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Physicochemical Characterization and Thermal Behavior of Different Wood Species from the Amazon Biome

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Abstract: The Brazilian Amazon is one of the main tropical wood-producing regions in the world, where exploration and industrial processing are among its main economic activities. Wood is characterized as a material consisting mainly of compounds with a high degree of polymerization and molecular weight such as cellulose, hemicellulose and lignin, in addition to other compounds such as ash and extractives. This chemical complexity of wood brings with it a wide possibility of chemical and thermochemical processing aiming at the production of bioproducts and biofuels. In this context, it is essential to know the physicochemical properties and thermal behavior of wood species from the Amazon biome to add value to the product, reducing waste and maximizing the species used. This work presents an investigation into the physicochemical and thermogravimetric characteristics of 21 species of wood from the Amazon, in addition to the determination of the higher heating value (HHV) of each one of them, focusing on the energy use of the biomass under analysis. The samples showed a high lignin content, varying between 26.8% and 33.9%, with a standard deviation of 1.7% and an average of 30.0%. The *Trattinnickia* sp. had the highest lignin content (33.86 ± 0.13%). The cellulose content varied from 31.3% to 55.9%, with a standard deviation of 7.3% and an average of 41.74%. The *Ruizterania albiflora* had the highest cellulose content (55.90 ± 1.20%). For the hemicellulose content, the variation ranged from 8.6% to 17.0%, with a standard deviation of 2.6% and an average of 12.38%. The samples that showed the highest HHVs were *Ocotea* sp. (18.588 ± 0.082 MJ kg^{-1}) followed by *Ferreiraa spectabilis* (18.052 ± 0.157 MJ kg^{-1}).

Keywords: wood species; Amazon biome; physicochemical composition; thermal behavior

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1. Introduction

The Amazon is currently the largest Brazilian biome and the largest continuous remaining block of tropical forest [1] with great biodiversity and harboring more than 20% of known terrestrial species [2]. This region has great ecological, environmental and hydrological relevance for the entire planet, and even with the negative anthropic actions it has been subjected to in recent decades [3–6] about 80% of its forests are still preserved, of which 60% are under Brazilian control [7].

The Brazilian Amazon Forest has enormous economic potential, especially in the timber sector from non-coniferous species [8]. Amazonian woods are sold in several countries and their applications go far beyond the conventional use for the production of furniture, paper and energy [9]. The chemical complexity of wood provides several possibilities for chemical and thermochemical processing to produce bioproducts and biofuels in the context of biorefineries. Emulsifiers, agglutinators, adhesives, dispersants, carbon fibers, alcohols, additives and even medicines can be developed using innovative processes and technologies [10,11]. For example, Pinheiro et al. (2022) [12] proved the potential of using forest residues of the *Bagassa guianensis* species to obtain bioactive compounds and the use of ethanolic extract as a bioproduct to combat oxidative stress. Lignocellulosic biomass is an abundant and renewable resource with carbon neutral potential, and its use can reduce CO_2 emissions and environmental pollution [13–15]. The woody biomass is constituted by a cellulose, hemicellulose and lignin matrix, with smaller amounts of extractives and inorganic compounds [16,17]. The chemical composition of lignocellulosic materials varies greatly due to genetic factors and environmental influences, and is a crucial factor that directly affects the production of fuels and chemicals during the conversion process [18,19]. The composition of the biomass can be determined through immediate analysis (moisture content, volatile material content, ash content and fixed carbon content), elemental/proximate analysis (carbon, hydrogen, nitrogen and oxygen content) and chemistry analysis in terms of lignin, cellulose, hemicellulose and extractives content.

In this sense, the objective of this research is to investigate the physical–chemical and thermogravimetric characteristics of 21 types of non-traditional wood from the Amazon biome and commercially promote new species aiming at industrial use, whether to produce paper and cellulose, sawn wood, bioproducts, charcoal or biofuels. The use of this resource must be governed by the principle of conservation, with wood coming from planted and properly managed forests. The results obtained may serve as a reference database for future studies which require the characterization of the types of wood in the Amazon biome, contributing to the appreciation of the great diversity in existing species, favoring sustainability in forest management, optimizing the use of wood, reducing waste and adding value to the product. Knowing the characteristics of these woods can subsidize the rational exploitation of the forest, allowing little-known species to reach the same market level as traditional species [20]. In addition, this study hopes to draw the attention of researchers and public authorities to the importance of the Amazon and the need for a more comprehensive understanding of its diversity.

2. Materials and Methods

2.1. Raw Material

Typical woods from the Amazon biome region were used in this study. Table 1 presents the woods employed with their respective common and scientific names, which were collected in the regions of Alta Floresta/MT, Cruzeiro do Sul/AC and Rio Branco/AC. The common names (in Portuguese) are those by which they are known in the Amazon region. The material was air-dried up to nearly 85%, ground in a Wiley mill, separated in Tyler standard sieves, assembled in a sieve shaker to adapt and standardize material sizes to values smaller than 0.841 mm (20 mesh) and stored in polyethylene bags at room temperature before use.

Table 1. Typical woods from Amazon biome used in this study. * The common names (in Portuguese) are those by which they are known in the Amazon region.

Samples	Scientific Name	Common Name *
1	*Chlorophora* sp.	Limoeiro
2	*Aspidosperma*	Quina
3	*Cecropeia hololeúca*	Embaúba Vermelha
4	*Pouteria* sp.	Leiteiro Branco
5	*Vochysia* sp.	Cambará
6	*Enterolobium maximum*	Timburí
7	*Couratari* sp.	Tauarí
8	*Ocotea* sp.	Canelão
9	*Trattinnickia burserifolia*	Amescla
10	*Pouteria* sp.	Leiteiro
11	*Peltogyne venosa*	Roxinho
12	*Ferreiraa spectabilis*	Sucupira Amarela
13	*Fagara* sp.	Mamica de Porca
14	*Pouteria* sp.	Pariri
15	*Ruizterania albiflora*	Mandioqueira

Table 1. *Cont.*

Samples	Scientific Name	Common Name *
16	*Psidium* sp.	Araça
17	*Mezilaurus itauba*	Itaúba
18	*Ceiba* sp.	Samaúma
19	*Esenbeckia* sp.	Guarantã
20	*Trattinnickia* sp.	Morcegueira
21	*Virola multicostata*	Ucuúba

2.2. Extraction with 95% Ethanol

The extraction was carried out for 7 h with 50 min solvent cycles in a large-scale Soxhlet apparatus containing 3 g of dry sample and 0.6 L of 95 % ethanol. The resulting ethanol extract was evaporated until dryness under a low pressure at 40 °C. The extraction yields were determined gravimetrically and expressed in relation to the dry mass of the raw material [21].

2.3. Analytical Methods

Sample moisture contents were determined through a Marte ID50 model infrared balance for fast dry weight, with a UV chamber, at 105 °C for approximately 10 min following the National Renewable Energy Laboratory NREL/TP-510-42621 [22]. Measurements were conducted in triplicate. Approximately 1.000 g of sample was used. The ash content was measured gravimetrically using the NREL/TP-510-42622 method [23]. The chemical composition of the woods was determined according to the proposed methodology by NREL/TP-510-42618 [24]. The presence of sugar (glucose, xylose, arabinose and cellobiose) as well as acetic acid in the samples was determined via high-performance liquid chromatography (HPLC) using the Shimadzu LC-10AD chromatograph and a refractive index detector RID-10A equipped with an Aminex HPX-87H (300 × 7.8 mm) BIO-RAD column (Hercules, CA, USA) maintained at 45 °C, with H_2SO_4 0.01 N being used as a mobile phase (eluent), and it was vacuum-filtered in a cellulose ester membrane (with porosity of 0.45 m and 47 mm in diameter) (Millipore) and simultaneously degassed in an ultrasound bath for 30 min, with 0.6 mL/min being the flow rate of the eluent and sample volume injected, equal to 20 µL. Calibration curves were made previously from the patterns of sugars and organic acids such as glucose, xylose, arabinose, cellobiose and acetic acid for the quantification of described compounds. Chromatograms of samples were compared with sugar and organic acids via pattern analysis.

2.4. Thermal Behavior Study of the Woods

Thermogravimetry studies (TGA) were performed using a thermal calorimeter from SDT-Q600 and TA instruments that employed the TA Advantage 5008TGA software. Samples of approximately 5 mg were pyrolyzed up to a temperature of 600 °C in synthetic air (<5 ppm H_2O, 80 mL min^{-1}) using 10 °C min^{-1} heating rates. Mass calibrations were conducted in zinc standard with a baseline and heat flow (sapphire standard) in the same analysis conditions. It was used as the standard for thermogravimetric analysis (TGA) and commercial chemicals were used to represent the main components of biomass, cellulose—Sigma-Aldrich Type 100/9004-34-6 (San Luis, MI, USA)—and Avicel; hemicellulose—Xylan, Sigma-Aldrich X4252—was obtained from beechwood and lignin (semi-concentrated; lignin was obtained via steam explosion of sugar cane).

2.5. Higher Heating Value (HHV)

Tests to determine the sample's higher heating value (*HHV*) were performed in a digital calorimeter (IKA-Werke model C2000) connected to a supply water chiller (IKA-Werke model KV600). A sample mass of approximately 0.500 g was employed, and analyses were performed in triplicate. The measured values were compared to those calculated from the literature (Equation (1)) linking the biomass lignin content to its *HHV*. Equation (1) was proposed for a model which includes lignin content [25]:

$$HHV = 0.0889(L) + 16.8218 \tag{1}$$

where (L) expresses the total lignin content (% dry basis, extractive-free) and the *HHV* is given as MJ kg^{-1}.

Amongst biomass chemical components, lignin is the fraction that presents higher thermal stability due to carbon-carbon bonds between phenylpropane monomeric units, and consequently higher stability of its aromatic matrix [26]. Therefore, the higher heating value of a biomass varies depending on the lignin content.

3. Results and Discussion

3.1. Analysis of Physicochemical Composition of the Biomasses

Table 2 shows the physicochemical characterization of the studied woods.

Table 2. Chemical composition of analyzed wood (% wt dry basis).

Samples	Moisture	Cellulose	Hemicellulose	Total Lignin *	Extractives	Ash
Chlorophora sp.	8.60	44.36 ± 0.26	16.25 ± 1.15	28.86 ± 0.15	1.70	0.82 ± 0.04
Aspidosperma	9.30	31.26 ± 1.32	10.30 ± 0.59	31.24 ± 0.79	1.25	0.93 ± 0.11
Cecropeia hololeúca	8.61	37.88 ± 1.12	12.94 ± 0.31	29.83 ± 0.24	2.50	1.35 ± 0.07
Pouteria sp.	8.28	38.70 ± 0.85	14.21 ± 0.18	30.58 ± 0.82	1.61	2.80 ± 0.35
Vochysia sp.	8.45	49.50 ± 0.39	12.56 ± 0.35	32.28 ± 1.18	0.18	3.90 ± 0.49
Enterolobium maximum	7.96	33.01 ± 0.09	16.15 ± 0.84	26.83 ± 1.83	6.86	0.85 ± 0.01
Couratari sp.	7.94	49.45 ± 1.68	8.63 ± 0.54	30.69 ± 0.71	3.16	0.50 ± 0.34
Ocotea sp.	7.09	37.69 ± 0.13	10.90 ± 0.03	30.08 ± 0.58	0.29	0.75 ± 0.01
Trattinnickia burserifolia	5.78	49.77 ± 2.57	14.20 ± 0.83	30.10 ± 0.54	3.77	1.04 ± 0.08
Pouteria sp.	8.28	45.37 ± 0.97	12.66 ± 0.06	27.63 ± 0.78	1.65	1,50 ± 0.07
Peltogyne venosa	7.29	47.57 ± 2.29	9.76 ± 0.94	30.80 ± 0.26	6.76	1.55 ± 0.28
Ferreiraa spectabilis	8.26	33.36 ± 2.48	12.66 ± 0.61	29.82 ± 0.08	3.40	0.65 ± 0.21
Fagara sp.	7.94	41.56 ± 0.88	17.00 ± 0.34	30.71 ± 0.68	5.22	0.70 ± 0.07
Pouteria sp.	8.04	40.00 ± 0.90	11.16 ± 0.47	29.96 ± 0.27	6.29	0.72 ± 0.11
Ruizterania albiflora	6.00	55.90 ± 1.20	9.23 ± 0.19	28.71 ± 0.31	3.29	1.12 ± 0.04
Psidium sp.	8.07	41.24 ± 0.55	15.75 ± 0.30	30.06 ± 0.18	1.47	1.65 ± 0.01
Mezilaurus itauba	8.55	37.15 ± 6.86	13.70 ± 0.22	30.25 ± 0.09	2.39	0.62 ± 0.11
Ceiba sp.	9.11	45.56 ± 1.19	12.53 ± 0.77	32.18 ± 0.06	0.53	1.50 ± 0.07
Esenbeckia sp.	7.40	41.69 ± 0.57	12.09 ± 0.25	27.81 ± 0.14	1.46	0.55 ± 0.01
Trattinnickia sp.	9.71	45.18 ± 0.08	13.38 ± 0.52	33.86 ± 0.13	0.71	1.72 ± 0.04
Virola multicostata	8.49	41.07 ± 0.09	13.59 ± 0.20	28.13 ± 0.52	2.62	0.85 ± 0.07
Average	8.05	41.74	12.38	30.02	2.72	1.27
Standard deviation	0.95	7.31	2.62	1.66	2.06	0.83

* Lignin total is the sum of the results of the soluble and insoluble lignin present in the sample.

The results confirm that cellulose is the most present element in the wood composition, even though its proportion varies from species to species. The lignin content was higher than the hemicellulose for all of the samples. The mean values for these samples were 41.7% for cellulose content, 12.4% for hemicellulose, 30.0% for lignin, 2.72% for extractives and 1.27% for ash (Table 2). The content of the main components varies significantly between the species. These results are within the ranges found in the literature. For the studied samples, the lignin content varied in a small range, between 26.8% and 33.9%, with a standard deviation of 1.7% and an average of 30.0%, which is a little bit higher than the range presented in the literature (10–25%) [27]. Among the components of wood, lignin is the one that has the most potential for new products [20]. For hemicellulose content, a variation from 8.6% to 17.0% was found, with a standard deviation of 2.6%, which is lower than expected (20–40%) [28]. Cellulose content presented a range between 31.3% and 55.9%, with a standard deviation of 7.3%, which is within the range presented in the literature (40–60%) [29].

The moisture contents in the biomasses analyzed by Zhang et al. (2015) [30] varied from 0.0% to 63.0% once the authors worked with different species of woods from several geographical regions. This parameter for the current study ranged from 5.8% to 9.7% with a standard deviation of 1.0% and an average of 8.1%, which are smaller mean values. The highest moisture content (9.7%) was found in *Trattinnickia* sp. and the second highest was found in *Aspidosperma* (9.3%). The wood with the smallest moisture content was *Trattinnickia burserifolia* (5.8%), followed by *Ruizterania albiflora* (6.0%).

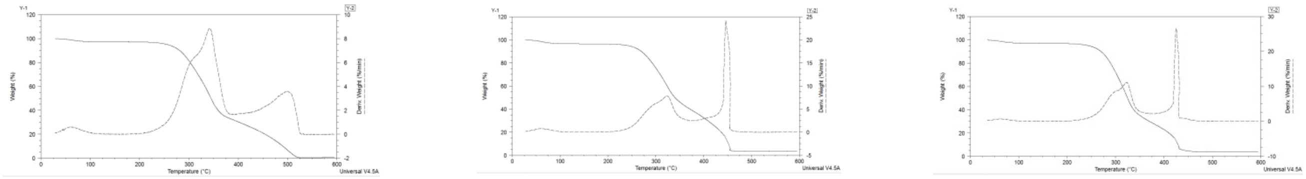
Extractives include non-structural components of wood that could potentially interfere in the analysis of the chemical composition [31]. For the studied samples, the mean content of extractives was 2.7%. The values varied from 0.3% to 6.9% and presented a standard deviation of 2.1%. According to Santos et al. (2022) [32], the extractives may vary quantitatively or qualitatively, fluctuating from 2% to 5% in materials derived from wood, and can reach contents of up to 15% in some tropical species [33]. Therefore, although some values are outside of the range found in the literature, the extractive contents were expected. For the ash content, the mean value was 1.3% and the standard deviation was 0.8%. The contents varied from 0.5% to 3.9%. This parameter in the biomasses studied by Zhang et al. (2015) [30] had a wide variation (0.15–29.73%), higher than in the Amazon wood samples. The ash contents of the current study's woods varied in a short range compared to the results found by [30], if they originated from the same biome and were under the same climate.

The chemical composition of wood, especially considering extractives, can provide a theoretical basis for the color changes seen in tropical woods. This is why it is possible to find wood with white, black, yellow, brown, pink and purple colors. The extractives also influence the odor of the wood, mainly in the tropical species which are diversified, from their quantity to the chemical nature of their composition [20].

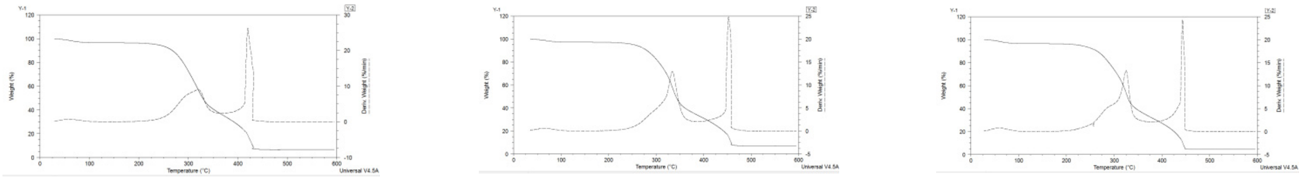
3.2. Thermal Behavior Analysis

Thermal analysis with the patterns to represent the major components of biomass showed that the two samples of cellulose (Sigma-Aldrich and Avicel) had a more-defined temperature range and faster decomposition from 300 to 400 °C [34]. The hemicellulose behaved as a disaccharide due to it presenting two major events: the first event was from 200 °C to 250 °C and the second event was from 250 to 400 °C [35,36]. Lignin showed a slower degradation, starting at 200 °C up until 1000 °C, and thereby may be the most responsible for the residual coal that is formed at the end of combustion [37]. This behavior can be attributed to lignin due to a more complex polymer.

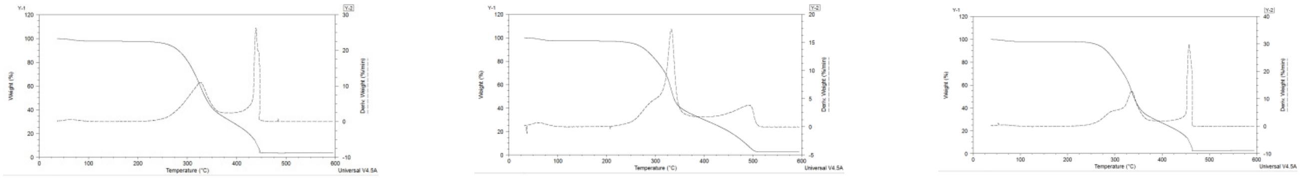
Figure 1 shows the thermogravimetric (TG) curves and derivative of thermogravimetric (DTG) curves for the samples of the woods. These curves can preview the major intervals for the studied decomposing woods. The main thermal degradation intervals were 25 °C $< T <$ 175 °C, related to the elimination of residual water, which can be attributed to wood moisture; $T >$ 200 °C, in which the hemicellulose decomposition predominates; 250 °C $< T <$ 300 °C, in which hemicellulose and cellulose decompose simultaneously, predominating hemicellulose decomposition; 300 °C $< T <$ 375 °C, related to cellulose decomposition and 375 °C $< T <$ 550 °C, in which lignin decomposition predominates.



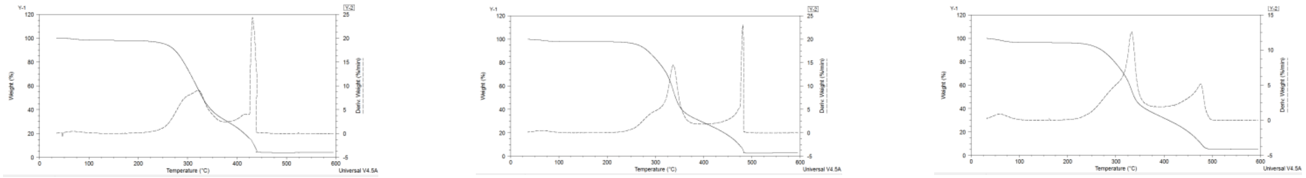
Chlorophora sp. *Aspidosperma* *Cecropeia hololeúca*



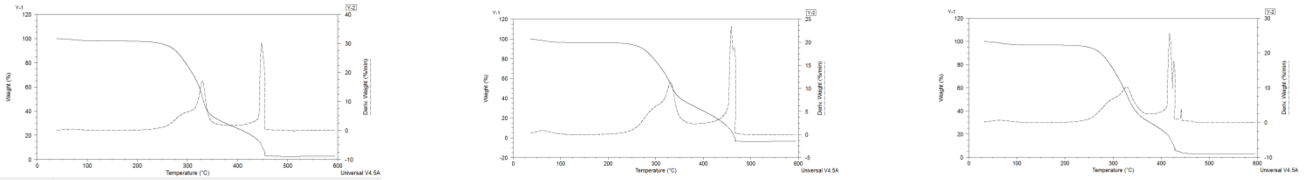
Pouteria sp. *Vochysia* sp. *Enterolobium maximum*



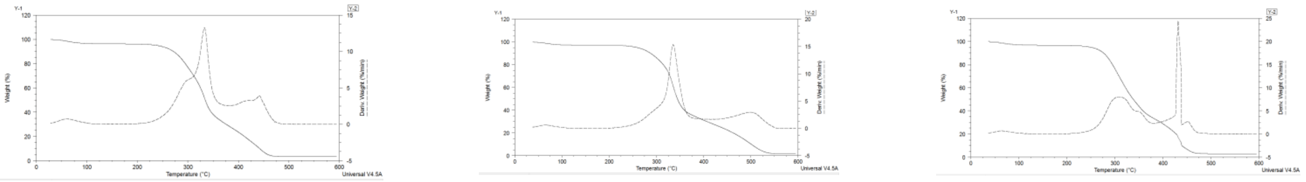
Couratari sp. *Ocotea* sp. *Trattinnickia burserifolia*



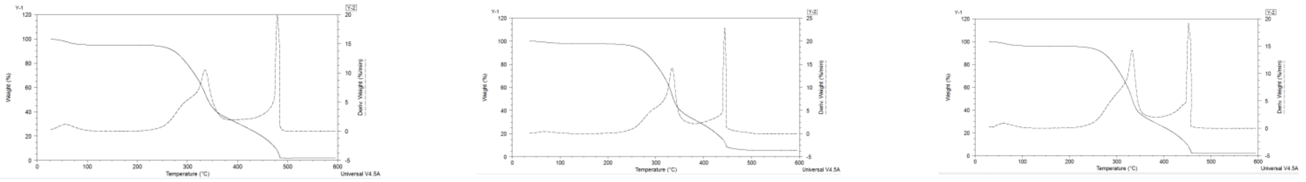
Pouperia sp. *Peltogyne venosa* *Ferreiraa spectabilis*



Socratea exorrhiza *Pouteria* sp. *Ruizterania albiflora*



Psidium sp. *Mezilaurus itauba* *Ceiba* sp.



Esenbeckia sp. *Trattinnickia* sp. *Virola multicostata*

Figure 1. Thermogravimetric (TG) curves and derivative of thermogravimetric (DTG) curves of the samples of the woods with synthetic air at a flow rate of 80 mL min^{-1} using a heating rate of 10 °C min^{-1}.

Ref. [29] studied the characteristics of hemicellulose, cellulose and lignin pyrolysis, and verified that among the three components, lignin was the most difficult one to decompose. Its decomposition happened slowly under the whole temperature range from ambient to 900 °C. These authors attributed the differences in the structures and chemical nature of the three components to this behavior. Hemicelluloses are a heterogeneous group of polysaccharides that have β-(1-4) linkages and are rich in branches, which are more easily broken. Cellulose consists of a long polymer of glucose without branches, its structure is very strong and the thermal stability is higher. Lignin has a large group of aromatic rings with various ramifications making them rigid and impervious. Lignin bonds are more difficult to break because it is more stable than wood carbohydrates [38].

3.3. Higher Heating Value

Comparing the results obtained experimentally through the calorimeter pump and the results calculated taking only the biomass total lignin content into consideration for each sample, the results are presented in Table 3. The percentage variation in each value regarding the calculated value was also determined. A value such as the one found by [39] was verified. The HHVs calculated considering only the total lignin content were superior to those determined through the calorimeter pump. Table 3 also shows experimental HHVs determined through the calorimeter pump with commercial standards of lignin isolated from vapor explosion, cellulose from Sigma and Xylan. These HHVs found were 20.0, 15.3 and 15.5 MJ kg^{-1}, respectively, for lignin, cellulose and hemicellulose.

Table 3. Comparison between experimental HHVs and calculated results using Equation (1), as well as HHVs from commercial isolated samples from lignocellulosic materials.

Samples	**Experimental HHV [MJ kg^{-1}]**	**Calculated HHV [MJ kg^{-1}]**	**Difference (%)**
Lignin—isolated	20.02 ± 0.083	—	—
Cellulose—Sigma	15.27 ± 0.033	—	—
Hemicellulose—commercial	15.47 ± 0.005	—	—
Chlorophora sp.	17.59 ± 0.040	18.11	2.88
Aspidosperma	17.49 ± 0.427	18.34	4.63
Cecropia hololeúca	17.70 ± 0.293	19.32	8.37
Pouteria sp.	17.86 ± 0.077	18.31	2.49
Vochysia sp.	17.31 ± 0.195	18.33	5.56
Enterolobium máximum	18.19 ± 0.054	18.56	1.98
Couratari sp.	17.79 ± 0.027	18.53	4.04
Ocotea sp.	18.59 ± 0.082	18.07	2.86
Trattinnickia burcerifolia	17.21 ± 0.026	18.54	7.18
Pouteria sp.	17.30 ± 0.072	18.87	8.30
Peutogyne venosa	16.83 ± 0.413	19.04	11.61
Ferreiraa spectabilis	18.05 ± 0.157	17.95	0.56
Fagara sp.	18.23 ± 0.126	17.95	1.53
Pouteria sp.	17.42 ± 0.327	18.31	4.85
Ruizterania albiflora	17.87 ± 0.167	18.23	1.95
Psidium sp.	17.35 ± 0.320	18.19	4.62
Mezilaurus itauba	18.54 ± 0.140	18.46	0.41
Ceiba sp.	17.33 ± 0.043	18.59	6.81
Esenbeckia sp.	17.66 ± 0.033	18.15	2.71
Trattinnickia sp.	17.59 ± 0.040	18.11	2.88
Virola multicostata	17.49 ± 0.427	18.34	4.63

This value confirms that lignin is a determining component in the biomass higher heating value. Considering that all substances contribute to the biomass HHV, to calculate such a value only taking account of the lignin content present in the sample means to only consider the energy release variation from this substance in combustion with the remaining substances being constant. As a matter of fact, the lignin presents more specific energy, and it is therefore the substance that most contributes to an HHV increase. This behavior shows that it is understandable that the empiric HHV is higher when compared to the experimental value.

Ref. [25] reported HHVs when analyzing wood samples, whereby cellulose and hemicellulose (holocellulose) have an HHV of 18.60 MJ kg^{-1}, whereas lignin has an HHV from 23.26 to 26.58 MJ kg^{-1}. From such results, it is possible to conclude that the HHV for a lignocellulosic fuel is a function of its lignin content. Generally, the HHV for a lignocellulosic fuel increases with an increase in its lignin content, since the HHV is highly correlated to the lignin content [39].

Ref. [30] also presented values of the HHV for several types of wood. The values showed variation from 7.6 to 24.0 MJ kg^{-1}, but most of them were within the range from 17 to 20 MJ kg^{-1}. If compared to those found in the analyzed samples of woods from the Amazon biome (Table 3), a short variation can be noticed.

In Figure 2, it is possible to observe that HHVs determined experimentally are close for all samples. In addition, standard deviation values vary according to the HHVs found in triplicate measurements.

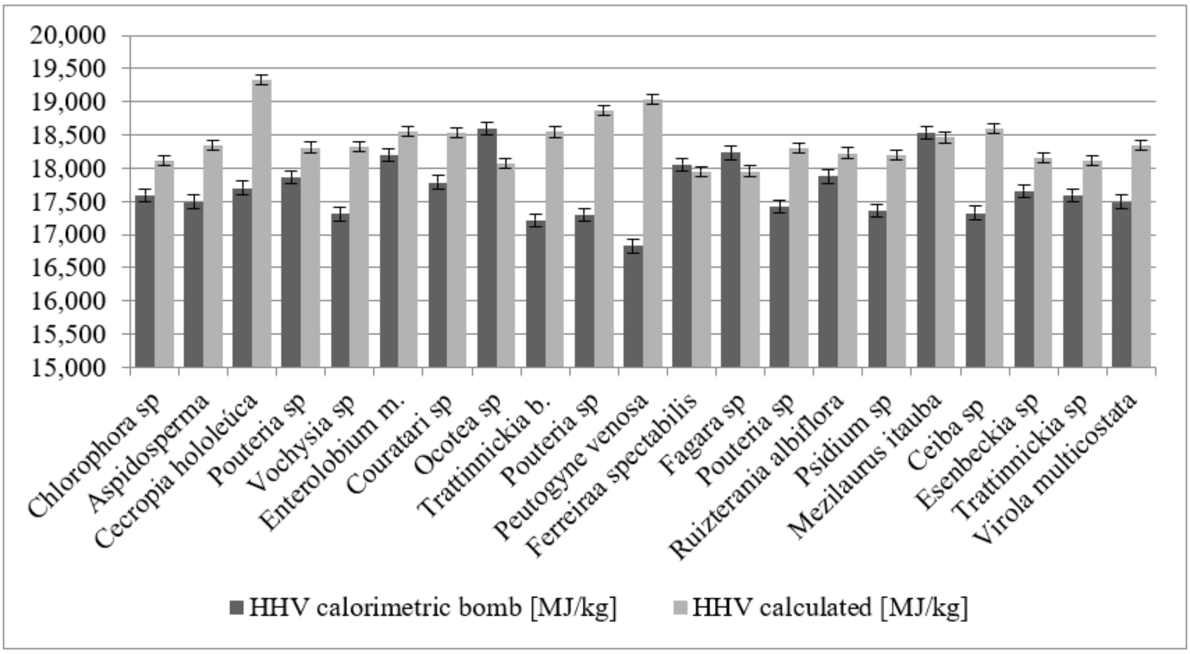


Figure 2. Comparison of the HHV average from different woods determined in a calorimeter pump and calculated empirically (Equation (1)), considering only lignin content.

The sample that has the highest HHV value is *Ocotea* sp., followed by a biomass sample from the wood *Ferreiraa spectabillis*, whereby both results are above 18.50 MJ kg^{-1}. Thus, these two types of wood are more susceptible to fires since they have higher ignition power. This is a relevant analysis when mapping a certain forest area since some behaviors relative to fire spreading and possible damage can be predicted. The smallest value found in the analysis (16.82 MJ kg^{-1}) refers to a sample wood of *Peltogyne venosa*. The average of all samples was 17.70 MJ kg^{-1}.

4. Conclusions

This work determined the physicochemical characteristics of the main woods from the Amazon biome, contributing to the knowledge of these lignocellulosic materials, for the rational management of forests and for the optimization of their use. These data can contribute to the protection of these plant biomasses and, at the same time, they promote the knowledge of their potential as a source of energy; for example, knowledge of the elemental chemical composition of wood is the basis for the analysis of combustion processes. *Trattinnickia* sp. had the highest lignin content (33.86% ± 0.13). The proportion of lignin may vary depending on the age of the individual, and woods in the adult stage have higher levels of lignin than juvenile woods. *Ruizterania albiflora* had the highest levels of cellulose (55.90% ± 1.20), *Enterolobium maximum* had the highest levels of extractives (6.86%), *Fagara* sp. had the highest levels of hemicellulose (17.00 ± 0.34) and *Vochysia* sp. had the highest levels of ash (3.90 ± 0.49). Based on the results found, applications in the pulp and paper industry and the production of charcoal and other bioproducts should be investigated.

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