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Physical, mechanical, and combustion properties of twelve wood species from the Brazilian Amazon

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Abstract:
Studying the combustibility and physical–mechanical properties of wood is important for recommending its use in construction. The objective of this study was to evaluate the combustibility, as well as the physical and mechanical properties, of twelve Brazilian Amazonian woods. Species. For each species, the combustibility parameters, fire exposure test, residual mass, loss mass, intact mass, charred area, proximate analysis, basic density, compressive strength and modulus of elasticity were determined. All the evaluated properties were significant affected by the wood species. In the fire exposure test, ignition time ranged from 21 s to 55 s while flame time was between 108 s and 233 s. Residual mass ranged from 60,7% to 82,7%, and intact areas ranged from 28,13 % to 62,68 %. Basic density values ranged from 335 kg/m^3 to 889 kg/m^3, compressive strength ranged from 29 MPa to 82 MPa, and the modulus of elasticity ranged from 9 GPa to 33 GPa. The wood of *Hymenaea courbaril* (courbaril), *Manilkara huberi* (masaranduba), *Handroanthus serratifolius* (yellow lapacho) was identified as the most suitable for structural components, ensuring greater safety against possible fires. Short-term fire exposure tests, particularly the ignition time parameter combined with residual mass and intact area, are key for assessing wood resistence to fires.

Keywords: Brazilian Amazon species, combustibility, flame time, fire exposure test, mechanical strength, wood density.

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Introduction

The Amazon Forest, located in South America, is the largest equatorial forest in the world. It has an area of 5,5 million km² and is spread across nine countries. Brazil stands out, with 60 % of the Amazon area (SNIF 2020). The Amazon has several large endemic tree species with straight stems. It is estimated that it has approximately 16000 large tree species (Ter-Steege *et al.* 2013). Furthermore, in Brazil, legalized forest exploitation is carried out to increase the economic, social, and environmental development of the region.

Low-impact forest management contributes to the commercialization of timber and increases the growth rates of remaining trees (Romero *et al.* 2020). Notably, the maximum volume of wood extracted following sustainable management plans corresponds to 30 cubic meters per hectare (ha), with 25--35 years of cutting cycles (BRASIL 2009). This value is equivalent to five trees.ha^{-1}, and the estimate is that there are, on average, 565 trees per hectare in the Amazon Basin (Ter-Steege *et al.* 2013).

After the trees are extracted, the logs undergo mechanical processing, from which they are processed by the timber industry and transformed into rectangular or square pieces intended for civil construction (Melo *et al.* 2019, Luz *et al.* 2021). The grouping of woods can be based on the most suitable applications, such as use in internal and external environments, structural or not, in addition to market value (Sousa *et al.* 2019, ITTO 2023). These categories consider the characteristics of wood, such as its physical and mechanical properties, in addition to its organoleptic properties. Commercialization of the following Amazonian Brazilian woods stands out: Angelim (*Hymenolobium petraeum* Ducke.), Garapa (*Apuleia leiocarpa* (Vogel) J.F. Macbr.), courbaril (*Hymenaea courbaril* L.), muiracatiara (*Astronium lecointei* Ducke.), goupie (*Goupia glabra* Aubl.), purpleheart (*Peltogyne angustiflora* Ducke.) and cumaru (*Dipteryx odorata* (Aubl.) Willd.) (Freitas *et al.* 2022, Luz *et al.* 2021, Nahuz *et al.* 2013).

When used as a construction material, wood has advantages over other materials, such as low cost and excellent mechanical, thermal and acoustic properties, and it provides a more pleasant and welcoming environment (Tondi *et al.* 2012). However, there is still mistrust in its use for structural purposes, as it is believed that wood is a material with low resistance and durability; therefore, people opt for other materials that they deem more suitable (Martinelli and Reis 2019). Another factor for this analysis is that wood is a combustible material and, therefore, that it should not be used as a structural part because of its behavior in fire situations.

Since wood is widely used in housing for both external structures and indoor environments such as floors, ceilings, and because it is vulnerable to fire, wood is evaluated to ensure occupant safety and prevent damage (Camargo and Ibáñez 2024). However, in a fire situation, other construction materials, such as steel and concrete, present a reduction in mechanical strength and rigidity when exposed to high temperatures, which may cause total or partial collapse of the construction (Dias and Karam 2021). When exposed to a fire, wood generates a charred layer, a thermal insulator that protects the interior of the material, which remains intact (Martins and Calil Junior 2017). Thus, it maintains its resistance and sustains construction.

Since Amazon woods show high variability (Santos *et al.* 2020b, Sousa *et al.* 2019), in addition to determining the physical and mechanical properties of wood intended for civil construction, the study of combustibility is important for understanding how woods of different species react to fire. In this way, it is possible to make more precise recommendations for use in construction. This is accomplished by verifying which wood would need the application of a flame retardant product and which wood already has greater natural resistance (Nunes 2015). This is because different species have different rates of ignition and burning, and it is necessary to study the behavior of each wood when exposed to fire. Despite the various studies that have been carried out in recent years (Viana *et al.* 2019, Nunes 2015, Figueroa and Moraes 2009), little is known about the behavior of tropical Amazon woods subjected to fire or high temperatures.

Thus, the objective of this work was to evaluate the physical and mechanical properties, combustibility, and fire behavior of twelve wood species from the Brazilian Amazon. This characterization will help identify the most fire-resistant wood, assist in selecting appropriate wood for construction, and increase fire safety.

Material and methods

Wood from twelve Brazilian Amazon species was used (Figure 1). They were obtained from a timber industry located in the municipality of Colniza, state of Mato Grosso, Brazil (geographical coordinates 9°28'10,36" S; 59°12'38,11" W).

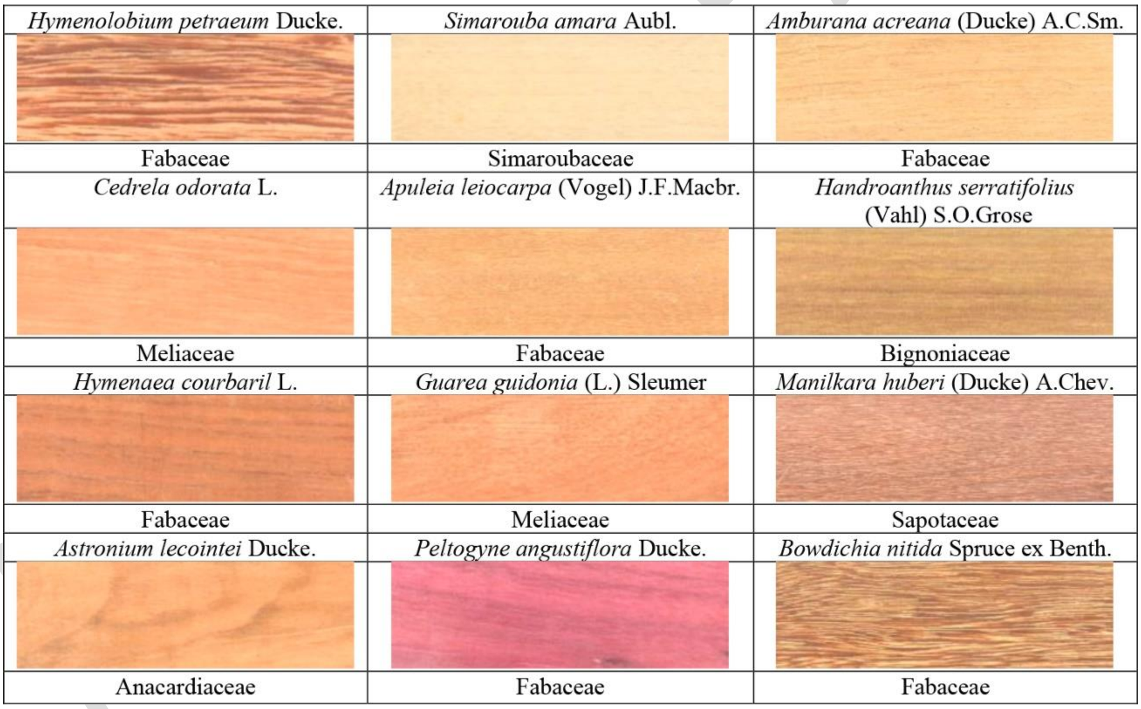

Figure 1: Identification of twelve woods of tropical species from the state Mato Grosso evaluated in the study.

In the storage yard, ten heartwood rafters (5,0 cm × 5,0 cm × 200,0 cm), without defects, were randomly selected per species. The wood batch had 12 m^3. Among these pieces, edges 30 cm in length were discarded, and the samples were cut to determine their physical and mechanical properties and perform the fire exposure test.

The wood of *Hymenolobium* is easily workable and suitable for sawing, turning, and drilling. The heartwood is reddish-brown, with darker spots (IPT 2024). Marupa (*Simarouba amara* Aubl.) is light-colored, has a low density, and is soft to cut, making it considered to have low natural durability (IPT 2024). The wood of cerejeira (*Amburana acreana* (Ducke) A.C.Sm.) has a medium density, is soft to cut, and has low durability (IPT 2024). Cedar (*Cedrela odorata* L.) is characterized by low-density wood with moderate durability, and it has a pleasant aroma; the heartwood is pinkish and distinct from the sapwood (IPT 2024). The wood of brazilian garapa (*Apuleia leiocarpa* (Vogel) J.F.Macbr.) varies in color from beige-yellowish to brown-yellowish and is easy to work with (IPT 2024). Yellow lapacho (*Handroanthus serratifolius* (Vahl) S.O.Grose) has high-density wood, is hard to cut, and is considered to have high natural resistance (IPT 2024).

Courbaril (*Hymenaea courbaril* L.) presents high-density wood, is hard to cut, and is recognized for its high natural resistance (IPT 2024). The wood of muskwood (*Guarea guidonia* (L.) Sleumer) has moderate density, is hard to cut, and shows good durability (IPT 2024). The wood of masaranduba (*Manilkara huberi* (Ducke) A.Chev.) is dense, hard to cut, and considered to have high natural resistance; the heartwood is red and distinct from the sapwood (IPT 2024). Muiracatiara (*Astronium lecointei* Ducke) also has high density, is hard to cut, and is considered highly resistant to decay (IPT 2024). Machaerium (*Peltogyne angustiflora* Ducke) is notable for its striking purple heartwood color and high natural resistance to wood-damaging organisms, making it moderately difficult to work with (IPT 2024). Finally, purpleheart (*Bowdichia nitida* Spruce ex Benth) has dark-brown heartwood with a fibrous texture and no luster, and its wood is resistant to wood-damaging organisms and weathering (IPT 2024).

Combustion parameters obtained via thermogravimetric analysis

Thermogravimetric analyses were carried out with a DTG-60H thermal analyzer (Shimadzu) using approximately 6 mg of ground material, with a particle size smaller than that of the 60 mesh, in an open alumina capsule. The parameters assessed were dry air atmosphere, constant flow rate of 100 $ml.min^{-1}$, and heating rate of 20 °$C.min^{-1}$ from room temperature to 800 °C. Three samples per species were evaluated.

On the basis of the thermogravimetric (TG) curve, which expresses mass loss as a function of temperature, and its derivative (DTG), which expresses mass variation as a function of temperature (dm/dT), the following combustion parameters were obtained: initial (ti), final (tf), total combustion (tt) times, ignition temperature (Ti), and final combustion temperature (Tf). The ignition temperature of the wood was defined as the temperature at which the combustion rate increased by 1 $\%.min^{-1}$, and the final combustion temperature was defined as the temperature at which the combustion rate decreased by 1 $\%.min^{-1}$ (Sahu *et al.* 2010).

Short-term fire exposure test

Short-term fire exposure tests were performed according to the procedure described by Tondi *et al.* (2012). Five specimens per species were cut, measuring 5 cm × 2,5 cm × 1,5 cm (longitudinal × tangential × radial). After acclimatization in a climate-controlled room (20 °C and 65 % relative humidity), the tangential surfaces of the samples were exposed, on a screened surface, to the flame of a Bunsen burner directly on the sample for two min; the base flames were at a distance of 7 cm (Figure 2). The flame was regulated so that it was completely blue.

The ignition, flame, and ember times were determined via a stopwatch (Tondi *et al.* 2012). The ignition time was considered the minimum time of exposure to the Bunsen burner flame necessary to maintain unaided combustion. The flame time was the time needed to extinguish the flame after two min of continuous exposure to the Bunsen burner flame. Ember time, on the other hand, referred to the time needed for complete ember exhaustion, which was observed when there were no smoke and/or red spots (Figure 2).

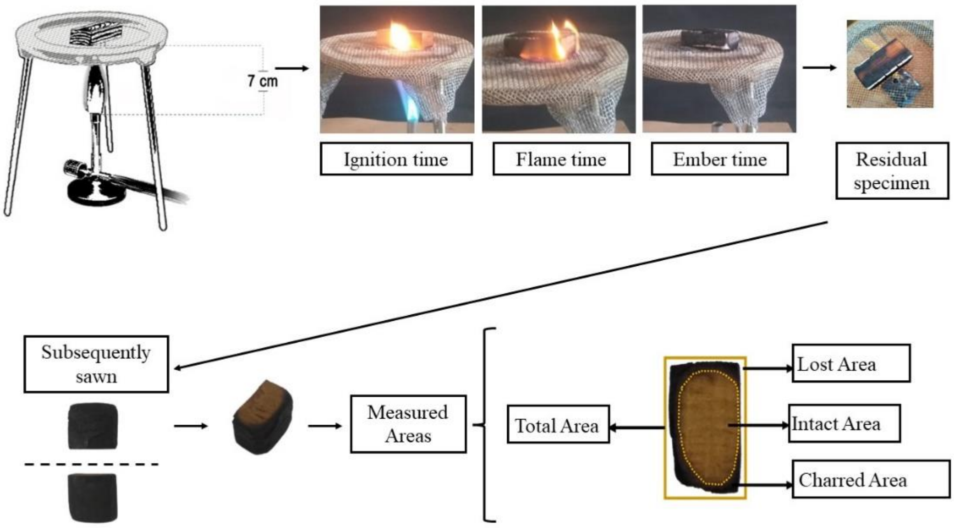

Figure 2: Scheme for performing the fire exposure test and visual analysis of the sample.

The percentage of residual mass was calculated as the ratio between the final mass and the initial mass, which was determined on a precision scale before and after the fire exposure test.

The samples were then sawed in half with a band saw perpendicular to the length of the piece, and the transverse surface was photographed on graph paper. The area affected by the fire, including the lost area, charred area and intact area, was measured via the open-source software ImageJ (version IJ 1,46r; Schneider *et al*. 2012) (Figure 2). The percentage of each area was then calculated relative to the original total area prior to the test.

Proximate analysis

The volatile matter and ash contents were determined in an electric muffle according to the ASTM E872-82 (2013a) and ASTM D1102-84 (2013b) standards, respectively. The fixed carbon content was determined by subtracting 100 from the sum of the volatile matter and ash contents. For the proximate analysis, four wood samples per species were evaluated, and the material was ground in a Wiley mill and classified via 40- and 60-mesh sieves.

Physical properties of wood

The determination of basic density, that is, the relationship between dry mass and volume above the fiber saturation point, followed the ABNT NBR 11941 standard (2003). Ten samples per species were cut, with dimensions of 2 cm × 3 cm × 5 cm in the tangential, radial and longitudinal directions, respectively. The volume was determined by measuring the width, thickness, and height of each sample under saturated conditions with a digital caliper (precision of 0,1 mm). Afterwards, the samples were dried in an oven with forced air circulation (105 °C ± 5 °C), and the dry mass was determined on a precision scale.

The calculation of the wood percentage porosity (Φ) was carried out according to Equation 1, considering the basic density of the wood determined for each species and the real specific mass of wood corresponding to 1,50 $g.cm^{-3}$ (Haygreen and Bowyer 1996).

$$\Phi = \left(\frac{Psm - Po}{Psm}\right) \times 100 \qquad (1)$$

Where Φ = wood percentage porosity (%); psm = real wood density (kg/cm^3); and po = basic density of the species (kg/cm^3).

Mechanical properties of wood

To determine the compressive strength parallel to the fibers (fc0) and the modulus of elasticity in compression parallel to the fibers (Ec0), ten specimens measuring 5 cm × 5 cm × 15 cm were cut. The samples were placed in an acclimatization room at 20 ± 5 °C and a relative humidity of 65 % until they reached an equilibrium moisture of approximately 12 %. The mechanical tests were carried out in an Amsler Wolpert Universal Testing Machine, Testa 200 kN, in accordance with the ABNT NBR 7190-3 standard (2022).

Statistical analysis

The experiment was performed in a completely randomized design (CRD) with 12 treatments (Amazon woods) and a number of repetitions, as described above. Statistical analyses were performed via RStudio version 4.2.1 software. Data were submitted to the Lilliefors test to test normality and the Cochran test to test homogeneity of variances. As they met the assumptions, the results were subjected to analysis of variance (ANOVA), and when significant differences were established ($p \leq 0,05$), the Scott-Knott mean test was performed.

To determine the existing correlations between the evaluated properties, Pearson's correlation coefficient was used ($p \leq 0,05$). For correlations with greater relevance, simple linear statistical models were fitted via the ordinary least squares method. Linear equations between the following pairs of variables were analyzed: i) compressive strength and basic density, modulus of elasticity and basic density; ii) volatile matter and ignition temperature; iii) ignition time and porosity, ignition time and flame time; and iv) residual mass and flame time, residual mass and porosity, residual mass and basic density, residual mass and lost area, and residual mass and intact area. The fitted models were evaluated by the coefficient of determination (R^2) via Microsoft Excel.

Results and discussion

Combustion parameters

Table 1 shows the combustion parameters obtained by thermogravimetric analysis for the wood of the twelve Amazon species. Their determination aimed to indicate the initial combustion time (ignition), the final time and the total combustion time, in addition to the ignition and final combustion temperatures.

Table 1: Parameters of combustion of wood from twelve Amazon species

Species	t_i (s)	T_i (°C)	t_f (s)	T_f (°C)	t_t (s)
H. courbaril	255,33 a $^{(0,23)}$	244,07 a $^{(0,22)}$	893,00b $^{(2,91)}$	468,60b $^{(1,80)}$	637,67b $^{(4,12)}$
G. guidonia	221,33b $^{(1,58)}$	231,99c $^{(0,49)}$	811,00b $^{(28,21)}$	441,25b $^{(17,2)}$	589,67b $^{(38,83)}$
M. huberi	253,67a $^{(0,82)}$	243,53 a $^{(0,25)}$	1004,67 a $^{(2,09)}$	506,65 a $^{(1,37)}$	751,00a $^{(2,57)}$
H. serratifolius	68,33c $^{(8,06)}$	175,63d $^{(1,07)}$	872,67b $^{(2,58)}$	461,88b $^{(1,64)}$	804,33 a $^{(3,31)}$
A. lecointei	240,00a $^{(1,10)}$	238,41b $^{(0,37)}$	850,00b $^{(0,35)}$	453,52b $^{(0,17)}$	610,00b $^{(0,33)}$
A. acreana	218,67b $^{(2,06)}$	230,42c $^{(0,56)}$	893,67b $^{(1,00)}$	467,54b $^{(0,69)}$	675,00b $^{(1,94)}$
C. odorata	225,00b $^{(11,56)}$	232,81c $^{(4,07)}$	859,33b $^{(3,32)}$	458,59b $^{(1,18)}$	634,33b $^{(0,78)}$
S. amara	241,67a $^{(0,86)}$	239,07b $^{(0,34)}$	840,33b $^{(2,51)}$	450,37b $^{(1,48)}$	598,67b $^{(3,37)}$
P. angustiflora	244,00a $^{(0,71)}$	240,17b $^{(0,10)}$	793,33b $^{(13,80)}$	434,91b $^{(8,34)}$	549,33b $^{(19,62)}$
B. nitida	241,00a $^{(3,73)}$	238,59b $^{(1,33)}$	1171,67 a $^{(0,99)}$	557,92 a $^{(0,67)}$	930,67 a $^{(0,55)}$
H. petraeum	242,00a $^{(2,48)}$	238,55b $^{(0,83)}$	1091,33 a $^{(1,61)}$	531,40 a $^{(1,22)}$	849,33 a $^{(2,78)}$
A. leiocarpa	229,00b $^{(0,44)}$	234,41c $^{(0,20)}$	874,67b $^{(7,62)}$	461,40b $^{(4,76)}$	645,67b $^{(10,34)}$

t_i = initial combustion time, in seconds (s); t_f = final combustion time, in seconds (s); t_t = total combustion time, in seconds (s); T_i = ignition temperature; T_f = final combustion temperature. Means followed by the same letter in the column do not differ significantly according to the Scott–Knott test ($p \leq 0,05$). Values in parentheses refer to the coefficient of variation.

The initial combustion time varied significantly, forming three groups. The woods of purpleheart (*Peltogyne angustiflora* Ducke.), angelim (*Hymenolobium petraeum* Ducke.), marupa (*Simarouba amara* Aubl.), purpleheart (*Bowdichia nitida* Spruce ex Benth), muiracatiara (*Astronium lecointei* Ducke.), courbaril (*Hymenaea courbaril* L.) and masaranduba (*Manilkara huberi* (Ducke) A.Chev.) presented the highest average time of 245 s (4,1 min) to initiate thermal degradation. This finding shows that these woods had more difficult and time-consuming ignitions; that is, they would be more resistant to fire. Garapa (*Apuleia leiocarpa* (Vogel) J.F. Macbr.), cedar (*Cedrela odorata* L.), muskwood (*Guarea guidonia* (L.) Sleumer) and cerejeira (*Amburana acreana* (Ducke) A.C.Sm.) had intermediate time (218 s to 229 s), while the shortest time (68,33 s) was observed for the wood of yellow lapacho (*Handroanthus serratifolius* (Vahl) S.O.Grose). This species also presented the lowest ignition temperature (175,63 °C) among the four groups formed for this property.

For the other species, the ignition temperatures ranged from 230 °C to 244 °C. The highest mean values were found for courbaril (*Hymenaea courbaril* L.) and masaranduba (*Manilkara huberi* (Ducke) A.Chev.). These two types of wood combust at higher temperatures (above 240 °C); that is, they are more resistant to the onset of combustion. This temperature range is within the range normally observed for hardwoods, as verified by Protásio *et al*. (2019) and Silva *et al*. (2021), but is lower than the 275 °C required for ignition, as defined by Altay *et al*. (2022).

There was a significant difference in the final combustion temperature among the species. Two groups formed: the first, composed of the species purpleheart (*Bowdichia nitida* Spruce ex Benth), angelim (*Hymenolobium petraeum* Ducke.) and masaranduba (*Manilkara huberi* (Ducke) A.Chev.), had temperatures greater than 500 °C. This result shows that these woods need a relatively high temperature for complete combustion and, consequently, a relatively long total burning time since the heating rate was the same for all the evaluated species. Therefore, in the case of fires, they sustain the structure longer, allowing more time for fire control actions. The other species presented final combustion temperatures ranging from 434 °C to 468 °C. These values are close to those Protásio *et al.* (2019) reported when evaluating the combustion of eucalyptus wood planted in Brazil and above the range of 368 °C to 400 °C of final temperature Tenorio and Moya (2013) reported in an evaluation of the combustion of wood from ten fast-growing species in Costa Rica.

For total combustion time, the formation of two groups was observed, in which the species masaranduba (*Manilkara huberi* (Ducke) A.Chev.), yellow lapacho (*Handroanthus serratifolius* (Vahl) S.O.Grose), purpleheart (*Bowdichia nitida* Spruce ex Benth) and angelim (*Hymenolobium petraeum* Ducke.) presented the longest combustion time. As all the species experienced the same heating rate, it is possible to state that the chemical composition affected the thermal stability and combustion process (Protásio *et al.* 2019, López-González *et al.* 2013, Poletto *et al.* 2012).

Higher levels of extractives contribute to greater flammability and acceleration of the thermal degradation process (Poletto *et al.* 2012), whereas cellulose crystallinity inhibits wood degradation; organized cellulose regions slow the degradation process because the well-packed cellulose chains prevent heat diffusion (Lengowski *et al.* 2016, Poletto *et al.* 2012). The extractive content in hot water is related to the final combustion temperature (Tenorio and Moya 2013), whereas the extractive content in acetone and higher proportion of guaiacyl units in the lignin macromolecule resulted in greater thermal stability and prolonged the combustion time in eucalyptus wood (Protásio *et al.* 2019).

Short-term fire exposure test

Table 2 shows the results of the fire exposure test (ignition, flame, and ember times). There was a significant difference in ignition time for the twelve Amazon woods evaluated. The shortest ignition time were for purpleheart (*Peltogyne angustiflora* Ducke.), angelim (*Hymenolobium petraeum* Ducke.), garapa (*Apuleia leiocarpa* (Vogel) J.F. Macbr.), and marupa (*Simarouba amara* Aubl.) (21,15 s to 22,65 s). courbaril (*Hymenaea courbaril* L.), muskwood (*Guarea guidonia* (L.) Sleumer), and masaranduba (*Manilkara huberi* (Ducke) A.Chev.) presented the longest ignition time (above 50 s); that is, they took longer to start burning (ignition). This is interesting with respect to wood used as structural components, as, in the case of a fire, it would result in greater difficulty in spreading it, in addition to allowing more time to evacuate the environment. yellow lapacho (*Handroanthus serratifolius* (Vahl) S.O.Grose) also presented a high ignition time: above 45 s.

Table 2: Ignition, flame, and ember times obtained from the short-term fire exposure test for wood of twelve Amazon species

Species	Ignition time (s)	Flame time (s)	Ember time (s)
H. courbaril	55,26 a (3,36)	136,26 b (9,05)	4,82 d (83,94)
G. guidonia	53,05 a (9,63)	108,25 b (4,63)	17,77 d (51,20)
M. huberi	51,03 a (8,13)	129,20 b (1,86)	72,43 b (30,32)
H. serratifolius	46,84 b (4,82)	150,46 b (7,28)	54,93 c (24,31)
A. lecointei	33,58 c (14,33)	142,49 b (12,60)	43,14 c (25,42)
A. acreana	32,72 c (17,11)	168,05 b (12,95)	42,25 c (41,68)
C. odorata	27,47 c (8,63)	230,60 a (8,81)	15,45 d (25,41)
S. amara	21,15 d (10,57)	170,01 b (12,99)	108,65 a (15,05)
P. angustiflora	22,65 d (18,96)	169,65 b (26,17)	51,23 c (91,74)
B. nitida	31,78 c (9,89)	218,77 a (30,05)	22,61 d (123,81)
H. petraeum	21,69 d (31,24)	184,39 b (18,47)	28,44 d (45,46)
A. leiocarpa	21,15 d (17,02)	233,09 a (53,52)	44,07 c (45,26)

Means followed by the same letter in the column do not differ significantly according to the Scott–Knott test ($p \leq 0,05$). (s) = time in seconds. Values in parentheses refer to the coefficient of variation.

There was a significant difference in flame time among the twelve species evaluated. The species garapa (*Apuleia leiocarpa* (Vogel) J.F. Macbr.), cedar (*Cedrela odorata* L.) and purpleheart (*Bowdichia nitida* Spruce ex Benth) presented the longest times: above 210 s. The other species did not differ significantly from each other; however, times shorter than 140 s were observed for courbaril (*Hymenaea courbaril* L.) (136,26 s), masaranduba (*Manilkara huberi* (Ducke) A.Chev.) (129,20 s) and muskwood (*Guarea guidonia* (L.) Sleumer) (108,25 s). Shorter flame times may result in less expansion of flames, allowing better control and even longer times to extinguish fires. One way to reduce the flame time is to treat the wood. Camargo and Ibáñez (2024) reported that wood samples treated with zinc borate had lower flame propagation and less mass loss after exposure to fire.

In this study, with twelve Amazon woods, the woods that had a longer ignition time had a shorter flame time, such as the woods of courbaril (*Hymenaea courbaril* L.), muskwood (*Guarea guidonia*

(L.) Sleumer) and masaranduba (*Manilkara huberi* (Ducke) A.Chev.). There was a moderate and inverse correlation (-0,51) between these two parameters. The flame time explained 26 % of the variation in the ignition time (Figure 3).

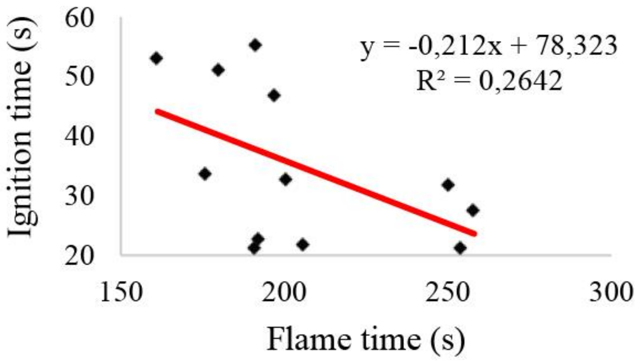

Figure 3: Variation in the ignition time as a function of the flame time.

With respect to the ember time (Table 2), the group of wood with the shortest duration was formed by muskwood (*Guarea guidonia* (L.) Sleumer), cedar (*Cedrela odorata* L.), purpleheart (*Bowdichia nitida* Spruce ex Benth), angelim (*Hymenolobium petraeum* Ducke.), and courbaril (*Hymenaea courbaril* L.). However, courbaril (*Hymenaea courbaril* L.) had the lowest average time (equal to 4,82 s), which was well below the times of the other species, whose average values ranged from 15,45 s to 28,44 s. The longest ember time (108,65 s) occurred for the wood of marupa (*Simarouba amara* Aubl.). Shorter ember time may indicate the completion of the burning process, whereas longer ember time indicate continued thermal degradation.

In general, the ember times were less expressive in relation to the other parameters. This is probably related to the conditions of wood burning, such as contact with oxygen, and to the formation of charred zones. This layer is a good thermal insulator that is three times more insulating than wood is, which makes it difficult for the temperature to rise inside the wood, thus delaying the progression of the fire (Cruz and Nunes 2005).

For the residual masses after the short-term fire exposure test, there was a significant difference among the Amazon woods evaluated (Figure 4), which formed four groups. muskwood (*Guarea* *guidonia* (L.) Sleumer), muiracatiara (*Astronium lecointei* Ducke.), yellow lapacho (*Handroanthus serratifolius* (Vahl) S.O.Grose), masaranduba (*Manilkara huberi* (Ducke) A.Chev.) and courbaril (*Hymenaea courbaril* L.) had the highest percentages, approximately 80 % each.

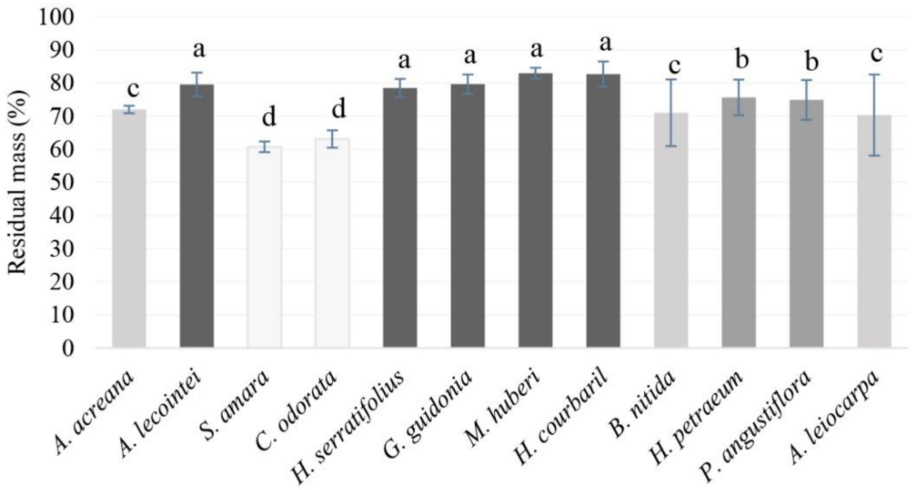

Figure 4: Mean values of residual mass (%) of wood from twelve Amazon species after the fire exposure test.

Means followed by the same letter in the same column do not differ significantly according to the Scott–Knott test ($p \leq 0,05$). The bars correspond to the standard deviation of the mean.

The woods of marupa (*Simarouba amara* Aubl.) and cedar (*Cedrela odorata* L.) presented the lowest residual masses: 60,74 % and 63,09 %, respectively. The lower residual mass may be related to the longer flame time, resulting in greater degradation of wood constituents by the action of fire. This is reinforced by the -0,59 correlation between these variables, showing that the longer the flame time is, the lower the residual mass (Figure 5). Flame time (s), lost area (%) and intact area (%) explained 35 %, 44 % and 55 %, respectively, of the variation in residual mass (Figure 5).

Structural pieces of wood must remain closer to the condition prior to exposure to fire (Figueroa and Moraes 2009) to maintain their properties and sustain capacity. As Pinto *et al.* (2008) verified, there was an average reduction of 20 % in the compressive strength parallel to the fibers of eucalyptus wood exposed to fire. Thus, for the use of wood as a structural component, woods with a greater residual mass, such as muskwood (*Guarea guidonia* (L.) Sleumer), muiracatiara (*Astronium lecointei* Ducke.), yellow lapacho (*Handroanthus serratifolius* (Vahl) S.O.Grose), and, in particular, courbaril

(*Hymenaea courbaril* L.) and masaranduba (*Manilkara huberi* (Ducke) A.Chev.), would be more suitable because, in the case of a fire, they can maintain greater construction integrity.

The woods of the Amazon species evaluated significantly differed in terms of loss area (Table 3) after the fire exposure test (Table 2). The woods of garapa (*Apuleia leiocarpa* (Vogel) J.F. Macbr.) and marupa (*Simarouba amara* Aubl.) presented the largest lost areas: greater than 40 %. This result is related to the lower percentages of residual mass of these species (Figure 5), confirming the -0,66 correlation between these variables and showing that the smaller the residual mass is, the greater the area. In addition, the degraded area in the species marupa (*Simarouba amara* Aubl.) can be associated with a shorter ignition time, leading to greater thermal degradation. Moreover, for garapa (*Apuleia leiocarpa* (Vogel) J.F. Macbr.), the large area lost may be due to the longer flame time of the fire exposure test, resulting in greater material consumption.

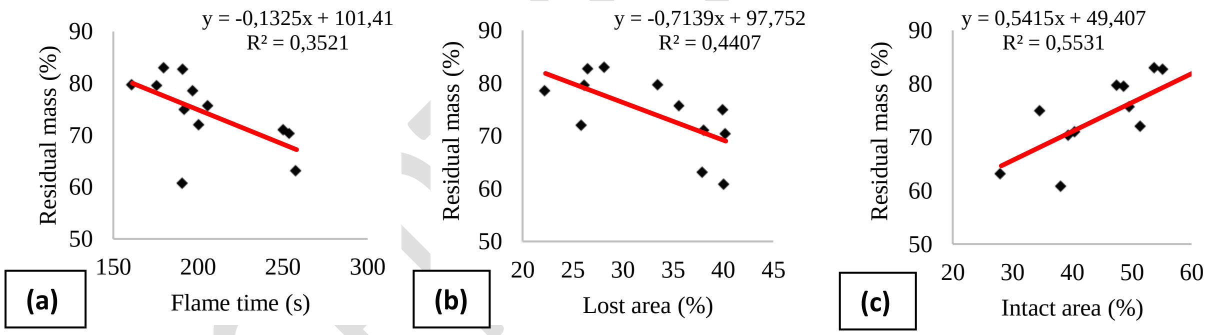

Figure 5: Variation in residual mass (%) as a function of (a) flame time (s), (b) lost area (%), and (c) intact area (%).

Table 3: Lost, charred, and intact area (%) after fire exposure test of wood of twelve Amazon species.

Species	Lost area (%)	Charred area (%)	Intact area (%)	Representative image
H. courbaril	26,59 c (6,82)	18,11 d (17,52)	55,30 b (5,07)	
G. guidonia	33,52 c (4,46)	18,91 d (15,34)	47,57 b (5,01)	
M. huberi	28,23 c (13,45)	17,89 d (3,90)	53,88 b (5,94)	
H. serratifolius	22,29 c (10,09)	15,04 d (23,69)	62,68 a (8,40)	
A. lecointei	26,22 c (15,02)	24,98 b (3,49)	48,80 b (6,28)	
A. acreana	25,92 c (17,34)	22,53 c (5,35)	51,55 b (6,49)	
C. odorata	37,98 c (8,22)	33,89 a (6,02)	28,13 d (11,58)	
S. amara	40,14 a (7,22)	21,67 c (9,65)	38,18 c (6,13)	
P. angustiflora	40,03 b (13,98)	25,29 b (14,93)	34,69 c (5,25)	
B. nitida	38,16 b (4,07)	21,23 c (3,78)	40,62 c (1,85)	
H. petraeum	35,67 c (2,46)	14,60 d (9,46)	49,73 b (1,72)	
A. leiocarpa	40,26 a (7,54)	20,29 c (15,21)	39,45 c (15,42)	

Means followed by the same letter in the column do not differ significantly according to the Scott–Knott test ($p \leq 0,05$). Values in parentheses refer to the coefficient of variation.

The woods of cedar (*Cedrela odorata* L.), angelim (*Hymenolobium petraeum* Ducke.), muskwood (*Guarea guidonia* (L.) Sleumer), masaranduba (*Manilkara huberi* (Ducke) A.Chev.), courbaril (*Hymenaea courbaril* L.), muiracatiara (*Astronium lecointei* Ducke.), cerejeira (*Amburana acreana* (Ducke) A.C.Sm.) and yellow lapacho (*Handroanthus serratifolius* (Vahl) S.O.Grose) presented the lowest percentages of lost area (Table 3), between 22 % and 38 %. These woods are reasonably resistant to burning since they can maintain more than 50 % of their structure intact after a fire.

There was a significant difference in the charred areas of the Amazon woods evaluated after the fire exposure test, with values ranging from 14,60 % for angelim (*Hymenolobium petraeum* Ducke.) to 33,89 % for cedar (*Cedrela odorata* L.). This higher value was probably due to the longer flame time associated with a short ember time in the fire exposure test (Table 2). The formation of a carbonized zone associated with the loss of area results in the loss of resistance of the wood used as a structural element (Pinto and Calil-Junior 2006. However, the lower conductivity of charcoal, approximately five times less than that of wood (Santos *et al.* 2020a, Glass and Zelinka 2010), helps extinguish the fire by making it difficult to heat the central part of the piece, thus keeping a part of the wood intact. This is because the formation of a charcoal layer provides thermal insulation, delaying thermal degradation (Camargo and Ibáñez 2024).

With respect to the intact areas visually analyzed after the fire exposure test, there was a significant variation among the evaluated species, which formed four groups. The wood of yellow lapacho (*Handroanthus serratifolius* (Vahl) S.O.Grose) had the highest percentage of intact area (62,68 %), one of the smallest charred areas and the smallest lost area (Table 3). The woods of angelim (*Hymenolobium petraeum* Ducke.), muskwood (*Guarea guidonia* (L.) Sleumer), masaranduba (*Manilkara huberi* (Ducke) A.Chev.), courbaril (*Hymenaea courbaril* L.), muiracatiara (*Astronium lecointei* Ducke.) and cerejeira (*Amburana acreana* (Ducke) A.C.Sm.) had a small loss area, resulting in approximately 50 % intact area. These intact areas are related to residual mass (Figure 5), whose correlation between variables was 0,74. This result shows that these woods are the most suitable for use in construction since a piece of wood exposed to fire will create three layers (charred, heated, and intact) and keep the central layer intact and its properties unchanged (Schmid *et al.* 2015).

The wood of cedar (*Cedrela odorata* L.) had the lowest percentage of intact area (28,13 %), that is, it was the wood that degraded the most, showing a low capacity to maintain a structure and ease of burning, confirming that, together with marupa (*Simarouba amara* Aubl.), it is a wood not resistant to exposure to fire. To enable the use of these woods, treatments can be applied, such as the one evaluated by Altay *et al*. (2022), who assessed wood treatment with fire retardants and coatings of polyurethane/polyurea hybrid resin and epoxy resin. They reported a reduction in mass loss while maintaining or enhancing mechanical strength.

Proximate analysis

The content of volatile matter in the wood of the species evaluated differed significantly ($p \leq 0,05$), separating them into two groups (Table 4). The group with the highest volatile content was courbaril (*Hymenaea courbaril* L.), yellow lapacho (*Handroanthus serratifolius* (Vahl) S.O.Grose), masaranduba (*Manilkara huberi* (Ducke) A.Chev.), cerejeira (*Amburana acreana* (Ducke) A.C.Sm.), cedar (*Cedrela odorata* L.), marupa (*Simarouba amara* Aubl.), and purpleheart (*Bowdichia nitida* Spruce ex Benth), whose volatile content ranged from 81,9 % to 83,90 %. The other species had mean values ranging from 80,26 % to 81,54 %, with the lowest percentage of volatile matter for muskwood (*Guarea guidonia* (L.) Sleumer), muiracatiara (*Astronium lecointei* Ducke.), purpleheart (*Peltogyne angustiflora* Ducke.), angelim (*Hymenolobium petraeum* Ducke.) and garapa (*Apuleia leiocarpa* (Vogel) J.F. Macbr.).

Table 4: Proximate analysis of wood from twelve wood Amazon species.

Species	Volatile matter (%)	Fixed carbon (%)	Ash (%)
H. courbaril	82,12 a $^{(0,91)}$	17,47 a $^{(4,44)}$	0,41 d $^{(41,77)}$
G. guidonia	80,26 b $^{(0,35)}$	18,31 a $^{(1,54)}$	1,43 a $^{(12,28)}$
M. huberi	82,99 a $^{(0,88)}$	16,66 b $^{(5,31)}$	0,35 d $^{(61,41)}$
H. serratifolius	83,90 a $^{(0,67)}$	15,90 b $^{(5,55)}$	0,19 d $^{(4,30)}$
A. lecointei	81,54 b $^{(1,69)}$	18,08 a $^{(7,82)}$	0,37 d $^{(10,35)}$
A. acreana	82,80 a $^{(1,03)}$	16,76 b $^{(5,17)}$	0,43 d $^{(26,91)}$
C. odorata	82,67 a $^{(0,87)}$	16,52 b $^{(4,05)}$	0,80 c $^{(9,86)}$
S. amara	82,35 a $^{(0,62)}$	17,22 b $^{(3,24)}$	0,44 d $^{(65,06)}$
P. angustiflora	81,36 b $^{(1,78)}$	17,80 a $^{(9,37)}$	0,83 c $^{(36,34)}$
B. nitida	81,91 a $^{(1,12)}$	17,86 a $^{(5,49)}$	0,23 d $^{(47,63)}$
H. petraeum	80,48 b $^{(1,23)}$	19,20 a $^{(4,56)}$	0,31 d $^{(43,26)}$
A. leiocarpa	80,38 b $^{(0,69)}$	18,47 a $^{(3,38)}$	1,15 b $^{(19,03)}$

Means followed by the same letter in the column do not differ significantly according to the Scott–Knott test ($p \leq 0,05$). Values in parentheses refer to the coefficient of variation.

Volatile matter is identified as the mass fraction of fuel that volatilizes during heating, affecting the dynamics of wood burning and promoting the ignition of the material as volatile levels increase

(Massuque *et al.* 2021, Lima *et al.* 2020). Thus, ignition is facilitated, and there is a longer flame time with woods with high volatile rates. However, for the wood samples evaluated here, the variation in volatile content between species was low (approximately 4 %), which indicates that the volatile content has little influence on the number of ignitions and flames.

According to Leroy *et al.* (2006), the ease of ignition is directly related to the amount of volatile gases emitted by the thermal decomposition of the fuel. For the wood samples evaluated in this study, there was a negative correlation of -0,50 between the ignition temperature and the volatile matter content. However, this relationship was verified mainly for wood of yellow lapacho (*Handroanthus serratifolius* (Vahl) S.O.Grose), resulting in an R^2 of 0,2483 according to regression analysis (Figure 6), which has the lowest time and ignition temperature (Table 1).

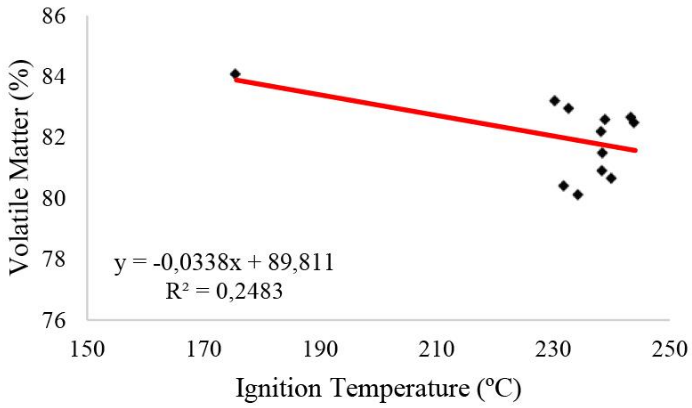

Figure 6: Variation in volatile matter content (%) as a function of ignition temperature (°C).

For the fixed carbon and ash contents, there was a significant difference ($p \leq 0,05$). For the fixed carbon content, which had a negative Pearson correlation with volatile matter (-0,94), two groups formed. The highest average values were found for courbaril (*Hymenaea courbaril* L.), muskwood (*Guarea guidonia* (L.) Sleumer), muiracatiara (*Astronium lecointei* Ducke.), purpleheart (*Peltogyne angustiflora* Ducke.), purpleheart (*Bowdichia nitida* Spruce ex Benth), angelim (*Hymenolobium petraeum* Ducke.) and garapa (*Apuleia leiocarpa* (Vogel) J.F. Macbr.): all above 17,47 %. Soares *et al.* (2014) reported that a greater presence of fixed carbon could lead to longer wood burning but more slowly, in the form of embers. However, according to the same authors, depending on the burning or fire conditions, fixed carbon may result in the formation of a charred layer.

Regarding the ash content, four groups were formed (Table 4), ranging from 0,19 % (yellow lapacho (*Handroanthus serratifolius* (Vahl) S.O.Grose)) to 1,43 % (muskwood (*Guarea guidonia* (L.) Sleumer)). Brun *et al.* (2018) reported that inorganic materials do not affect the dynamics of fires since they are noncombustible materials and occur in small proportions in wood.

Physical properties

The average basic density values of the evaluated wood ranged from 335,89 kg·m^{-3} (marupa (*Simarouba amara* Aubl.)) to 889,64 kg·m^{-3} (courbaril (*Hymenaea courbaril* L.)), and the species were divided into nine groups according to the Scott–Knott test (Table 5). The values are in line with what is expected for Amazon woods (Lima *et al.* 2020, Sousa *et al.* 2019, Fearnside 1997).

Table 5: Physical properties of wood from twelve Amazon species.

Species	Basic density (kg/m³)	Porosity (%)
H. courbaril	889,64 a (0,85)	40,88 h (1,36)
G. guidonia	556,12 h (1,73)	62,88 c (1,09)
M. huberi	870,19 b (1,47)	41,73 h (2,14)
H. serratifolius	787,03 c (1,04)	47,62 g (1,41)
A. lecointei	614,17 f (2,80)	58,23 e (1,57)
A. acreana	570,86 g (1,39)	61,48 d (0,16)
C. odorata	437,05 j (6,22)	70,50 b (2,49)
S. amara	335,89 j (1,54)	77,77 a (0,23)
P. angustiflora	653,92 d (1,38)	56,55 f (0,94)
B. nitida	775,24 c (1,52)	48,44 g (2,28)
H. petraeum	633,40 e (0,98)	58,07 e (0,63)
A. leiocarpa	648,90 d (3,18)	56,38 f (1,37)

Means followed by the same letter in the same column do not differ significantly according to the Scott–Knott test ($p \leq 0,05$). The values in parentheses refer to the coefficient of variation.

Species with heavy wood (750 kg/m^3 to 1000 kg/m^3), according to the classification proposed by Csanády *et al.* (2015) – courbaril (*Hymenaea courbaril* L.), yellow lapacho (*Handroanthus serratifolius* (Vahl) S.O.Grose), masaranduba (*Manilkara huberi* (Ducke) A.Chev.) and purpleheart (*Bowdichia nitida* Spruce ex Benth) – are recommended for heavy civil construction, especially for structural uses such as roof structures and bridges and to produce external floors, such as decks and walkways (Melo and Camargos 2016). This is due to the high correlation of mechanical strength with wood density (Reis *et al.* 2019).

Medium-density woods (500 kg/m^3 to 750 kg/m^3) – purpleheart (*Peltogyne angustiflora* Ducke.), angelim (*Hymenolobium petraeum* Ducke.), garapa (*Apuleia leiocarpa* (Vogel) J.F. Macbr.), muiracatiara (*Astronium lecointei* Ducke.), muskwood (*Guarea guidonia* (L.) Sleumer), and cerejeira (*Amburana acreana* (Ducke) A.C.Sm.) – are recommended for use in the furniture industry and light civil construction, such as frames, doors, slats, baseboards, and linings (Melo and Camargos 2016). These woods can also be used for the production of solid floors, provided that they are intended for installation in residential environments with light traffic, where the loads are low (Costa *et al.* 2021).

Light woods (300 kg/m^3 to 500 kg/m^3) – marupa (*Simarouba amara* Aubl.) and cedar (*Cedrela odorata* L.) – are easy to work with and ideal for making shutters, ceilings, turned objects, panels, and frames (Melo and Camargos 2016). Notably, light wood should never be used for structures or even as frames in civil construction.

The average porosity values are inversely proportional to the basic density values. According to the Scott–Knott test, eight groups were formed. marupa (*Simarouba amara* Aubl.) has the highest porosity value (77,76 %), and masaranduba (*Manilkara huberi* (Ducke) A.Chev.) and courbaril (*Hymenaea courbaril* L.) have the lowest porosity value (~ 40 %).

Greater porosity in wood results in a greater void volume filled with air, which can contribute to faster ignition as well as a higher burning speed, as verified for the wood of marupa (*Simarouba amara* Aubl.). This accelerates burning due to the greater contact and volume of O_2 available, a necessary factor for starting and maintaining the flame during burning and/or fire.

Higher basic density and lower porosity result in fewer empty spaces and less air inside the wood, properties that can promote longer ignition time. Nunes (2015) reported the same relationship. When different lignocellulosic materials were evaluated, longer ignition times were observed for higher-density materials. This result differs from the combustion parameters determined via thermogravimetric analysis because powdered material was used there; therefore, the physical properties of the wood affected the results to a lesser extent.

The correlation between porosity and ignition time was -0,60, a moderate and negative correlation; that is, the lower the porosity was, the longer the ignition time. The porosity explained 35% of the variation in the ignition time (Figure 7). This behavior clearly occurred in the woods of courbaril (*Hymenaea courbaril* L.) and masaranduba (*Manilkara huberi* (Ducke) A.Chev.), which are resistant to the onset of burning (ignition) and have lower porosity percentages, and the wood of marupa (*Simarouba amara* Aubl.), which has a higher porosity, has a shorter ignition time.

When wood is considered for construction, one aspect that deserves attention is its natural aging. When evaluating the effect of aging on the flammability of pine (Deng *et al.* 2023), they reported that an increase in porosity, the formation of cracks and a decrease in moisture content reduced the flash point of the pine to 15,2 °C because of the increased heat transfer to the wood interior. However, compared with fresh wood, natural aging increases the dry cracking temperature of wood, reduces the carbonization temperature and combustion performance and promotes the formation of a larger carbonized layer.

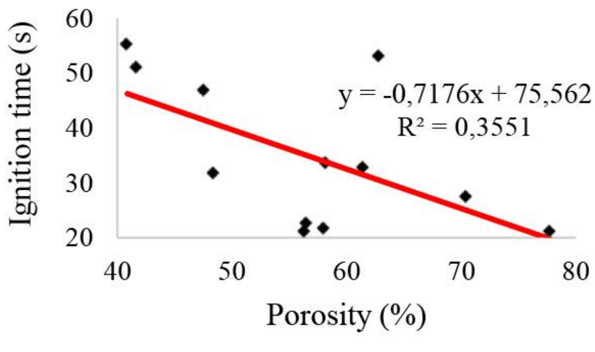

Figure 7: Variation in ignition time (s) as a function of wood porosity (%).

Mechanical properties

Table 6: Mechanical properties of wood from twelve Amazon species.

Species	f_{c0} (MPa)	E_{c0} (GPa)
H. courbaril	82,21 a (2,33)	28,59 a (3,50)
G. guidonia	51,41 e (2,93)	29,76 a (6,33)
M. huberi	64,49 c (4,64)	30,36 a (4,47)
H. serratifolius	70,88 b (2,83)	33,61 a (6,37)
A. lecointei	47,96 e (4,93)	32,38 a (20,50)
A. acreana	47,49 e (5,69)	18,71 b (4,75)
C. odorata	38,63 f (2,63)	15,71 b (1,26)
S. amara	29,35 g (4,12)	9,03 c (1,65)
P. angustiflora	69,45 b (2,44)	29,44 a (3,37)
B. nitida	73,95 b (9,63)	26,23 a (1,53)
H. petraeum	59,71 d (4,08)	31,38 a (2,89)
A. leiocarpa	59,78 e (1,87)	22,56 b (4,49)

fc0: compressive strength parallel to the fibers; Ec0: modulus of elasticity in compression parallel to the fibers. Means followed by the same letter in the same column do not differ significantly according to the Scott–Knott test ($p \leq 0,05$). The values in parentheses refer to the coefficient of variation.

For the compressive strength parallel to the fibers, there was a significant difference among the species, and the values ranged from 29,35 MPa (marupa (*Simarouba amara* Aubl.)) to 82,21 MPa (courbaril (*Hymenaea courbaril* L.)). The modulus of elasticity in compression parallel to the fibers ranged from 9,03 GPa (marupa (*Simarouba amara* Aubl.)) to 33,61 GPa (yellow lapacho (*Handroanthus serratifolius* (Vahl) S.O.Grose)) (Table 6). The wood of purpleheart (*Peltogyne angustiflora* Ducke.) stands out. It is classified as wood of moderate density (653,92 kg/m^3) but has mechanical properties similar to those of heavy wood. Thus, when used in heavy civil construction, the wood of courbaril (*Hymenaea courbaril* L.), yellow lapacho (*Handroanthus serratifolius* (Vahl) S.O.Grose), masaranduba (*Manilkara huberi* (Ducke) A.Chev.), purpleheart (*Bowdichia nitida*

Spruce ex Benth) and purpleheart (*Peltogyne angustiflora* Ducke.) ensures greater resistance and rigidity to structures.

Pearson's correlation analysis revealed a positive correlation between the basic density and mechanical properties: 0,91 for resistance to compression parallel to the fibers and 0,72 for the modulus of elasticity in compression parallel to the fibers, confirming that the greater the density is, the greater the strength and rigidity of the wood of the evaluated species. The basic density explained 82 % of the variation in the compressive strength and 52 % of the variation in the modulus of elasticity (Figure 8).

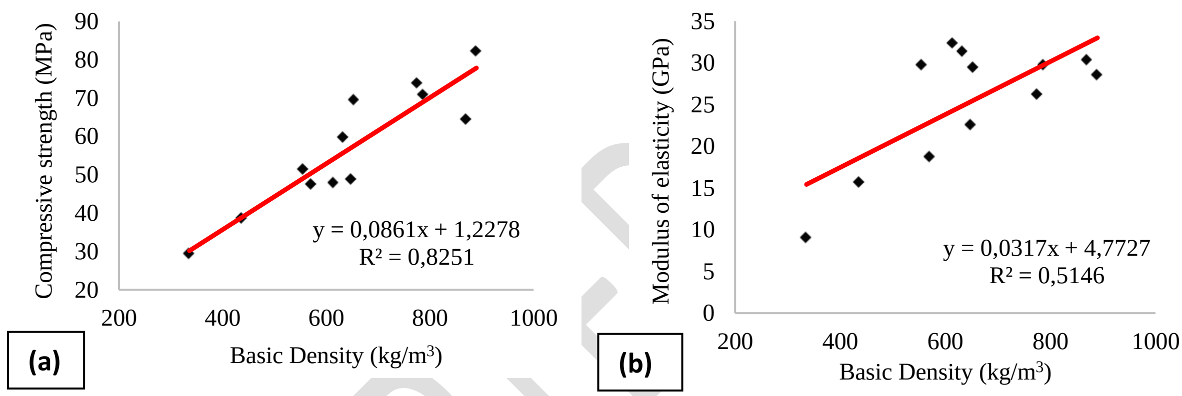

Figure 8: Variation in mechanical properties. (a) Compressive strength parallel to the fibers (MPa) and (b) modulus of elasticity (GPa) as a function of basic density (kg/m^3).

Considering their physical and mechanical properties, the woods of *Hymenaea* spp., *Manilkara* spp., *Handroanthus* spp., and *Bowdichia* spp. are recommended for use in heavy civil construction, both external and internal, as sawn wood pieces in the form of beams, rafters, planks, and boards. *Apuleia* spp., *Hymenolobium* spp., *Peltogyne* spp., *Astronium* spp., *Amburana* spp., and *Guarea* spp. can be used in heavy civil construction but primarily in light internal and external civil construction in the form of boards, slats, and rafters. The woods of *Cedrela* spp. and *Simarouba* spp. should be used in light civil construction for joinery.

Conclusions

The Amazon woods of *Hymenaea courbaril* L. (courbaril), *Manilkara huberi* (Ducke) A.Chev. (masaranduba), and *Handroanthus serratifolius* (Vahl) S.O.Grose (yellow lapacho)exhibit high basic density and mechanical resistance. Combined with their lower degradation when exposed to fire, these woods are the most suitable for use as structural elements in construction.

Among the medium-density woods, *Guarea guidonia* (L.) Sleumer (muskwood) and *Astronium lecointei* Ducke. (muiracatiara) with, are recommended for structural use due to their high rigidity and fire resistance The determination of the initial combustion time (ti) and ignition temperature (Ti) through thermogravimetric analysis is essential for evaluating the fire resistance of woods.

Short-term fire exposure tests, particularly the ignition time parameter combined with residual mass and intact area, are important the fire resistance of wood.

Authorship contributions

L. V. C. S.: Conceptualization, data curation, formal analysis, investigation, methodology, supervision, visualization, writing-original draft, writing-review & editing. B. P. Z: Conceptualization, data curation, formal analysis, investigation, methodology, supervision, visualization, writing-original draft. A. B. S.: Formal analysis; methodology. B. L. C. P.: Formal analysis, investigation, writing-review & editing. E. C. L.: Conceptualization, methodology, visualization, writing-review & editing. A. C. O.: Conceptualization, formal analysis, funding acquisition, methodology, project administration, supervision, visualization, writing-original draft, writing-review & editing.

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