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Articles

Valuation of seven Cerrado woods in charcoal production

Valorização de sete madeiras do Cerrado na produção de carvão vegetal

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ABSTRACT

Considering the importance of charcoal in promoting sustainable steelmaking as an agent for environmental decarbonization, the aim of this research was to examine the energy quality of charcoal produced from the wood of seven Cerrado forest species. The material used in this study came from trees located in various municipalities in the state of Minas Gerais, Brazil, within the area of occurrence of the Cerrado Sensu Stricto biome. The disks were collected at breast height (1.3 m above the ground) and then subdivided into four wedges, passing through the pith. Two of these wedges were allocated for determining physical and anatomical properties, while the other two were designated for carbonization. The anatomical and physical elements of the wood were described, and a multivariate analysis of charcoal quality was conducted. Among the seven species investigated, the best results were obtained for *Bowdichia virgilioides*, a specimen with a higher basic wood density and longer fibers, important characteristics for its high performance in charcoal production and quality. The medium-density *Persea willdenovii* wood produced low-density charcoal, while *Qualea grandiflora* and *Tabebuia aurea* were not recommended for use in the metallurgical industries, as they did not meet satisfactory fixed carbon standards. This study aims to provide a significant role in charcoal production by diversifying the sources of wood currently used.

Keywords: Charcoal; Native species; Cerrado; Multivariate analysis

RESUMO

Devido à importância do carvão vegetal na promoção da siderurgia sustentável como agente de descarbonização ambiental, esta pesquisa teve como objetivo avaliar a qualidade energética do carvão vegetal produzido a partir da madeira de sete espécies florestais do Cerrado. O material empregado neste estudo foi oriundo de árvores localizadas em diversos municípios do estado de Minas Gerais, Brasil, dentro da área de ocorrência do bioma Cerrado *Sensu Stricto*. Os discos foram coletados na região da altura do peito (1,3 m acima do solo) e posteriormente subdivididos em quatro cunhas, passando pela medula. Duas dessas cunhas foram alocadas para determinação de propriedades físicas e anatômicas, enquanto as outras duas foram designadas para carbonização. Realizou-se a descrição dos elementos anatômicos e físicos da madeira e a análise multivariada da qualidade do carvão vegetal. Dentre as sete espécies investigadas, os melhores resultados foram obtidos para *Bowdichia virgilioides*, exemplar com maior densidade básica de madeira e fibras mais longas, características importantes para seu alto desempenho na produção e qualidade de carvão vegetal. A madeira de *Persea willdenovii* de densidade média produziu carvão de baixa densidade, enquanto *Qualea grandiflora* e *Tabebuia aurea* não são recomendadas para uso nas indústrias metalúrgicas, pois não atendem aos padrões desejáveis de carbono fixo. Este estudo pode desempenhar um papel significativo na produção de carvão vegetal, diversificando as fontes de madeira atualmente utilizadas.

Palavras-chave: Carvão vegetal; Espécies nativas; Cerrado; Análise multivariada

1 INTRODUCTION

In Brazil, the use of wood for energy generation has a long historical association with charcoal production, primarily due to the demand for this product by the steel industry. The country is an absolute leader in steel production using charcoal as a bioreducing agent, resulting in what is known as “green steel”. For example, in 2021, 4.25 million tons of charcoal were incorporated into the iron and steel, ferroalloys, and metallic silicon sectors, reaffirming the environmental commitment of the entire production chain (IBÁ, 2022).

In the cultivated tree sector, the percentage of total charcoal production is significant, accounting for 94% (PEVS - IBGE, 2020). Among the raw materials used, *Eucalyptus* stands out for its high silvicultural productivity, environmental adaptability, uniformity and wood quality. Despite the exponential increase in the establishment of homogeneous forest plantations, they are still not able to fulfill all the demand from companies, resulting in an average annual deficit of approximately 47%. This deficit is filled by natural forests, with the Cerrado biome being one of the main suppliers of charcoal (Cachoeira *et al*., 2019).

The silviculture of Cerrado species is still underexplored in the establishment of plantations for commercial uses, representing a challenge that needs to be overcome for the diversification of forest biomass. Studies conducted by Mendonça *et al*. (2008), Pilon and Durigan (2013), and Oliveira *et al*. (2015) indicate a high survival rate of seedlings from different species of the biome, exceeding 70%, which confirms their plasticity and tolerance to the climatic and soil conditions at the planting sites. Oliveira *et al*. (2015) discuss some growth strategies of Cerrado species compared to exotic species, highlighting a greater average growth in diameter during the early years, in contrast to traditionally planted species, which initially develop more in height. This would be a physiological adaptation for water and nutrient uptake related to seasonality.

The Cerrado is a tropical savannah region in South America, including a large part of central Brazil, part of northeastern Paraguay and eastern Bolivia, and is Brazil's second largest domain. The Cerrado occupies approximately 24% of Brazil's territory, in a total estimated area of 2,036,448 km² (Santos *et al*., 2021). The Brazilian Cerrado is recognized as one of the most biodiverse biomes in the world, with more than 12,000 plant species found there, many of which have significant economic and environmental potential (Carvalho, 2022).

Throughout the years, significant transformations in land use and occupation have been observed in this biome (Carvalho, 2022). Despite the appropriate environmental licenses, areas are cleared for agricultural activities, predominantly pastures and reforestation, or for road construction, resulting in a considerable amount of forest waste. Charcoal production has emerged as a solution, not only to add value to this waste, but also to ensure proper environmental disposal. Furthermore, charcoal from native species should also be considered as a promising economic potential, providing income-generating opportunities for local communities and contributing to regional development.

The use of wood from a particular forest species for bioenergy should be based on an analysis of its chemical, anatomical, physical and energy properties (Soleymani *et al*., 2023). Thus, high-quality biomass must have a high fixed carbon content, thick-walled tissues, few empty spaces in the lumen, low moisture content, high basic density and high calorific value. These variables are influenced by the characteristics of the wood, such as species, age and position in the tree, as well as by silvicultural techniques related to the production of energy forests.

The literature indicates that species native to the Cerrado are suitable for producing heat (Vale *et al*., 2010; Marques *et al*., 2020; Siqueira *et al*., 2020). Notably, genera such as *Astronium*, *Dalbergia* and *Sclerolobium* are highlighted for their high dry mass production, higher specific masses, calorific values above the general average and excellent results for fixed carbon. Costa *et al*. (2014), evaluating the energy potential of five species native to the Cerrado region of Minas Gerais, highlighted the gravimetric yields (30.88 - 34.39%) and promising charcoal properties of these species, including apparent relative density (0.255 - 0.475 $g.cm^{-3}$), higher calorific value (7.135 - 7.730 $kcal.kg^{-1}$), fixed carbon (77.2 - 81.0%) and fixed carbon yield (24.3 - 26.56%).

Due to the importance of charcoal in promoting sustainable steelmaking as an agent of environmental decarbonization, in line with the practice of using native forests that would otherwise be cleared for agricultural substitution, this research aimed to evaluate the energy quality of charcoal produced from the wood of seven Cerrado species. The researchers are convinced that, in addition to proper management of forest resources and evaluation of the waste generated, the results obtained can contribute significantly to diversifying the sources of wood used in charcoal production. Furthermore, the research project aims to promote the field of forestry by encouraging studies into the implementation and management of energy plantations involving alternative species. Thus, the objective is not only to diversify raw materials for energy production, but also to promote sustainable development through the responsible management of natural resources.

2 MATERIALS AND METHODS

2.1 Biomass characterization

The trees used in this study came from mature native vegetation in the Cerrado Sensu Stricto Biome, harvested under a sustainable forest management plan and donated to the university for scientific research, as shown in Table 1. The disks were collected at breast height (1.3 m above the ground) and then subdivided into four wedges, passing through the pith. Two of these wedges were used to determine physical and anatomical properties, whereas the other two were used for carbonization.

Table 1 – Botanical information, collection location, and dendrometric data of the species

Specie/ Botanical family	Collection location	Th (m)[1]	DBH (cm)[1]
Agonandra brasiliensis Benth. & Hook.f. (Opiliaceae)	Pompéu (19° 12′ 25″ S, 44° 56′ 14″ O)	8.10	19.16
Bowdichia virgilioides Kunth (Leguminosae)	Corinto (18° 24′ 14″ S, 44° 27′ 32″ O)	9.90	21.42
Casearia mariquitensis Kunth (Flacourtiaceae)	Berizal (15° 36′ 50″S, 41° 44′ 57″O)	12.89	25.30
Qualea grandiflora Mart. (Vochysiaceae)	Brasilândia de Minas (17° 1′ 10″ S, 46° 0′ 55″ O)	10.70	35.65
Strychnos pseudoquina A.St.-Hil. (Loganiaceae)	Curral de Dentro (15° 56′ 47″ S, 41° 50′ 53″ O)	7.80	25.05
Persea willdenovii Kosterm. (Lauraceae)	Mariana (20° 22′ 41″ S, 43° 25′ 0″ O)	15.10	18.02
Tabebuia aurea (Silva Manso)Benth. & Hook.f. ex S.Moore (Bignoniaceae)	Salinas (16° 8′ 36″ S. 42° 18′ 11″ O)	6.59	16.65

Source: Authors (2023)

In where: [1] Total height (Th); Diameter at Breast Height (DBH).

2.2 Physical and anatomical characterization of wood

A moisture analyzer with halogen light was used to determine the moisture content of the wood. The basic density of the wood was determined using the immersion method, in accordance with standard NBR 7190 (ABNT, 2022). The dry mass of the samples was determined on a precision analytical balance (0.1g), after reaching constant weight in an oven at 103 ± 2ºC, and the volumes were determined using the Archimedes principle.

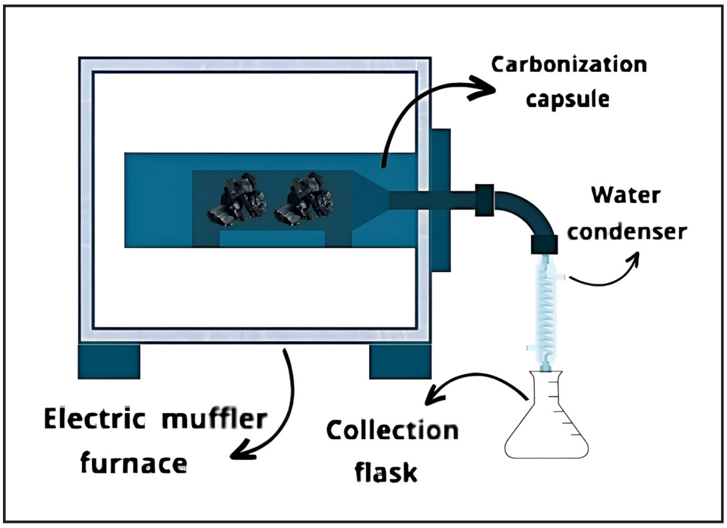
For the anatomical analysis of fiber biometrics, macerated slides were prepared. Small fragments were taken from the heartwood and sapwood portions and immersed in a macerating solution adapted from Franklin (1945), consisting of 50% glacial acetic acid, 58% hydrogen peroxide, and 12% distilled water. The Eppendorf containing wood fragments and the solution were placed in an oven at 50°C for 24 hours to soften the material, followed by maceration through friction. Once the fibers were disaggregated, the macerate was washed in distilled water and filtered using filter paper. Subsequently, the fibers were stained with safranin, and permanent slides were prepared with Entellan. Measurements of length, total diameter, and lumen diameter of 25 fibers were taken under a microscope, and the wall thickness was calculated using the ratio, according to Equation (1):

$$\text{Wall thickness} = \frac{(\text{fiber diameter}) - (\text{lumen diameter})}{2} \quad (1)$$

2.3 Wood carbonization and charcoal quality

Previously, charring wood involved extracting a sample from each wedge to determine moisture content using an infrared scale. The laboratory carbonizations were performed in an electric muffle furnace connected to a water-cooled condenser, which is coupled to a condensable gas collector (Figure 1). Heating control was manual, with temperature increments following the specified ramp, corresponding to an average heating rate of 1.25°C/min. The initial temperature was set at 150°C, reaching a final temperature of 450°C, with a total carbonization time of 4 hours.

Figure 1 – Schematic of the carbonization system



Source: Authors (2023)

To evaluate the charcoal, the gravimetric yield was measured as the difference between the mass of charcoal and wood, free of water. In order to evaluate the charcoal, the gravimetric yield was measured by the difference between the mass of the charcoal and that of the wood without water. The moisture content, fixed carbon, volatile material and ash content were determined according to the specifications of standard D1762-84 (ASTM, 2013). The higher heating value was estimated according to Dulong's empirical Equation (2), which considers the fixed carbon content of the sample, as proposed by Green and Perry (2008) and Jenkins (1998).

$$PCS = 338 * FC \quad (2)$$

where: PCS – higher heating value ($KJ. Kg^{-1}$); FC – Fixed Carbon.

The determination of apparent relative density was based on the ASTM D-167-93 standard (ASTM, 1999) for mineral coal, adapted for charcoal, in conjunction with the methodology suggested by Oliveira *et al*. (1982). The charcoal was previously weighed and carefully placed in a wire basket. The basket was immersed in a container of distilled water at room temperature, where it remained for 15 minutes. After this time, the hole in the container was opened to collect the displaced water. After removing the basket from the water, allowing the excess water to drain off, it was left to stand for 1 to 2 minutes and then the moistened charcoal and the displaced water were measured. The apparent density was calculated according to Equation (3):

$$ARD = \frac{Wcd}{[Wcb + (Wcw - Wcd)]} \tag{3}$$

where: ARD – Apparent Relative Density (Kg/m³); Wcd – Weight of charcoal after drying in an oven (g); Wcb – Weight of water displaced from the container by the immersion of charcoal + basket (g) ; Wcw – Weight of wet charcoal (g).

The pyrolyzed liquor was collected in a suitable recipient during carbonization and, after completion, the recipient was left to cool at room temperature for 15 hours and then weighed to determine the yield of the condensed liquids. The yield was calculated as the ratio between the mass of pyroligneous liquor formed afterwards and the dry mass of the wood before carbonization. The yield of non-condensable gases was calculated by difference, according to Equation (4):

$$NCGY = 100 - (CGY + PLY) \tag{4}$$

where: NCGY – non-condensable gases yield (%, dry basis); CGY – gravimetric yields of charcoal (%, dry basis); PLY – pyroligneous liquid yield (%, dry basis).

2.4 Data analysis

The experiment was evaluated using a completely randomised design (CRD), considering different species as the variation factor. A total of three discs per species were evaluated in the experiment. To analyze the basic density of the wood and the quality of the charcoal - volatile material, fixed carbon and ash content, apparent relative density and moisture content - the average values of the duplicates are presented. On the other hand, variables such as gravimetric charcoal yield, condensable gases, non-condensable gases (3 repetitions) and fiber biometry (25 repetitions) were assessed using ANOVA. The data were subjected to the Shapiro-Wilk normality test and their means were statistically compared using the Tukey test at a significance level of 5% with the ASSISTAT© statistical software.

A group analysis was conducted using a dendrogram constructed using the hierarchical grouping method proposed by Ward (1963). The Mahalanobis distance was adopted as a measure of dissimilarity, as suggested by Cruz and Carneiro (2006), indicating characteristics measured for the species in this study, along with information on other species taken from the literature (Table 2), for the attributes of basic density, gravimetric charcoal yields, apparent relative density, volatile material, fixed carbon and ash content. The Elbow method (Thorndike, 1953) was used to determine the ideal number of groups in the dendrogram. By means of multivariate data analysis, the authors sought to observe the proximity or distance of the native species in this study in relation to those already described in the literature and even some used commercially. The analysis was processed using R Studio software version 4.0.2 (R Core Team 2020).

Table 2 – Information used for multivariate analysis

Species	Evaluated data						References
	BD wood (g/cm^3)	CGY (%)	ARD (g/cm^3)	VM (%)	FC (%)	Ashes (%)	
Agonandra brasiliensis	0.71	33.32	0.575	25.9	71.8	2.3	Our research
Bowdichia. virgilioides	0.72	34.83	0.688	26.1	71.6	2.3	
Casearia mariquitensis	0.56	29.85	0.446	27.1	70.2	2.7	
Qualea grandiflora	0.61	36.84	0.45	36.1	60.9	2.9	
Strychnos pseudoquina	0.51	32.57	0.44	27.5	70.2	2.3	
Persea willdenovii	0.53	30.16	0.273	26.5	71.3	2.2	
Tabebuia aurea	0.58	31.28	0.381	35.8	61.9	2.4	

To be continued ...

Table 2 – Continuation

Species	Evaluated data						References
	BD wood (g/cm³)	CGY (%)	ARD (g/cm³)	VM (%)	FC (%)	Ashes (%)	
Luehea divaricata	0.48	34.39	0.386	18.1	77.2	5.2	Costa *et al*. 2014
Casearia sylvestris	0.63	33.08	0.475	17.6	77.6	4.7	
Rapanea ferruginea	0.51	30.88	0.366	18	79.4	2.6	
Trema micranta	0.36	31.73	0.255	20	77.7	2.4	
Guazuma ulmifolia	0.55	31.38	0.462	14.4	81	3.3	
Sclerolobium aureum	0.472	27.74	0.314	24.23	73.54	2.24	Souza *et al*. 2022
Astronium fraxinifolium	0.577	27.54	0.405	43.03	53.89	3.09	
Handroanthus ochraceus	0.643	27.17	0.491	24.79	74.16	1.05	
Anacardium humile	0.49	34.78	0.38	30.18	59.22	11.61	Silva *et al*. 2020
Palicourea rigida	0.58	34.48	0.49	25.9	70.74	4.25	
Terminalia glabrescens	0.74	36.25	0.66	25.81	73.27	0.96	
Vatairea macrocarpa	0.65	31.34	0.58	21.21	75.26	0.55	
Xylopia aromatica	0.54	29.41	0.41	28.41	70.99	0.67	
Miconia cinnamomifolia	0.665	36	0.268	30.47	68.18	1.35	Brant *et al*. 2013
Mimosa scabrella	0.684	33	0.229	30.39	68.05	1.64	Friederichs *et al*. 2015
Eucalyptus spp. (clone 1277)	0.40	31.4	0.397	20	78.6	1.5	Protásio *et al*. 2014
Eucalyptus spp. (clone 1277)	0.52	32.2	0.403	20.5	78.8	0.7	
Eucalyptus spp. (clone 0321)	0.48	31.7	0.341	21.7	77	1.2	
Eucalyptus spp. (clone 0321)	0.49	31.6	0.398	18.5	80.7	0.9	
E. urophylla x *E. grandis*	0.54	30	0.345	11.74	87.52	0.39	Santos *et al*. 2011
E. urophylla x *E. grandis*	0.52	29	0.29	14.27	87.52	0.39	
E. urophylla x *E. grandis*	0.49	28	0.266	11.74	87.52	0.76	
E. benthamii 5 anos	0.449	34	0.24	29.7	69.3	1	Nones *et al*. 2015
E. benthamii 13 anos	0.505	36	0.36	31.11	66.17	2.72	

To be continued ...

Table 2 – Conclusion

Species	Evaluated data						References
	BD wood (g/cm³)	**CGY (%)**	**ARD (g/cm³)**	**VM (%)**	**FC (%)**	**Ashes (%)**	
Eucalyptus spp. (Areão I144)	0.466	31.88	0.348	19.1	80.17	0.73	Neves *et al*. 2011
Eucalyptus spp. (I220)	0.504	30.26	0.374	18.28	80.95	0.78	
Eucalyptus spp. (3334)	0.454	30.54	0.331	19.38	79.74	0.88	
Eucalyptus spp. (Ponte I144)	0.412	32.47	0.32	20.26	79.19	0.55	
Eucalyptus spp. (I220)	0.473	32.11	0.376	18	81.32	0.69	
Eucalyptus spp. (3334)	0.461	31.65	0.311	20.03	79.26	0.72	
E. urophylla x E. grandis	0.525	34.8	0.38	23.4	76.4	0.15	Ramos *et al*. 2023
E. urophylla x E. grandis	0.475	32.9	0.36	22.5	77.3	0.21	
E. urophylla x E. grandis	0.575	34.4	0.45	23.9	75.9	0.1	
E. urophylla x E. grandis	0.525	34.2	0.36	21.7	78.1	0.21	
E. urophylla	0.658	33.74	0.343	35.2	63.4	1.1	Andrade *et al*. 2018
(E. camaldulensis x E. grandis) x E. urophylla	0.567	38.99	0.321	33.5	64.1	1.9	
E. urophylla x E. grandis	0.696	35.68	0.371	29.7	69.2	1.1	
Eucalyptus spp. (GG 100) - 3	0.452	32.98	0.301	21.34	77.43	1.24	Castro *et al*. 2016
Eucalyptus spp. (GG 100) - 4	0.458	33.1	0.31	21.57	77.55	0.89	
Eucalyptus spp. (GG 100) - 5	0.461	33.18	0.262	23.21	75.83	0.96	
Eucalyptus spp. (GG 100) - 7	0.525	33.53	0.33	23.77	75.75	0.48	
Eucalyptus spp. (GG 157) - 3	0.448	32.61	0.32	22.05	76.52	1.44	
Eucalyptus spp. (GG 157) - 4	0.466	34.29	0.291	22.42	76.63	0.96	
Eucalyptus spp. (GG 157) - 5	0.531	34.49	0.341	24.35	75.1	0.55	
Eucalyptus spp. (GG 157) - 7	0.543	34.81	0.322	25.4	74.25	0.35	
Eucalyptus spp. (GG680) - 3	0.486	34.31	0.337	2313	76.36	0.51	
Eucalyptus spp. (GG680) - 4	0.504	33.91	0.327	23.89	75.46	0.65	
Eucalyptus spp. (GG680) - 5	0.528	34.65	0.345	24.97	74.71	0.32	
Eucalyptus spp. (GG680) - 7	0.565	34.96	0.355	24.05	75.77	0.17	

Source: Authors (2023)

In where: BD – Basic Density; CGY – Gravimetric Yields of Charcoal; ARD – Apparent Relative Density; VM – Volatile material; FC – Fixed Carbon.

3 RESULTS AND DISCUSSION

3.1 Physical and anatomical characterization of wood

The average moisture content of the wood was 10.30 per cent, below the equilibrium moisture content of 12.4 per cent for the city of Montes Claros, where the material was stored and the experiment was conducted (Baraúna *et al*., 2022). These values are in line with the specifications described in DN 227 (COPAM, 2018) for charcoal production, which recommends carbonizing wood with a moisture content below 40%.

Among the evaluated woods, only two are classified as having low basic density: *Strychnos pseudoquina* and *Persea willdenovii*, while the others were categorized as having medium density (Table 2), according to the classification by Melo *et al*. (1990); Vale *et al*. (2002); Silveira *et al*. (2013); and Silva *et al*. (2015). The fibers exhibit medium length and thin to thick walls in all species, except for *Casearia mariquitensis*, which has short fibers, and *Strychnos pseudoquina*, which has fibers with thin walls (IAWA, 1989).

The specimen of *Bowdichia virgilioides* proved to be the densest, a factor that can be attributed to the length of the wood fibers. Conversely, fibers with thin walls confer the lowest basic density value to *Strychnos pseudoquina*. The results corroborate the statement that wood basic density is highly dependent on the dimensions of the cells composing it (Panshin; Zeeuw, 1980).

In order to provide a broader explanation of basic density values through the wood's anatomical constitution, other equally important characteristics should be validated, such as pore frequency and diameter. These assessments could elucidate, for example, how *Persea willdenovii* had the second lowest basic density value (0.527 g/cm^3), despite having long fibers (1193.05 μm) and thin to thick walls (3.37 μm).

Dense woods with long, thick fiber walls, such as *A. brasiliensis* and *B. virgilioides*, generally have a higher lignin content. Lignin is the main chemical component that influences the production and quality of charcoal. In addition, trees with higher densities generally have a lower S/G ratio in the lignin, which is considered an ideal scenario for pyrolysis because the guaiacyl unit is more stable and preserved during the process (Massuque *et al*., 2023).

Table 3 – Wood basic density and fiber measurement of the species

Specie	BD (g/cm³)	Fiber Biometric (μm)		
		Length	Width	Wall thickness
Agonandra brasiliensis	0.705	1219.04 [b]	20.89 [a]	3.28 [ab]
Bowdichia virgilioides	0.722	1495.42 [a]	18.05 [b]	3.10 [b]
Casearia mariquitensis	0.565	754.85 [e]	14.10 [c]	3.90 [a]
Qualea grandiflora	0.614	1023.72 [cd]	15.90 [bc]	2.41 [c]
Strychnos pseudoquina	0.512	1106.76 [bc]	21.99 [a]	2.41 [c]
Persea willdenovii	0.527	1193.05 [bc]	23.13 [a]	3.37 [ab]
Tabebuia aurea	0.577	919.79 [de]	16.51 [bc]	2.83 [bc]

Source: Authors (2023)

In where: BD – Wood Basic Density; Values followed by the same letter in the column do not differ significantly from each other according to Tukey's significance level.

According to Pereira *et al*. (2016), the presence of positive correlations between high density, fiber dimensions with thick cell walls and reduced lumens indicates the potential for producing denser charcoal with a smaller pore volume. According to the authors, the selection of tree species which provide wood for the production of high-quality charcoal is based on the assumption of high basic density, representing mass gains per volume allocated within the carbonization furnace. In addition, the higher density of the wood will result in charcoal with a higher density and greater mechanical strength, desirable properties for most applications of this input.

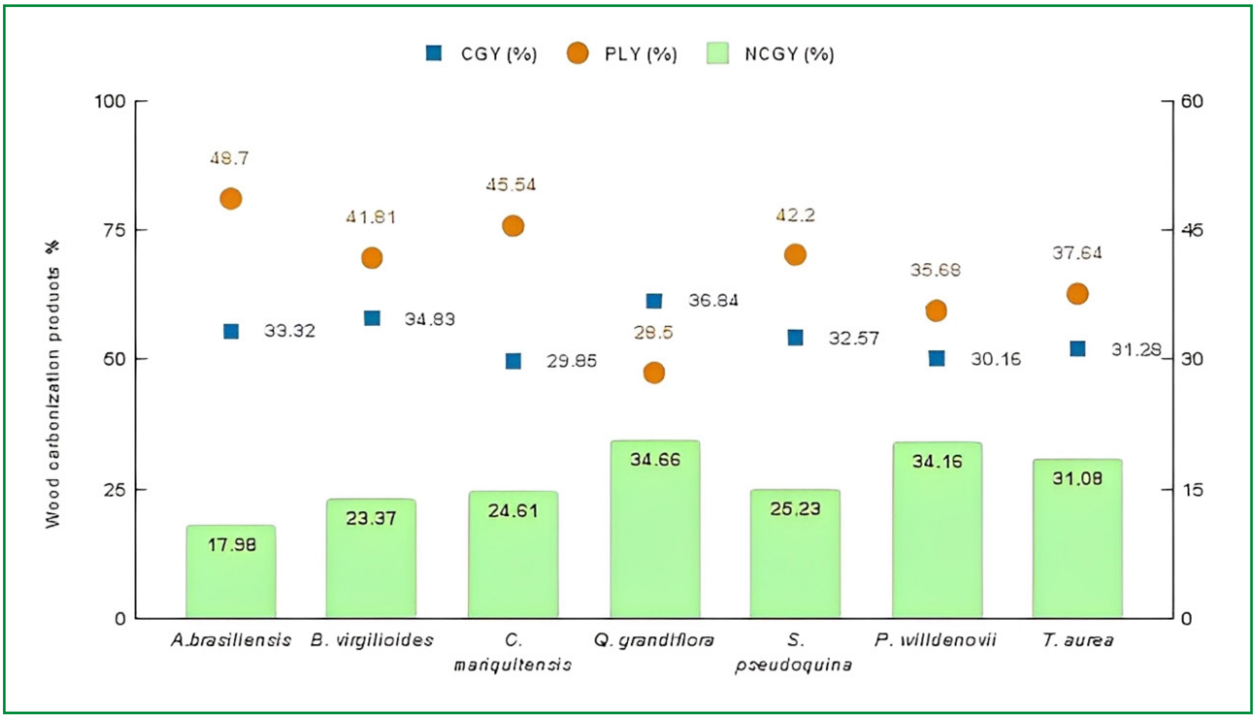
The basic density of *Eucalyptus* wood, which is used commercially to produce charcoal, must exceed 0.500 g/cm³ (Santos *et al*., 2011; Pereira *et al*., 2016; Protásio *et al*., 2021). Therefore, considering this characteristic in isolation, all the native species evaluated show high potential as biomass for carbonization.

3.2 Wood carbonization and charcoal quality

The average moisture content of the charcoal produced was 3.31 %, suitable for use as an energy input for combustion. Humidity levels below 6 per cent in the dry season and 12 per cent in the rainy season are desirable because higher values significantly reduce the heat of combustion, the temperature of the combustion chamber and the temperature of the exhaust gas. In addition, it is worth noting that moisture content has an inverse relation with calorific value (Fortaleza *et al*., 2019).

The average gravimetric coal yield with the method used was 32.70%, with values ranging from 29.85% to 36.84%. There was no significant effect of the species factor (Figure 2). Notably, *Qualea grandiflora* showed the highest conversion of wood into charcoal, consequently producing lower quantities of pyroligneous liquor.

Figure 2 – Yield of wood carbonization products (%), where CGY= gravimetric yields of charcoal; PLY= pyroligneous liquid yield; NCGY= non-condensable gases yield



Source: Authors (2023)

In order to meet the demands of the consumer market, it is desirable to obtain a high gravimetric yield in charcoal, as this maximizes the use of wood in carbonization furnaces, leading to greater energy production and lower yields in liquid and non-condensable gases, two by-products of the pyrolysis process. However, there are currently changes in the evaluation of carbonization products, in which pyroligneous liquor is also gaining commercial importance, ceasing to be a discarded waste product and becoming an additional source of income for the producer.

The average charcoal yield in Brazil is approximately 35 % (Rosillo-Calle; Bezzon, 2005; Ramos *et al*., 2023), which is very similar to the performance of *Q. grandiflora* and *B. virgilioides*. Similar results are reported in the literature for carbonizations at final temperatures similar to those of this research, 450 degrees Celsius. Costa *et al*. (2014) for five Cerrado species (*Luehea divaricata*, *Casearia sylvestris*, *Guazuma ulmifolia*, *Rapanea ferruginea* and *Trema micranta*), with an average of 32.29 %. Santos *et al*. (2016) and Protásio *et al*. (2021) found average values ranging from 31.25% to 35.80%, respectively, for commercial *Eucalyptus* clones. Fortaleza *et al*. (2019), during the carbonization of residues from the native species *Ceiba pentandra*, *Guatteria* sp. and *Brosimum* sp. in final carbonizations at 500 ºC, found values ranging from 30.03% to 32.35%.

The gravimetric yield is affected by the carbonization process and the quality of the wood. The increase in temperature results in lower yields, with a higher fixed carbon content and, consequently, higher calorific value. The density of wood results in denser charcoal, but the high density value must be a reflection of the increased length and thickness of the fibers (Silva et al., 2020). This relation may be observed in *B. virgilioides*, with the highest basic density (0.722 g/cm³) and longest fibers (1495.42 μm), crucial factors for the high gravimetric yield in charcoal (34.83%). In agreement with this fact, Santos *et al*. (2011) mention that 60% of the wood’s mass is degraded during the carbonization process in the production of charcoal; therefore, the greater the specific mass of the woody material, the greater the mass of charcoal by volume, resulting in a product with superior mechanical strength.

Regarding wood quality, it is important to note that, in addition to basic density, moisture content and chemical composition play significant roles in influencing the outcome of carbonization. Lower moisture content wood, a higher proportion of lignin and a lower proportion of holocellulose have been shown to be factors that contribute positively to obtaining higher yields in charcoal production (Massuque *et al*., 2021).

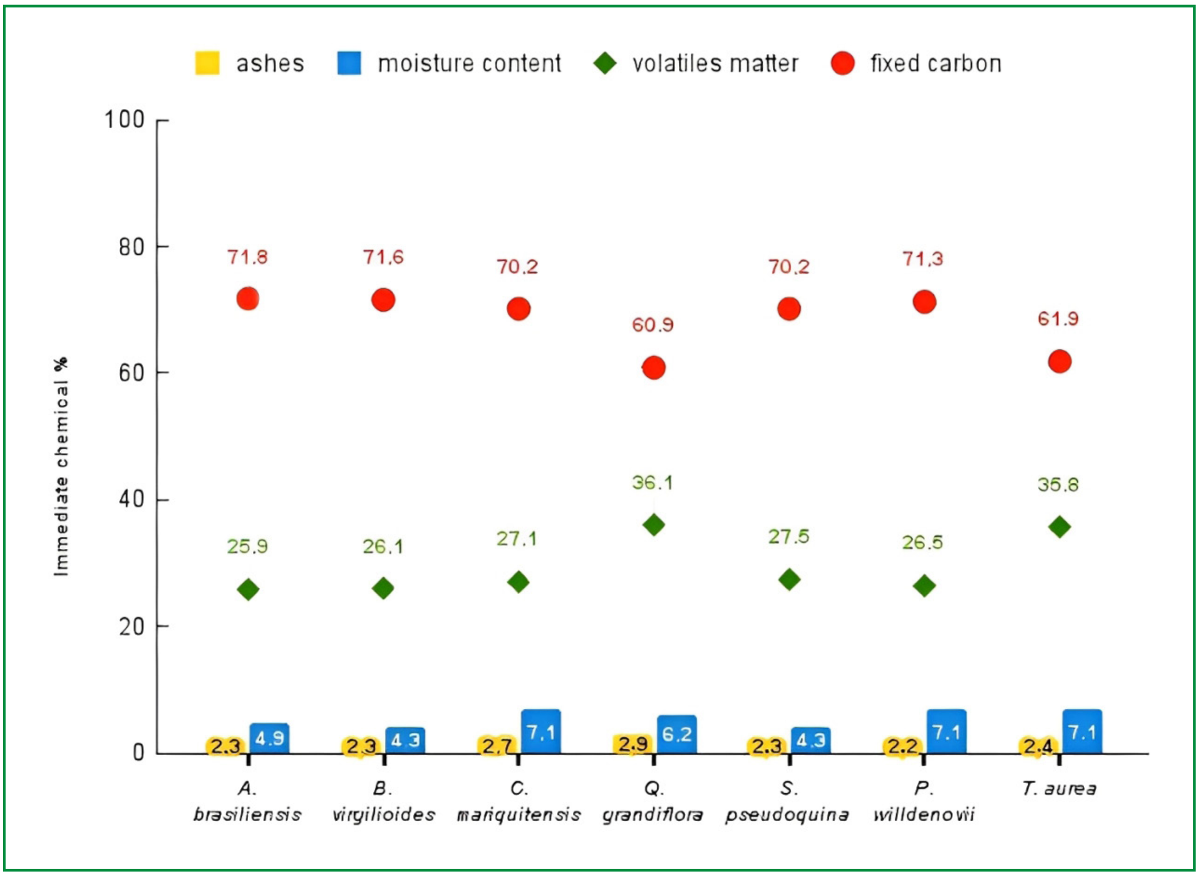
The results were good for the apparent density of the charcoal, with a maximum value of 0.688 g/cm³ (*B. virgilioides*) and a minimum of 0.273 g/cm³ (*P. willdenovii*). These specimens also have the highest and lowest basic wood density, respectively. Therefore, it is possible to state that dense wood generates dense charcoal, as reported by Numazawa (1986), Pastore, Okino and Pastore Junior (1989), Santos *et al*. (2011), Fortaleza *et al*. (2019) and Delatorre *et al*. (2020). The other species in the study produced charcoal at decreasing densities: *A. brasiliensis* (0.575 g/cm³), *Q. grandiflora* (0.450 g/cm³), *C. mariquitensis* (0.446 g/cm³), *S. pseudoquina* (0.440 g/cm³) and *T. aurea* (0.381 g/cm³).

The denser charcoal tends to increase its mechanical strength and energy density, which are crucial characteristics, especially when the product is used in the steel industry. In the blast furnace, charcoal is stacked with iron ores and melting materials, which makes its mechanical strength essential to support the load on it. If the charcoal is not strong enough, it can crumble and compromise the operation. In addition, charcoal with good mechanical strength is less likely to break during transportation, reducing losses and improving the energy efficiency of the steelmaking operation (Massuque *et al*., 2023). Thus, according to the results of the analyses evaluated in this research, the *B. virgilioides* species is an excellent option for this industrial segment. The authors recommend specific analyses for the mechanical strength of charcoal in the future to complement these results.

A charcoal with a density higher than 0.380 g/cm³ is preferable for industrial steel production, as it increases energy productivity (Massuque *et al*., 2023). The authors mention that bulk density also reflects the stock of fixed carbon per volume of the bioreductor and therefore higher values are recommended. Among the species studied, *P. willdenovii* (0.273 g/cm³) does not meet this prerequisite.

It is important to highlight the results obtained with regard to the immediate chemical composition of the *A. brasiliensis* and *Q. grandiflora* species (Figure 3) in this scientific article. The species in question had the highest concentrations of fixed carbon and volatile material, respectively. In terms of ash, the values were remarkably similar, although numerically higher for *Q. grandiflora* and lower for *P. willdenovii*. However, it is important to emphasize that, assuming a uniform charcoal yield for all species, the variability in fixed carbon, volatile material and ash can be attributed to the use of different genetic materials.

Figure 3 – Results of immediate chemical values of charcoal



Source: Authors (2023)

The increase in fixed carbon content results from a rise in the final carbonization temperature, followed by a simultaneous reduction in volatile material, yield and loss of strength. The increase in temperature and fixed carbon content also implies a decrease in the yield of the carbonization process. However, a significant reduction in carbon, associated with a higher volatile material content, compromises the efficiency of charcoal in the blast furnace, as it generates a high fines content (Picancio *et al*., 2018).

The performance levels of more than half of the charred wood were less than ideal, and some were significantly below the limit recommended by the steel industry (below 4%). However, the ash content of charcoal from *Bowdichia virgilioides* (4.2%) and *Strychnos pseudoquina* (4.2%) could meet the industry's desired limit. According to the literature, the ideal percentage of ash for charcoal from the *Eucalyptus* genus is lower, specifically below 1.5% (Pincelli; Mineiro, 2022).

The presence of ash in charcoal should be reduced to a minimum because, as well as reducing its calorific value, it causes wear in the blast furnace and can compromise the quality of pig iron (Santos, 2008). In the steelmaking process, ash acts as a catalyst in the C - CO2 reaction due to the presence of metal oxides such as CaO, Fe_2O_3, K_2O, and MgO (Matos; Rios, 1982). It should be noted that the ash content is related to the wood and is not influenced by the carbonization process at the same final temperature, but rather by the species, the amount of bark and, above all, contamination with soil and/or sand in the wood (Donato *et al*., 2020).

The relative proportions of fixed carbon, volatile material, and ashes are crucial for recommending biomasses for heat generation, as they influence combustibility and facilitate fuel ignition. Therefore, the essential characteristics of charcoal highlighted by metallurgical industries are: 70 to 80% fixed carbon, 25 to 35% volatile material, 1 to 6% moisture, and 0.5 to 4% ashes (Delatorre *et al*., 2020; Dias Júnior *et al*., 2021).

Charcoal properties varied among species, higher heating value from 20.584 to 24.268 $kJ.kg^{-1}$. The highest averages were for the species *Agonandra brasiliensis*, *Bowdichia virgilioides*, and *Persea willdenovii*. However, *Q. grandiflora* showed the lowest value. Similar results were reported by Nisgoski *et al*. (2014) for five native Amazonian species (26.878 to 31.117 $kJ.kg^{-1}$). The higher the content of fixed carbon and the lower the levels of volatiles and ash, the greater the higher heating value of the wood or charcoal will be (Vale *et al*., 2010).

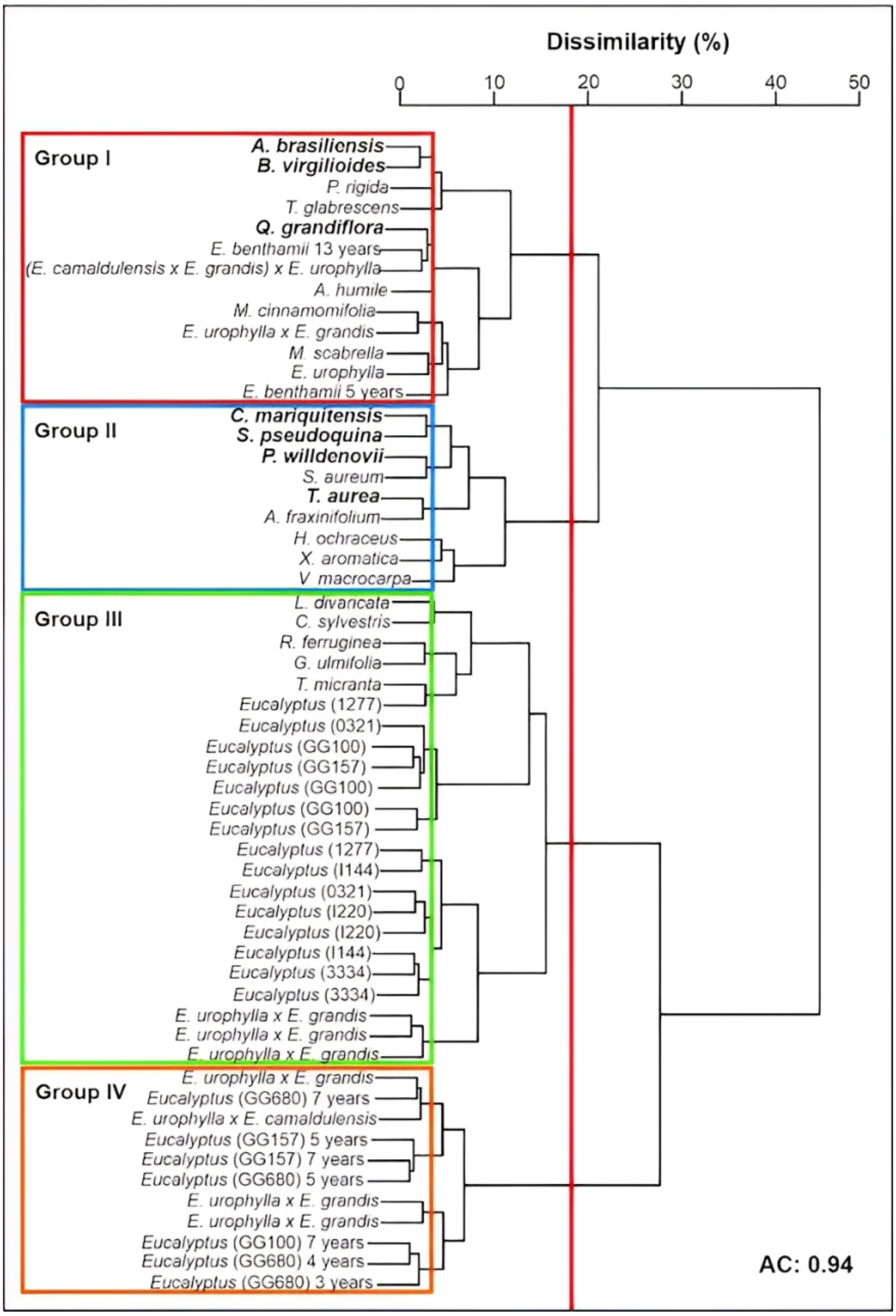
3.3 Multivariate analysis

The Agglomerative Coefficient (AC) was adopted as a metric in this study to analyze the quality and accuracy of the dendrogram produced, as suggested by Roth *et al*. (2016). The AC obtained was 0.94, indicating a strong grouping arrangement in the data sets, as values close to 1 denote a satisfactory grouping structure (Crispim *et al*., 2020). Thus, the dendrogram obtained can be considered consistent, and inferences of interest can be made based on its visual assessment (Figure 4).

The use of the Elbow Method allowed the number of clusters to be determined, and the appropriate number for the set of forest species based on attributes such as basic wood density, charcoal yield, apparent relative charcoal density, volatile material, fixed carbon content and ash content was determined in 4 groups, with a breakpoint equivalent to 18% of the total distance. It was observed that, for the species evaluated in this study, *A. brasilliensis*, *B. virgilioides* and *Q. grandiflora* were classified as group I, while *C. mariquitensis*, *S. pseudoquina*, *P. willdenovii* and *T. aurea* were classified as group II. As for the data on *Eucalyptus* species obtained from the literature, most were classified in groups III and IV.

The presence of species characterized as suitable for charcoal production for use in the steel industry, such as *E. benthamii* (Nunes *et al*., 2015) and the hybrids *E. urophylla* x *E. grandis* and (*E. camaldulensis* x *E. grandis*) x *E. urophylla* x *E. grandis* (Andrade *et al*., 2018) in group I, alongside *A. brasilliensis* and *B. virgilioides*, reinforces the performance and quality of these species for charcoal production.

Figure 4 – Illustrates the dendrogram grouping the set of variables related to wood and charcoal extracted from forest species found in the literature



Source: Authors (2024)

In where: AC = Agglomerative Coefficient.

However, for the other species under study, *Q. grandiflora*, *C. mariquitensis*, *S. pseudoquina*, *P. willdenovii* and *T. aurea*, caution should be exercised when comparing them with the *Eucalyptus* genus. The average data from groups I and II for volatile materials, fixed carbon and ash content diverged from the average values obtained for groups III and IV, which are mainly made up of species normally used to produce charcoal in the steel industry (Table 4).

Table 4 – Average values of the variables analyzed in each group formed by cluster analysis

	Group			
Specie	**I**	**II**	**III**	**IV**
BD wood (g/m³)	0.621	0.562	0.483	0.518
CGY (%)	35.22	29.67	31.77	34.25
ARD (g/m³)	0.413	0.416	0.349	0.345
VM (%)	30.00	28.73	18.78	23.76
FC (%)	67.38	69.05	79.89	75.71
Ashes (%)	2.70	1.91	1.39	0.52

Source: Authors (2023)

In where: Subtitle: BD: Basic Density; CGY= Gravimetric Yields of Charcoal; ARD: Apparent Relative Density; VM: Volatile material; FC: Fixed Carbon.

5 CONCLUSIONS

Among the seven species studied, the best results were achieved by *Bowdichia virgilioides*, which presented the highest basic wood density and the longest fibers, important characteristics for its high performance in charcoal production and quality. The multivariate analysis reinforces that this species offers performance and quality for charcoal production, approaching that of some commercial *Eucalyptus* species. The medium-density wood of *Persea willdenovii* produced low-density charcoal, while *Qualea grandiflora* and *Tabebuia aurea* are not recommended for use in metallurgical industries as they do not meet desirable fixed carbon standards.

This study aims to contribute to the production of charcoal by diversifying the sources of wood currently used. Furthermore, it serves to stimulate the field of forest silviculture in the development and implementation of energy forests involving alternative species to *Eucalyptus*.

REFERENCES

AMERICAN SOCIETY FOR TESTING AND MATERIAL. **D-167-93**: Standard Test Method for Apparent and True Specific Gravity and Porosity of Lump Coke. West Conshohocken, 1999.

AMERICAN SOCIETY FOR TESTING AND MATERIAL. **D1762** – 84:1–2. Standard Test Method for Chemical Analysis of Wood Charcoal. Philadelphia, USA: American Society for Testing and Materials, 2013.

ANDRADE, F. W. C.; FILHO, M. T.; MOUTINHO, V. H. P. Influence of wood physical properties on charcoal from Eucalyptus spp. **Floresta e Ambiente**, v. 25, 2018. DOI 10.1590/2179-8087.017615.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 7190 -3**: Projeto de estruturas de madeira. Parte 3: Métodos de ensaio para corpos de prova isentos de defeitos para madeiras de florestas nativas. Rio de Janeiro: ABNT, 2022

BARAÚNA, E. E. P.; NUNES, S. M. V.; NUNES, R. F.; DIAS, T. L.; BALDIN, T.; ARANTES, M. D. C.; MONTEIRO, T. C.; GOULART, S. L. Estimativa da umidade de equilíbrio da madeira de *Eucalyptus* Spp. para o município de Montes Claros, Minas Gerais. **Research, Society and Development**, v. 9, p. e15711931160, 2022. DOI: 10.33448/rsd-v11i9.31160.

CACHOEIRA, J. N.; SILVA, A. D. P.; OLIVEIRA, L. N.; GANASSOLI NETO, E.; GIONGO, M.; BATISTA, A. C. Mercado interestadual de carvão vegetal no estado do Tocantins. **Revista Verde de Agroecologia e Desenvolvimento Sustentável**, v. 14, n. 2, p. 258-265, 2019. DOI: 10.18378/rvads.v14i2.6351.

CARVALHO, A. P. M. Bioma cerrado e meio ambiente. *In*: **Contribuições para alcançar os Objetivos de Desenvolvimento Sustentável: relatos e práticas**, v. 2, 2022. p. 133- 146. Available in: https://ayaeditora.com.br/livros/L303.pdf#page=133. Accessed on: 6 dec. 2023. DOI: 10.47573/aya.5379.2.159.11.

CASTRO, A. F. N. M.; CASTRO, R. V. O.; CARNEIRO, A. C. O.; SANTOS, R. C. S.; CARVALHO, A. M. M. L.; TRUGILHO, P. F.; MELO, I. C. N. A. Correlations between age, wood quality and charcoal quality of *Eucalyptus* clones. **Revista Árvore**, v. 40, p. 551-560, 2016. DOI: 10.1590/0100-67622016000300019.

CONSELHO ESTADUAL DE POLÍTICA AMBIENTAL- COPAM. **Deliberação Normativa** COPAM n. 227. Minas Gerais, 2018. Available in: https://www.legisweb.com.br/legislacao/?id=367024#:~:text=Estabelece%20procedimentos%20para%20redu%C3%A7%C3%A3o%20das,entorno%20e%20d%C3%A1%20outras%20provid%C3%AAncias. Accessed on: 25 may 2019.

COSTA T. G.; BIANCHI, M. L.; PROTÁSIO, T. P.; TRUGILHO, P. F.; PEREIRA, A. J. Qualidade da madeira de cinco espécies de ocorrência no cerrado para produção de carvão vegetal. **Cerne**, v. 20, p. 37-46, 2014. DOI: 10.1590/S0104-77602014000100005.

CRISPIM, D. L. FERNANDES, L. L.; FERREIRA FILHO, D. F.; LIRA, B. R. P. Comparação de métodos de agrupamentos hierárquicos aglomerativos em indicadores de sustentabilidade em municípios do estado do Pará. **Research, Society and Development**, v. 9, n. 2, p. e60922067-e60922067, 2020. DOI: 10.33448/rsd-v9i2.2067.

CRUZ, C. D.; CARNEIRO, P. C. S. **Modelos biométricos aplicados ao melhoramento genético**. Viçosa: UFV, 2006. 585 p. Available in: https://www.researchgate.net/publication/292797696_Modelos_biometricos_aplicados_ao_melhoramento_genetico. Access in: 20 mar. 2024.

DELATORRE, F. M. CUPERTINO, G. F. M.; SANTOS JUNIOR, A. J.; ÁLISON MOREIRA DA SILVA, A. M.; DIAS JÚNIOR, A. F.; SILVEIRA, M. P. R. Insights acerca do uso de finos de carvão vegetal para geração de bioenergia. **Agropecuária Científica no Semiárido**, Patos-PB, v.16, n.2, p.138-144, 2020. DOI: 10.30969/acsa.v16i3.1272.

DIAS JÚNIOR, A. F.; SUUCHI, M. A.; SANT'ANNA NETO, A.; SILVA, J. G. M.; SILVA, Á. M.; SOUZA, N. D.; PROTÁSIO, T. P.; BRITO, J. O. Blends of charcoal fines and wood improve the combustibility and quality of the solid biofuels. **Bioenergy Research**, v. 14, p. 344–354, 2021. DOI 10.1007/s12155-020-10179-8.

DONATO, D. B.; CARNEIRO, A. C. O.; CARVALHO, A. M. L. M.; VITAL, B. R.; MILAGRES, E. G.; CANAL, W. D. Influência do diâmetro da madeira de eucalipto na produtividade e propriedades do carvão vegetal. **Revista Ciência da Madeira**, v. 11, n. 2, p. 63-73, 2020. DOI: 10.12953/2177-6830/rcm.v11n2p63-73

FRANKLIN, G. Preparation of Thin Sections of Synthetic Resins and Wood-Resin Composites, and a New Macerating Method for Wood. **Nature**, v. 155, n. 51, 1945. DOI: 10.1038/155051a0.

FRIEDERICHS, G. BRAND, M. A.; CARVALHO, A. F.; KÜSTER, L. C. Qualidade da madeira e do carvão vegetal de bracatinga (*Mimosa scabrella* Benth.). **Revista Ciência da Madeira**, v. 6, n. 2, 2015. DOI: 10.12953/2177-6830/rcm.v6n2p79-87.

FORTALEZA, A. P.; NASCIMENTO FILHO, J. J. P. do; CERETTA, R. P. da S.; BARROS, D. de S.; DA SILVA, S. S. Biomassa de espécies florestais para produção de carvão vegetal. **Ciência Florestal**, v. 29, n. 3, p. 1436–1451, 2019. DOI: 10.5902/1980509831639.

GREEN, D.W.; PERRY, R. H. **Perry's Chemical Engineers' Handbook**. McGraw-Hill. McGraw-Hill Professional Publishing, 8ED. 2008. 2400p.

INDÚSTRIA BRASILEIRA DE ÁRVORES – IBÁ. Brasília, v. 80, 2022. Available in: https://iba.org/datafiles/publicacoes/relatorios/iba-relatorioanual2019.pdf. Accessed on: 15 sep. 2023.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA - IBGE. **Produção da Extração Vegetal e da Silvicultura**. 2020. Available in: https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/9105-producao-da-extracao-vegetal-e-da-silvicultura.html. Accessed: 13 Nov. 2023.

INTERNATIONAL ASSOCIATION OF WOOD ANATOMY. LIST OF MICROSCOPIC FEATURES FOR WOOD IDENTIFICATION. IAWA Bulletin, Leiden, v. 10, n. 3, p. 226-332, 1989.

JENKINS, B. M.; BAXTER, L. L.; MILES JR, T. R.; MILES, T.R. Combustion properties of biomass. **Fuel Processing Technology**, v. 54, n.1-3, p. 17-46 1998.

MARQUES, R. D.; CUNHA, T. Q. G.; CHAGAS, M. P.; VENTUROLI, R. D.; BELINI, G. B.; YAMAJI, F. M.; SETTE JÚNIOR, C. R. Wood quality of five species of the Cerrado for energy purposes**. Scientia Forestalis**, v. 48, n. 125, e3225, 2020. DOI: 10.18671/scifor.v48n125.11.

MASSUQUE; J.; ASSIS, M. R.; LOUREIRO, B. A.; MATAVEL, C. E.; TRUGILHO, P. F. Influence of lignin on wood carbonization and charcoal properties of Miombo woodland native species. **European Journal of Wood and Wood Products**, v. 79, p. 527–535, 2021. DOI: 10.1007/s00107-021-01669-3

MASSUQUE, J.; LIMA, M. D. R.; SILVA, P. H. M.; PROTÁSIO, T. P.; TRUGILHO, P. F. Potential of charcoal from non-commercial *Corymbia* and *Eucalyptus* wood for use in the steel industry. **Renewable Energy**, p. 1-27, 2023. DOI: 10.2139/ssrn.4271331.

MATOS, M.; RIOS, C. A. Reatividade do carvão vegetal. *In*: **Produção e utilização de carvão vegetal**. Belo Horizonte: CETEC. 92-111p. 1982. Available in: http://www.bibliotecadigital.mg.gov.br/consulta/consultaDetalheDocumento.php?iCodDocumento=73148. Accessed on: 12 dec. 2023.

MELO, J. E.; CORADIN, V. R.; MENDES, J. C. Classes de densidade para madeiras da Amazônia brasileira. In: ANAIS DO CONGRESSO FLORESTAL BRASILEIRO, 1990, Campos do Jordão. São Paulo. **Anais[...]** São Paulo: 1990. v. 3. p. 695-705.

MENDONÇA, R. C.; FELFILI, J. M.; WALTER, B. M. T.; SILVA JÚNIOR, M. C.; REZENDE, A. V.; FILGUEIRA, J. S.; NOGUEIRA, P. E.; FAGG, C. W. Flora vascular do bioma Cerrado. *In*: SANO, S. M.; ALMEIDA, S.P.; RIBEIRO, J.F. (Eds.) **Cerrado**: ecologia e flora. Brasília: Embrapa Informação e Tecnologia, 2008. p. 421-1279.

NEVES, T. A.; PROTÁSIO, T. P.; COUTO, A. M.; TRUGILHO, P. F.; SILVA, V. O.; VIEIRA, C. M. M. Avaliação de clones de *Eucalyptus* em diferentes locais visando à produção de carvão vegetal. **Pesquisa Florestal Brasileira**, v. 31, n. 68, p. 319-319, 2011. DOI: 10.4336/2011.pfb.31.68.319.

NISGOSKI, S.; MAGALHÃES, W. L. E.; BATISTA, F. R. R; FRANÇA, R. F.; MUÑIZ, G. I. B. Anatomical and energy characteristics of charcoal made from five species. **Acta Amazonica**, v. 44, n. 3, p. 367 – 372, 2014.

NONES, D. L.; BRAND, M. A.; CUNHA, A. B.; CARVALHO, A. F.; WEISEET, S. M. K. Determinação das propriedades energéticas da madeira e do carvão vegetal produzido a partir de *Eucalyptus benthamii*. **Floresta**, v. 45, n. 1, p. 57-63, 2015. DOI: 10.5380/rf.v45i1.30157.

OLIVEIRA, J. B.; GOMES, P. A.; ALMEIDA, M. R. **Estudos preliminares de normalização de testes de controle de qualidade do carvão vegetal** - Propriedades do carvão vegetal. Série de Publicações Técnicas-Fundação Centro Tecnológico de Minas Gerais (Brazil), n. 6, 1982.

OLIVEIRA, M. C.; RIBEIRO, J. F.; PASSOS, F. B.; AQUINO, F. G.; OLIVEIRA, F. F.; SOUSA, S. R. Crescimento de espécies nativas em um plantio de recuperação de Cerrado sentido restrito no Distrito Federal, Brasil. **Revista Brasileira de Biociências**, Porto Alegre, v. 13, n. 1, p. 25-32, jan./mar. 2015.

PANSHIN, A. J.; ZEEUW, C. **Textbook of wood technology**. 4th ed. New York. Mc-Graw Hill, 1980. 722 p. Online version available at: Textbook of wood technology. Panshin, A.J. (Alexis John), 1901-629786255.

PEREIRA, B. L. C.; CARVALHO, A. M. M. L.; OLIVEIRA, A. C.; SANTOS, L. C.; CARNEIRO, A. de C. O.; MAGALHÃES, M. A. de. Efeito da carbonização da madeira na estrutura anatômica e densidade do carvão vegetal de *Eucalyptus*. **Ciência Florestal**, v. 26, n. 2, p. 545–557, 2016. DOI: 10.5902/1980509822755.

PICANCIO, A. C. S.; ISBAEX, C.; SILVA, M. L.; SALLES, T. T.; RÊGO, L. J. S.; SILVA, L. F. Controle do processo de produção de carvão vegetal para siderurgia. **Caderno de Administração**, v. 12, n. 1, 2018. Available in: https://revistas.pucsp.br/caadm/article/view/31654. Accessed on: 12 dec. 2023.

PILON, N. A. L.; DURIGAN, G. Critérios para indicação de espécies prioritárias para a restauração da vegetação de cerrado. **Scientia Forestalis**, v. 41, n. 99, p. 389-399, 2013.

PINCELLI, A. L. P. S. M.; MINEIRO, V. A. Análise da qualidade do carvão vegetal para uso doméstico produzido em sistema artesanal. **Bioenergia em Revista: Diálogos**, v. 12, n. 2, p. 82-99, 2022. Available in: http://fatecpiracicaba.edu.br/revista/index.php/bioenergiaemrevista/article/view/478. Accessed on: 21 feb. 2024.

PROTÁSIO, T. P.; GOULART, S. L.; NEVES, T. A.; TRUGILHO, P. F.; RAMALHO, F. M. G.; QUEIROZ, L. M. R. S. B. Qualidade da madeira e do carvão vegetal oriundos de floresta plantada em Minas Gerais. **Pesquisa florestal brasileira**, v. 34, n. 78, p. 111-123, 2014. DOI: 10.4336/2014.pfb.34.78.657.

PROTÁSIO, T. P.; LIMA, M. D. R.; SCATOLINO, M. V.; SILVA, A. B.; FIGUEIREDO, I. C. R.; HEIN, P. R. G.; TRUGILHO, P. F. Charcoal productivity and quality parameters for reliable classification of *Eucalyptus* clones from Brazilian energy forests. **Renewable Energy**, v. 164, p. 34-45, 2021. DOI: 10.1016/j.renene.2020.09.057.

RAMOS, D. C.; CARNEIRO, A. C. O.; SIQUEIRA, H. F.; OLIVEIRA, A. C.; PEREIRA, B. L. C. Qualidade da madeira e do carvão vegetal de quatro clones de *Eucalyptus* com idades entre 108 e 120 meses. **Ciência Florestal**, Santa Maria, v. 33, n. 1, e48302, p. 1-27, 2023. DOI: 10.5902/1980509848302.

R CORE TEAM. **R**: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria, 2020.

ROSILLO-CALLE, F.; BEZZON, G. Produção e uso industriais do carvão vegetal. *In*: ROSILLO-CALLE, F.; BAJAY, S. V.; ROTHMAN, H. Uso da biomassa para produção de energia na indústria brasileira, 2008, Campinas. **Anais** [...] Campinas SP: Ed. da UNICAMP, 2008.

ROTH, K. L.; CASAS, A.; HUESCA, M.; USTIN, S. L.; ALSINA, M. M.; MATHEWS, S. A.; WHITING, M. L. Leaf spectral clusters as potential optical leaf functional types within California ecosystems. **Remote Sensing of Environment**, v. 184, p. 229-246. 2016. DOI: 10.1016/j.rse.2016.07.014.

SANTOS, M. A. S. Parâmetros de qualidade do carvão vegetal para uso em alto-forno. *In*: Fórum nacional sobre carvão vegetal, 1., 2008, Belo Horizonte. **Anais** [...] Belo Horizonte: UFMG, 2008.

SANTOS, R. C.; CARNEIRO, A. C. O.; CASTRO, A. F. M.; CASTRO, R. V. O.; BIANCHE, J. J.; SOUZA, M. M.; CARDOSO, M. T. Correlações entre os parâmetros de qualidade da madeira e do carvão vegetal de clones de eucalipto. **Scientia Forestalis**, Piracicaba, v. 39, n. 90, p. 221-230, jun. 2011.

SANTOS, R. C.; CARNEIRO, A. C. O.; VITAL, B. R.; CASTRO, R. V. O.; VIDAURRE, G. B.; TRUGILHO, P. F.; CASTRO, A. F. N. M. Influência das propriedades químicas e da relação siringil/guaiacil da madeira de eucalipto na produção de carvão vegetal. **Ciência Florestal**, v. 26, n. 2, p. 657–669, 2016. DOI: 10.5902/1980509822765.

SANTOS, G. L.; PEREIRA, M. G.; DELGADO, R. C.; MAGISTRALI, I. C.; SILVA, C. G.; OLIVEIRA, C. M. M.; LARANGEIRA, J. P. B.; SILVA, T. P. Degradation of the Brazilian Cerrado: Interactions with human disturbance and environmental variables. **Forest Ecology and Management**, v. 482, 2021. DOI: 10.1016/j.foreco.2020.118875.

SILVA, C. J.; VALE, A. T.; MIGUEL, E. P. Densidade básica da madeira de espécies arbóreas de Cerradão no estado de Tocantins. **Pesquisa Florestal Brasileira**, v. 35, n. 82, p. 63–75, 2015. DOI: 10.4336/2015.pfb.35.82.822.

SILVA, R. C.; MARCHESAN, R.; MENDES, G. A.; CARVALHO, L. A.; SANTOS, W. M. F. L.; SOUZA, P. B. Effect of the final carbonization temperature on the quality of five species of Cerrado. **Floresta**, v. 50, n. 4, p. 1902-1911, 2020. DOI: 10.5380/rf.v50i4.66996.

SILVEIRA, L. H. C.; REZENDE, A. V.; VALE, A. T. Moisture content and basic wood density of nine commercial Amazonian tree species. **Acta Amazônica**, Manaus, v. 43, n. 2, p.179 – 184, 2013. DOI: 10.1590/S0044-59672013000200007.

SIQUEIRA, H. F.; PATRÍCIO, E. P. S.; LIMA, M. D. R.; GUIMARÃES JUNIOR, J. B.; CARNEIRO, A. C. O.; TRUGILHO, P. F.; PROTÁSIO, T. P. Avaliação de três madeiras nativas do cerrado goiano visando à utilização energética. **Nativa**, Sinop, v. 8, n. 5, p. 615-624, set./out. 2020. DOI: 10.31413/nativa.v8i5.10338.

SOLEYMANI, M.; SHOKRPOOR, S.; JAAFARZADEH, N. A comprehensive study of essential properties of *Conocarpus erectus* as a potential bioenergy crop. **International Journal of Environmental Science and Technology**, v. 20, p. 6147–6160, 2023. DOI: 10.1007/s13762-023-04878-w.

THORNDIKE, R. L. Who belongs in the family? **Psychometrika**, v. 18, n. 4, p. 267-276, 1953.

VALE, A. T.; BRASIL, M. A. M.; LEÃO, A. L. Quantificação e caracterização energética da madeira e casca de espécies do cerrado. **Ciência Florestal**, v. 12, p. 71-80, 2002. Available in: https://periodicos.ufsm.br/cienciaflorestal/article/view/1702. Access in: 13 jan. 2024. DOI: 10.5902/198050981702.

VALE, A. T.; DIAS, I. S.; SANTANA, M. A. E. Relações entre as propriedades químicas, físicas e energéticas da madeira de cinco espécies do cerrado. **Ciência Florestal**, Santa Maria, v. 20, n. 1, p. 137-145, 2010. DOI: 10.5902/198050981767.

WARD, J. H. Hierarchical grouping to optimize an objective function. **Journal of the American Statistical Association**, USA, v. 58, p.236-244, 1963. DOI: 10.1080/01621459.1963.10500845. Available in: https://www.tandfonline.com/doi/abs/10.1080/01621459.1963.10500845. Access in: 1 mar. 2024.

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