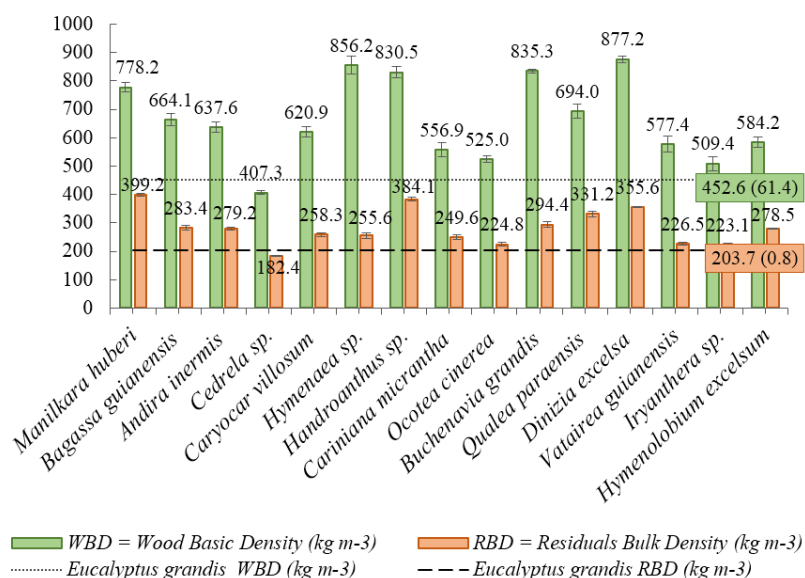


Figure 1. Average values obtained for wood basic density and bulk density of wood waste produced by sawmills in the Amazon Area and *Eucalyptus grandis*.

The species with the highest residue bulk density (RBD) was *Manilkara huberi* and the lowest were observed for *Cedrela* sp. and *Eucalyptus grandis*, which varied from 399.2 kg.m⁻³ to 182.4 kg.m⁻³ (Figure 1). The residuals' bulk density (RBD) results differ from those obtained by Pinheiro et al. (2005) at 150.00 kg.m⁻³ (*Vochysia* sp.) and 200.00 kg.m⁻³ (*Couratari* sp.), that were both obtained at 12% humidity. It is noted that different species, moisture, wood density, and granule size may have influenced RBD.

Bulk density represents the amount of material considering as empty space. At constant volume, this characteristic is strongly associated with the granule size of the waste. It is important to note that the higher the bulk density results in greater the amount of material for energy conversion. However, according to Obernberger and Thek (2004), low bulk density values result in increased transportation and storage costs.

Based on Figure 2, it can be seen that only *Qualea paraensis* (4.5%) and *Cariniana micranta* (4.7%) had a total extractive content of less than 5%. The species that presented the highest extractive content was *Vatairea guianensis* (21.7%), approximately seventeen times higher than *Eucalyptus grandis* (1.3%). In the literature, the values of total extractives of Amazonian species vary from 0.6% to 20.1% for *Pouteria pachycarpa* (abiurana) and *Dipteryx odorata* (cumaru), respectively (Santana & Okino, 2007; Zau et al., 2014), and this interval contains all the species studied with the exception of *Vatairea guianensis*. Despite the high value obtained by *Vatairea guianensis*, Bowyer et al. (2003) explain that the total extraction of wood can reach 30% of the wood dry weight.

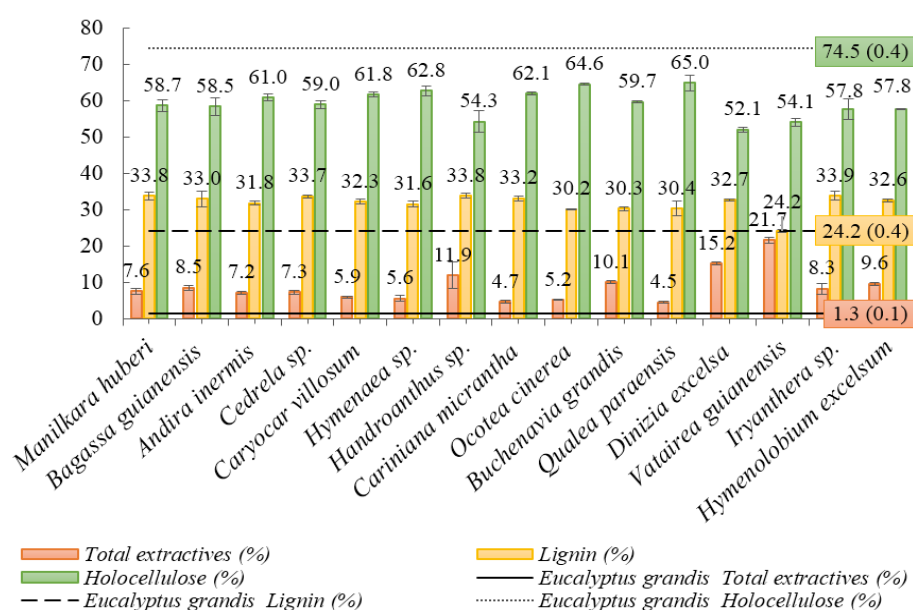


Figure 2. Average values obtained for total extractives, lignin and holocellulose of wood residues produced by sawmills in the Amazon Area and *Eucalyptus grandis*.

For energy use, high percentages of extractives present in the wood can contribute to the corrosion of the equipment used in the energy conversion of biomass (Sarto & Sansigolo, 2010), mainly due to the acidic nature of some woods (Table 3). As a result, there may be an increased need for maintenance and replacement of parts, resulting in an increase in the energy production costs. The higher presence of volatile matters also implies in a non-constant supply of combustion chambers, since they are more easily released during thermal degradation.

It can be seen in Figure 2 that the percentages of lignin for Amazonian species ranged from 24.2% (*Vatairea guianensis*) to 33.9% (*Handroanthus* sp.). In the literature, the lignin values of Amazonian species vary from 26.0% to 34.3% for breu-branco (*Dacryodes* sp.) and cumaru (*Dipteryx odorata*), respectively (Santana & Okino, 2007; Zau et al., 2014), and this interval

encompasses all species studied in this work, except for *Vatairea guianensis*. According to Klock et al. (2006) and Castro et al. (2015), lignin can vary from 20% to 35% of the wood's dry weight, and this interval includes all presently evaluated species.

Species with high lignin values above 30% usually result in a longer burning time in the combustion chamber, facilitating control and, consequently, increasing the process performance (Brand, 2010; Dorez et al., 2014). This can be attributed to the higher thermal resistance of lignin when compared to holocellulose, and this is caused by the difference in the percentage of fixed carbon, 65% and 45%, respectively (Pereira et al., 2000). Therefore, the other Amazonian species have lignin levels above 30% with the exception of *Vatairea guianensis*.

The highest holocellulose values among the Amazonian species were observed for *Qualea paraensis* (65.0%) and *Ocotea cinerea* (64.6%), respectively. However, *Qualea paraensis* and *Ocotea cinerea* showed lower values than *Eucalyptus grandis* (Figure 2). In the literature, the holocellulose values of Amazonian species vary from 58.3% to 72.3% for cumaru (*Dipteryx Odorata*) and breu-branco (*Dacryodes* sp.), respectively (Santana & Okino, 2007; Zau et al., 2014), and this interval represents all presently studied species except for *Vatairea guianensis*. This behavior from *Vatairea guianensis* was expected, mainly due to the values obtained for extractives and lignin. As for energy use, according to Santos et al. (2013), cellulose and hemicellulose have lower calorific values when compared to lignin; however, holocellulose is important mainly due to its higher percentage in wood.

The highest values obtained for volatile matter (VM) were obtained in *Caryocar villosum* and *Eucalyptus grandis* (Figure 3). The MV values of Amazonian species ranged from 76.6% to 84.0%, and in the literature, values between 78.1% (*Dinizia excelsa*) and 83.0% (*Caryocar villosum*), respectively, were found for *Hymenolobium petraeum* (Cruz et al., 2016) and *Dalbergia* sp. (Dias et al., 2019), which are both Amazonian species. Note that only *Dinizia excelsa* does not belong to the range mentioned above. It is known that volatile matter when burned is mainly composed of gases (hydrogen, CO e CO₂) and hydrocarbons, among others, and these result from the plant physiological reactions in response to edaphic-climatic conditions, which can explain the behavior of *Dinizia excelsa*.

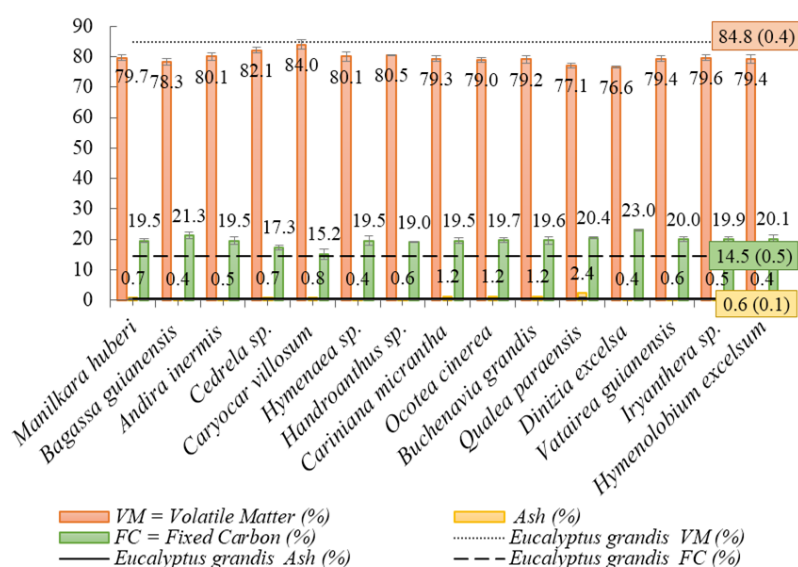


Figure 3. Average values obtained for volatile matter, ash and fixed carbon of residues produced by sawmills in the Amazon Area and *Eucalyptus grandis*.

For energy use, according to Lins et al. (2020), species that have high values of volatile matter are easier to ignite. With this information, species with high values of volatile matter could, for example, be used to start burning biomass in a combustion chamber.

Of the fifteen species studied, ten were below 0.8% for ash (Figure 3), as well as *Eucalyptus grandis*, a species commonly used for energy plantations (Couto et al., 2013). In this study, ash ranged from 0.4% (*Bagassa guianensis*, *Hymenaea* sp., *Dinizia excelsa* and *Hymenolobium excelsum*) to 2.4% (*Qualea paraensis*). In the literature, ash values between 0.1% and 2.0% were found, respectively, for *Bixa arborea* (Moutinho et al., 2016) and *Dalbergia* sp. (Dias et al., 2019); and these are both Amazonian species.

Ash represents the inorganic material present in the wood, and this value represents the amount of material produced at the end of combustion. Ashes are materials that delay the formation of flames, and their accumulation results in incrustations and thickening of the boiler internal wall. This negatively influences the energy conversion rate, making maintenance essential for the removal of this material and, consequently, increasing the production cost (Chen et al., 2016). It is noted that the main species deployed in Rorainópolis, 83% of the total produced (Crivelli et al., 2017), had an ash content below 0.8%.

When considering the latent need for energy production in the interior regions of the Amazon and the available volume of wood waste produced and stored in the piles, the low ash values measured in most species contributes to the reduction of the amount spent for energy production. This may be explained by the lower need to interrupt the combustion process to remove ash from the boilers. Brand (2010) adds that ash is considered abrasive and with continuous use can cause corrosion of metallic equipment.

In Figure 3, it can be seen that the highest values of fixed carbon (FC) content were obtained from *Dinizia excelsa* (23.0%) and *Bagassa guianensis* (21.3%). It is noted that *Eucalyptus grandis* presented the lowest value observed for FC, which was indistinguishable from *Caryocar villosum*. The observed FC values were between 15.2% (*Caryocar villosum*) and 23.0% (*Dinizia excelsa*) for the Amazonian species. In the literature, the observed range was 9.1% to 21.6% of fixed carbon content, respectively, for *Copaifera* sp. and *Brosimum rubescens* (Trugilho et al., 1991), which are both Amazonian species. Note that the range obtained in the literature represents all the species analyzed with the exception of *Dinizia excelsa*. The explanation for the discrepancy which occurred in *Dinizia excelsa* may be attributed to the variation of the fixed carbon, based on the age of the individual.

High values of fixed carbon are desirable for biomasses for energy use. The high fixed carbon contributes to the slower burning of biomass. This reduces the constant refueling and helps preventing the formation of flames, which can be a problem depending on the use (Santos et al., 2019).

The high heating value, shown in Figure 4, ranged from 18.13 MJ.kg⁻¹ (*Bagassa guianensis*) to 20.74 MJ.kg⁻¹ (*Handroanthus* sp.). The high heating value (HHV) of Amazonian species in the literature ranged from 20.58 MJ.kg⁻¹ to 20.70 MJ.kg⁻¹ for *Ormosia paraensis* (Barros et al., 2009) and *Ocotea* sp. (Silva et al., 2014), respectively. In the study by Quirino et al. (2004), the Brazilian species *Buchenavia* and *Parapiptadenia* presented HHV values between 16.09 MJ.kg⁻¹ and 22.36 MJ.kg⁻¹, respectively. The values found in the literature are in the range obtained for all analyzed Amazonian species.

Increased high heating values are desirable for energy production, since this represents the maximum amount of heat released in combustion of a wood mass. However, it is noteworthy that, in addition to the HHV, the species must have a favorable potential for biomass production. Of the fifteen Amazonian species, only *Handroanthus* sp. and *Manilkara huberi* obtained values greater than 20.50 MJ.kg⁻¹ (Figure 4) for the lower heating value (LHV) and 5000 MJ m⁻³ (Figure 5) for the net energy density. These results can be explained by the negative effect of moisture on the LHV, since part of the energy produced is demanded in the drying of the material. Agreeing with previous studies; the species *Handroanthus* sp. and *Manilkara huberi* presented the lowest moisture contents in the study (Table 3).

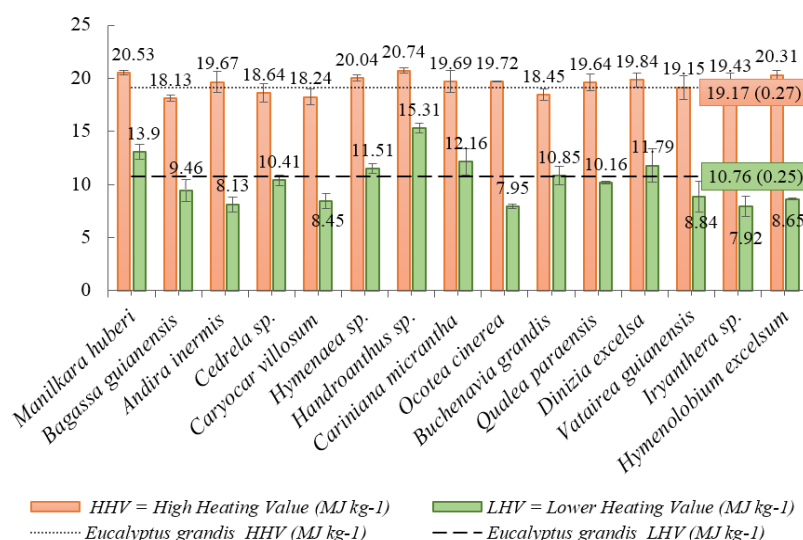


Figure 4. Average values obtained for high and lower heating value of residues produced by sawmills in the Amazon Area and *Eucalyptus grandis*.

Based on the lower heating values obtained for the material net energy density (Figure 5), it is essential to adopt methods that aim to reduce the residue moisture content. The purpose is to maximize the energetic potential of these species, mainly for the rainy season in the Amazon. It is suggested that studies be carried out to evaluate residue solar drying under a cover (rainy season in the region) or longer storage time in the dry season.

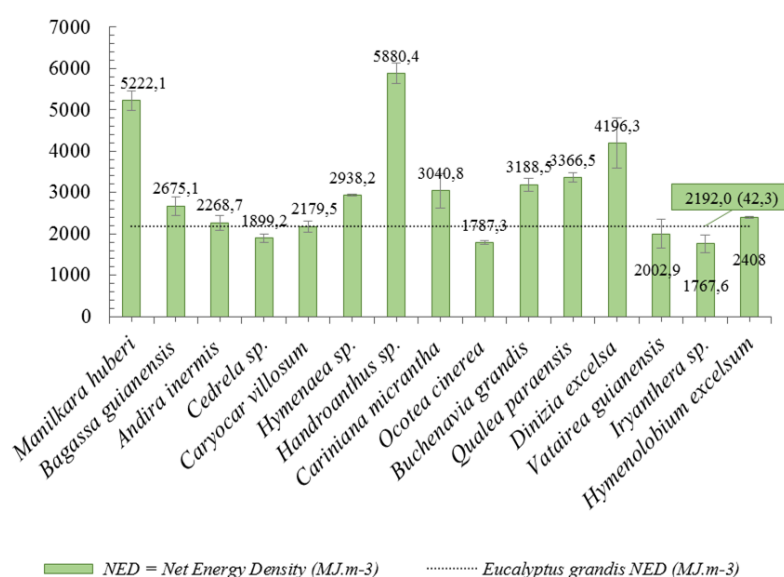


Figure 5. Average values obtained for net energy density of residues produced by sawmills in the Amazon Area and *Eucalyptus grandis*.

Diesel plants are commonly used in the interior of the Amazon region to generate energy for industries and homes; however, the biomass can be promising, whether *in natura* or mechanically transformed (pellet or briquette), considering the characteristics analyzed. Damasceno et al. (2017) reported that the cost of kilowatt-hours (kWh) generated by biomass plant is lower than that of the diesel plant. For each 1 kWh produced with the use of biomass, 1.02 kg of carbon equivalent is emitted to the atmosphere, and this value is lower than those of diesel thermo-electric plants; this should be considered in carbon emissions of the biomass

life cycle. The same authors reported that biomass plants must prevent the retention of and reduce particulate material and control dioxin and furan emissions.

CONCLUSIONS

The evaluated species presented different characteristics for the physical, chemical, and energetic tests of wood residues. In general, the Amazonian species showed superior characteristics in comparison to *Eucalyptus grandis* for energy production. *Qualea paraenses*, *Cedrela* sp., *Dinizia excelsa*, *Ocotea cinerea* and *Buchenavia grandis* species are less valuable for energy production, due to the low pH (below 5.0) that might make boiler tubes more vulnerable to corrosion. Based on the data obtained, it would be recommended to adopt pretreatments to dry the residues, as a way to increase the energy performance of biomass and adding value to waste in the Amazon Area.

It is recommended that studies be carried out to assess the chemical and physical effects of storage in different positions in the pile and the behavior of FRLBS subjected to carbonization.

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