Wood quality of *Astronium fraxinifolium* and *Enterolobium gummiferum* for charcoal production

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Abstract

This paper aimed to evaluate the quality of wood and charcoal of *Astronium fraxinifolium* and *Enterolobium gummiferum* from Brazilian savannas (Cerrado). Discs from three trees of each species were removed at a height of 1.30 m above ground level. The samples were prepared for the analysis of the energy density and chemical components of the wood and for the production of charcoal at two final carbonization temperatures (350 and 450 ºC). After characterizing the charcoal, the carbonization yield and charcoal productivity per unit of wood volume were calculated. The wood of native species had potential for energy purposes. *E. gummiferum* charcoal stood out for its low ash content, and *A. fraxinifolium* wood presented higher apparent density and, consequently, higher carbonization yield and charcoal productivity per unit of wood volume. Charcoals produced at the two final carbonization temperatures presented adequate parameters for the steel industry and domestic use. The final temperature of 350 ºC is indicated as it presents higher gravimetric yield and energy yield of carbonization.

1. Introduction

Brazil is the largest producer and consumer of charcoal in the world. Part of the material comes from planted trees, such as the *Eucalyptus* genus, and the other comes from native species from different Brazilian regions [25]. Charcoal is mainly employed in the steel industry, acting as a reducing agent for iron ore and an energy supplier due to its high degree of purity and low production cost [32]. It also contributes as an alternative energy source to fossil fuels in other national sectors: industrial, commercial, agricultural, and residential [12].

Charcoal production originates from wood carbonization. In this process, a solid product (charcoal) is generated, having a high concentration of carbon in the residual structure and a volatile fraction composed of condensable gases (pyroligneous liquor) and non-condensable gases – for instance, CO, H2, and CH4 [43, 54]. The proportion of these products results from parameters of the carbonization process, such as the heating rate, final carbonization temperature, and oven pressure [50, 65].

In addition, the charcoal quality for the steel industry is directly related to wood parameters, thus hindering the maximization of the gravimetric yield in its production process [10]. Since the properties of hardwood impact charcoal yields and its physical, chemical, and mechanical properties [23, 20], research on the quality of native species for energy purposes is necessary.

Brazilian savannas (Cerrado) are the second-largest biome in Brazil and stand out for the high number of trees species and biomass production. Thus, studies with species from this biome can help in its Sustainable Management Plan and the introduction of little-known trees with high energy potential in the market. *Astronium fraxinifolium* and *Enterolobium gummiferum*, for example, are native and endemic species of the Cerrado, with a high potential for reforestation and management of degraded areas [13, 41]. Besides, their wood has commercial value for civil construction and structural purposes. Therefore, they are viable options for planted forests.

Astronium fraxinifolium Schott is a pioneer tree species belonging to the Anacardiaceae family, whereas *Enterolobium gummiferum* (Mart.) J.F.Macbr. belongs to the Fabaceae family. Both forest species present deciduous, heliophytic, and xerophytic behavior – a characteristic of the Cerrado. Their wood has economic importance and commercial value since these species have heavy, rigid wood with good natural resistance. It is indicated for civil construction, furniture industry, and manufacture of frames. Besides, *E. gummiferum* has bark with tannin, which can be used in the tanning industry, and its resin has adhesive power [26, 29, 30, 31].

Considering the wide availability of these species' trees and that charcoal quality is directly correlated with properties of the raw material and the carbonization process, the present study aimed to evaluate the energy potential of *A. fraxinifolium* and *E. Gummiferum* woods for charcoal production at two final carbonization temperatures.

2. Materials And Methods

2.1 Material collection and sample preparation

Two discs with 5 cm of thickness were cut from three *Astronium fraxinifolium* trees at DBH (diameter at 1.30 m above ground level). They were collected in the municipality of Montes Claros, state of Minas Gerais, Brazil (coordinates: 16º 41' 04" S, 43º 50' 50" W). In addition, discs also cut from three *Enterolobium gummiferum* trees were collected in the municipality of Carbonita, state of Minas Gerais, Brazil (coordinates: 17º 32' 23" S, 43º 8' 21" W). Both species came from an area of remaining vegetation characterized as the Seasonal Semideciduous Forest of the Cerrado biome.

According to the Köppen-Geiger classification, the climate in the municipalities of Montes Claros and Carbonita is tropical Aw. Montes Claros has an average annual temperature of 23.1°C and an average annual rainfall of 869 mm. Carbonita has an average annual temperature of 21.9 ºC, with a average annual rainfall of 855 mm [7,16].

The disks from each tree were divided perpendicularly into four wedges. Two opposing wedges were used to determine wood basic density. The other wedges were sampled for wood chemical and energetic analysis, charcoal production and characterization.

2.2 Wood characterization

For the wood chemical and energetic analysis, small fragments of the materials were ground in a Wiley mill. They were classified using the fraction retained between the 40 and 60 mesh sieves. The analyses were performed in triplicate, and the absolute dry content of the samples was determined according to TAPPI 264 om-88 [58].

The total extractive content of wood was determined as specified by TAPPI T204 cm-97 [59]. The extraction was performed with dichloromethane, alcohol-toluene (1:2), and alcohol 96º GL using a complete Soxhlet apparatus. The ash content of wood was determined according to TAPPI 211 om-12 [60], which consisted of quantifying the ash via incineration in a muffle furnace at a temperature of 525 ± 25 ºC for three hours. Moreover, the higher heating value was calculated using an adiabatic bomb calorimeter, in accordance with NBR 8633 [4].

The wood basic density was determined according to NBR 11941 [3], considering the relation between the dry mass of wood and its saturated volume. Finally, the energy density was obtained by calculating the product of the wood basic density and the higher heating value.

2.3 Wood carbonization

Laboratory carbonizations were performed using an electric muffle furnace. Approximately 300 g of wood previously dried at 105 ± 3 ºC were used. They were measured considering two final carbonization temperatures (350 and 450 ºC). The average heating rate to perform the pyrolysis was 1.67 $ºC.min^{-1}$, according to the methodology of Trugilho et al. [62].

2.4 Charcoal characterization

Charcoal characterization was performed in triplicate. The following characteristics were analyzed: moisture content, according to the Brazilian method MB 15 [1]; friability test, with the aid of a Friabilometer MA 79, as specified by Figueiredo et al. [24]; higher heating value, according to NBR 8633 [4]; apparent density of charcoal, following the hydrostatic method with immersion in mercury (replacing water with mercury), as described by Vital [67]; and energy density, calculating the product of apparent density and higher heating value.

For immediate chemical analysis of charcoal, the content of volatile materials, ash, and fixed carbon was determined, in accordance with NBR 8112 [3]. The charcoal was crushed, and the fraction retained between the 40 and 60 mesh sieves was used as a sample.

Finally, the gravimetric yield, fixed carbon yield, energy yield of carbonization, and productivity of charcoal per unit of wood volume were calculated in order to verify whether it was feasible to use higher final carbonization temperatures, following the methodology by Protásio et al. [45].

2.5 Statistical analysis

Data were submitted to Shapiro-Wilk and Levene tests at 5% of significance in order to verify the normality of residues and homogeneity between the variances. The analysis of variance (ANOVA) was applied for the variables that met the assumptions of parametric statistics, using the F-test and Tukey test, when necessary, both at 5% of significance. For variables with residuals that were not normal, the Kruskal-Wallis test was applied at 5% of significance. The analyses were performed with the aid of the R Core Team [48] software.

3. Results And Discussion

3.1 Wood characterization

Both forest species showed significant differences for all wood parameters evaluated in this research (Table 1). For the total extractive content, the wood of *Enterolobium gummiferum* presented values 1.3 times higher than *Astronium fraxinifolium*. The result is similar when compared to *Eucalyptus* (1 to 5%), which is the main genus employed in the forest energy sector [46, 65, 68].

Table 1
Average values for wood characteristics of *Astronium fraxinifolium* and *Enterolobium gummiferum*.

Species	TE (%)	Ash (%)	HHV (MJ kg^{-1})	BD (kg m^{-3})	ED (GJ m^{-3})
A. fraxinifolium	4.89 b	1.54 a	17.59 a	632 a	11.12 a
E. gummiferum	6.44 a	0.61 b	17.21 b	548 b	9.43 b
F *(p)*	(*0.0028*)	–	–	(*0.0479*)	(*0.0305*)
H *(p)*	–	(*0.0463*)	(*0.0334*)	–	–

Where: TE = total extractives of wood; HHV = higher heating value; BD = wood basic density; ED = energy density; F = p-value of the F-test; H = p-value of the Kruskal-Wallis test. Averages followed by the same letter in the same column do not differ statistically by the F-test or Kruskal-Wallis test at 5% of significance.

The nature and diverse composition of extractives and their amounts in the wood determine the biofuel heating value for energy purposes [21]. In this sense, woods with a high content of this compound, such as those in the present study (especially *E. gummiferum*), are indicated for charcoal production. The results for total extractives of wood in this research were similar to those presented in the literature for Cerrado species, ranging from 4 to 10% – for example, *Pterodon pubescens*, 6.94%, and *Anadenanthera colubrina*, 4.85% [18, 39, 64].

The wood of *E. gummiferum* presented wood ash values 2.5 times lower than *A. Fraxinifolium*. Thus, it is favorable for charcoal production in the steel sector, given that a high percentage of ash in charcoal can cause segregation during the process [42]. Both forest species presented relatively low ash content for energy purposes. Besides, their values were close to those described by Vale et al. [63] and Siqueira et al. [55] for wood from Cerrado species, from 0.27 to 2.73%.

For the higher heating value, the wood of *A. fraxinifolium* had the highest energy potential (17.59 MJ kg^{-1}). However, the values were slightly lower than those reported in the literature for Cerrado species, from 18.12 to 20.89 MJ kg^{-1} [37, 63], and for the *Eucalyptus* genus, from 17.63 to 20.57 MJ kg^{-1} [27, 35; 61].

This may be associated with other wood chemical components, such as lignin, considering that higher heating value is directly associated with the fixed carbon content of the material.

Regarding the wood basic density, the wood of *A. fraxinifolium* had a specific mass 13.30% higher than *E. Gummiferum*. Nevertheless, both species were classified as having medium density (between 500 and 700 kg m^{-3}), according to the classification of Melo et al. [34]. Punctually analyzing this parameter, the species are within the average required by the energy sector (> 500 kg m^{-3}) – especially *A. fraxinifolium* – as the higher the wood density, the higher the density and mechanical resistance of the charcoal produced [20, 40, 47].

Since energy density is directly correlated to basic density and higher heating value of the wood, *A. fraxinifolium* (11.12 GJ m^{-3}) presented a higher amount of heat in a given volume than *E. gummiferum* (9.43 GJ m^{-3}). Nonetheless, both of them exhibited satisfactory values for energy purposes, being consistent with the literature for native species, from 7.82 to 16.16 GJ m^{-3} [6, 51], and for the *Eucalyptus* genus, from 6.61 to 12.20 GJ m^{-3} [33, 49, 68].

3.2 Charcoal characterization

Charcoal moisture content did not exhibit a significant difference between forest species and between final carbonization temperatures (Table 2).

Table 2
Average values for charcoal characteristics of *Astronium fraxinifolium* and *Enterolobium gummiferum* at two final temperatures.

Parameters	Final temperature	Species		F (*p*)	H (*p*)
		A. fraxinifolium	*E. gummiferum*		
Moisture content (%)	**350 ºC**	3.25 A a	3.54 A a	(*0.576*)	–
	450 ºC	3.09 A a	3.47 A a	(*0.527*)	–
F (*p*)		(*0.792*)	(*0.890*)		
Friability (%)	**350 ºC**	8.39 B a	8.89 B a	(*0.165*)	–
	450 ºC	12.72 A a	12.22 A a	(*0.273*)	–
F (*p*)		(*0.0273*)	(*0.0016*)		
HHV (MJ kg^{-1})	**350 ºC**	28.45 B b	29.84 B a	–	(*0.0339*)
	450 ºC	30.11 A b	31.56 A a	–	(*0.0334*)
H (*p*)		(*0.0339*)	(*0.0334*)		
AD (kg m^{-3})	**350 ºC**	477 A a	343 A b	(*0.0002*)	–
	450 ºC	461 A a	313 B b	–	(*0.0495*)
F (*p*)		(*0.256*)	(*0.0004*)		
ED (GJ m^{-3})	**350 ºC**	13.57 A a	10.24 A b	(*0.0004*)	–
	450 ºC	13.88 A a	9.88 B b	–	(*0.0495*)
F (*p*)		(*0.418*)	(*0.0128*)		

Where: HHV = higher heating value; AD = apparent density of charcoal; ED = energy density; F = p-value of the F-test; H = p-value of the Kruskal-Wallis test. Averages for each parameter followed by the same uppercase letter in the same column or the same lowercase letter in the same row do not differ statistically by the F-test or Kruskal-Wallis test at 5% of significance.

The charcoal of both forest species had low moisture content (< 5%). This variable can influence the yield of processes in which charcoal will be used. Similar values were obtained by Arantes et al. [8] for charcoal from *Eucalyptus grandis* W. Hill ex Maiden x *Eucalyptus urophylla* (3.54%). This result can be explained by the degradation of the wood hydrophilic chemical components, such as hemicelluloses, during carbonization. The amount of hydroxyl (OH) is reduced and, consequently, the hygroscopicity of the material as well – in this case, charcoal.

For charcoal friability, a significant difference was observed only between the final carbonization temperatures (Table 2). This variable is correlated with mechanical strength. Thus, the lowest temperature (350°C) presented desirable results for industrial purposes since friable charcoal causes economic losses due to the excess of fines generated during production and handling [53]. Other studies have also indicated that increasing the final carbonization temperature influences the mechanical properties of charcoal, thus reducing its resistance [5, 24].

Regarding the higher heating value, there was a statistical difference in all treatments. The highest energy potential was verified for the charcoal of *E. gummiferum* (31.56 MJ kg^{-1}), followed by the charcoal of *A. fraxinifolium* (30.11 MJ kg^{-1}), both at the final carbonization temperature of 450 ºC. This same tendency was observed in other studies [9, 18, 24]. All values were consistent with the literature for charcoal from Cerrado species, ranging from 27.94 to 33.36 MJ kg^{-1} [11, 24, 55], and from the *Eucalyptus* genus, from 29.29 to 31.96 MJ kg^{-1} [35, 47, 68].

The high final carbonization temperatures produced charcoal with a superior heating value due to the greater concentration of carbon in its structure during its conversion into carbon dioxide in combustion [11]. Other parameters should also be considered, such as gravimetric yield and raw material losses during the use of high temperatures to carbonize wood.

In addition, there was no significant difference between the final carbonization temperatures of the wood of *A. fraxinifolium* for the apparent density of charcoal (Table 2). However, the charcoal density of both species was reduced as the final carbonization temperature increased. This is related to the greater loss of mass of the material as the temperature and time increase during the process, reflecting the decrease of charcoal density and resistance.

At both final carbonization temperatures, the charcoal of *A. fraxinifolium* had a higher apparent density than *E. gummiferum*. This is associated with the higher basic density of its wood as these parameters are highly correlated [64]. Besides, all average values were similar to those described in the literature for charcoal from Cerrado species produced at 450 ºC, ranging from 255 to 475 kg m^{-3} [18, 55, 64], and for *Eucalyptus* charcoal, from 227 to 425 kg m^{-3} [14, 47, 68].

The energy density and apparent density of charcoal presented the same behavior since these parameters are directly correlated (Table 2). *A. fraxinifolium* had a higher amount of heat in a given volume than *E. Gummiferum*. This result was also higher than the values for the *Eucalyptus* genus, from 6.68 to 12.61 GJ m^{-3} [47, 68]. Thus, it is a favorable species for the steel and domestic sectors, in which higher-density charcoal is desired since, in addition to being more resistant, this property results in a greater heat capacity per unit of volume [22, 54].

Regarding the immediate chemistry of charcoal, the statistical analysis indicated that, between forest species, there was a significant difference for all parameters analyzed. The final carbonization temperature did not influence the ash content (Fig. 1).

The charcoal of *A. fraxinifolium* presented higher ash content than *E. gummiferum*. This can be associated with the higher ash content of its wood, which contributes to the high mineral content of the charcoal produced. The values are above the recommendation for the steel sector (< 3%), given that minerals can affect the mechanical properties of pig iron, increase equipment corrosion, and decrease the heating value of the fuel [40, 44]. A study by Barcellos [11] indicated that the final carbonization temperature did not influence the ash content of charcoal, and its values for Cerrado species – such as *Qualea grandiflora*, 5.66%, *Bowdichia virgiloides*, 5.26%, and *Magonia pubencens*, 5.22% – were similar to those for *A. fraxinifolium*. The values for *E. gummiferum* were similar to those for *Tachigali vulgaris*, 1.14% [55], and for the clone of *E. urophylla* x *E. grandis*, 1.16% [14].

With regards to the content of volatile materials for charcoal, the values for both forest species reduced as the final carbonization temperature increased (Fig. 1). There was a higher concentration of carbon in charcoal due to the increase in the final carbonization temperature since the percentage of fixed carbon has a negative correlation with the content of volatile materials [56]. Similar results were observed in the literature for charcoal produced at the final carbonization temperature of 450 ºC, such as 24.72% for *Amburana cearensis*, native to the Cerrado [55], and 24% for the clone of *E. urophylla* x *E. camaldulensis*, used for energy purposes [47].

The fixed carbon content in charcoal is considered one of the most important parameters since it is related to the heating value of the material. The highest percentages were observed in the charcoals produced at the highest final carbonization temperature, especially from *E. gummiferum* (Fig. 1). This is explained by the fact that the wood of *E. gummiferum* presented more favorable extractive and ash contents, which potentiate its energy purposes. In addition, the increase in temperature provided a higher concentration of carbon in the charcoal. Similar values were observed in the charcoal of *Cenostigma macrophyllum*, 78.17%, and *Guazuma ulmifolia*, 81.0% [9, 18], and *Eucalyptus* clones, ranging from 73.30 to 81.36% [47, 68].

Charcoal should have a fixed carbon content ranging from 73 to 77% and a content of volatile materials between 22 and 25.50% for the steel and domestic sectors [10, 52]. Thus, charcoal of *A. fraxinifolium* and *E. gummiferum* is indicated for these industries, even when produced at the lowest final carbonization temperature (350 ºC). Since these parameters are inversely proportional, some authors have also found that the higher the final carbonization temperature, the lower the percentage of volatile materials and the higher the concentration of fixed carbon in charcoal [14, 19, 23].

The increase in the final carbonization temperature also showed a reduction in the gravimetric yield, energy yield of carbonization, and productivity of charcoal per unit of wood volume (Fig. 2). This can be related to the loss of mass resulting from the thermal degradation of elementary constituents of wood due to the increase in temperature, such as hydrogen and oxygen from hydroxyls (OH), which simultaneously provide concentration of carbon in the final product.

The differences between the average values of the charcoal parameters studied for both forest species are associated with wood-specific characteristics. *A. fraxinifolium*, for instance, can be highlighted for all carbonization yields and charcoal productivity per volume of wood as its wood has a higher basic density and higher heating value than *E. gummiferum*. The average values for charcoal and fixed carbon yields were consistent with the literature for charcoal from Cerrado species produced at 450 ºC – ranging from 24.87 to 35.34% for gravimetric yield, and 23.26 to 26.54% for fixed carbon yield [24, 55, 64]. However, only the charcoal of *A. fraxinifolium* had a similar gravimetric yield with the *Eucalyptus* genus, from 28.58 to 37.62% [14, 15].

For energy yield of carbonization and charcoal productivity per unit of wood volume, the charcoal of *A. fraxinifolium* presented higher values than the charcoal of *Eucalyptus* produced at 450 ºC, from 51 to 53% and 159 to 201 kg m^{-3}, respectively [45]. These results are associated with the high basic density of the wood of *A. fraxinifolium* (632 kg m^{-3}) when compared to the wood used in the national energy sector. Thus, it provides higher mass production in charcoal.

Therefore, the final carbonization temperature of 350 ºC is indicated for the production of charcoal of *A. fraxinifolium* and *E. gummiferum*. In addition to presenting more profitable results, the charcoal produced in this temperature exhibited satisfactory characteristics for the steel sector and domestic use. Even though the energy sector favors the use of species of the *Eucalyptus* genus, investigations and studies on other lignocellulosic materials aim at the future diversification of raw materials. Besides, they suggest a multiple, rational, and sustainable use of different species, which can generate income for regional populations. The results of this research indicate the potential of the wood from two Cerrado species for energy purposes, which can be further optimized with silvicultural treatments and genetic improvement.

4. Conclusions

- The wood of the species evaluated in this research has satisfactory characteristics for energy purposes. The wood of *Enterolobium gummiferum* presented lower ash content and higher extractive content, while the wood of *Astronium fraxinifolium* had a higher basic density and higher heating value.
- Charcoal from the wood of *E. gummiferum* was characterized by low ash content, and high calorific value and fixed carbon, whereas charcoal from *A. fraxinifolium* had a higher apparent density and, consequently, a higher carbonization yield and charcoal productivity per unit of wood volume.
- Regarding the final carbonization temperatures, both charcoals presented parameters suitable for the steel sector and domestic use. Employing the final temperature of 350 ºC is recommended due to the higher gravimetric yield and energy yield of carbonization.

Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

Vaniele Bento dos Santos: Conceptualization, Methodology, Investigation, Formal analysis. Writing - original draft. Edy Eime Pereira Baraúna: Conceptualization, Methodology, Supervision. Fernando Colen: Conceptualization, Methodology, Writing - review & editing. Talita Baldin: Writing - review & editing. Thiago Campos Monteiro: Writing - review & editing. Marina Donária Chaves Arantes: Writing - review & editing.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

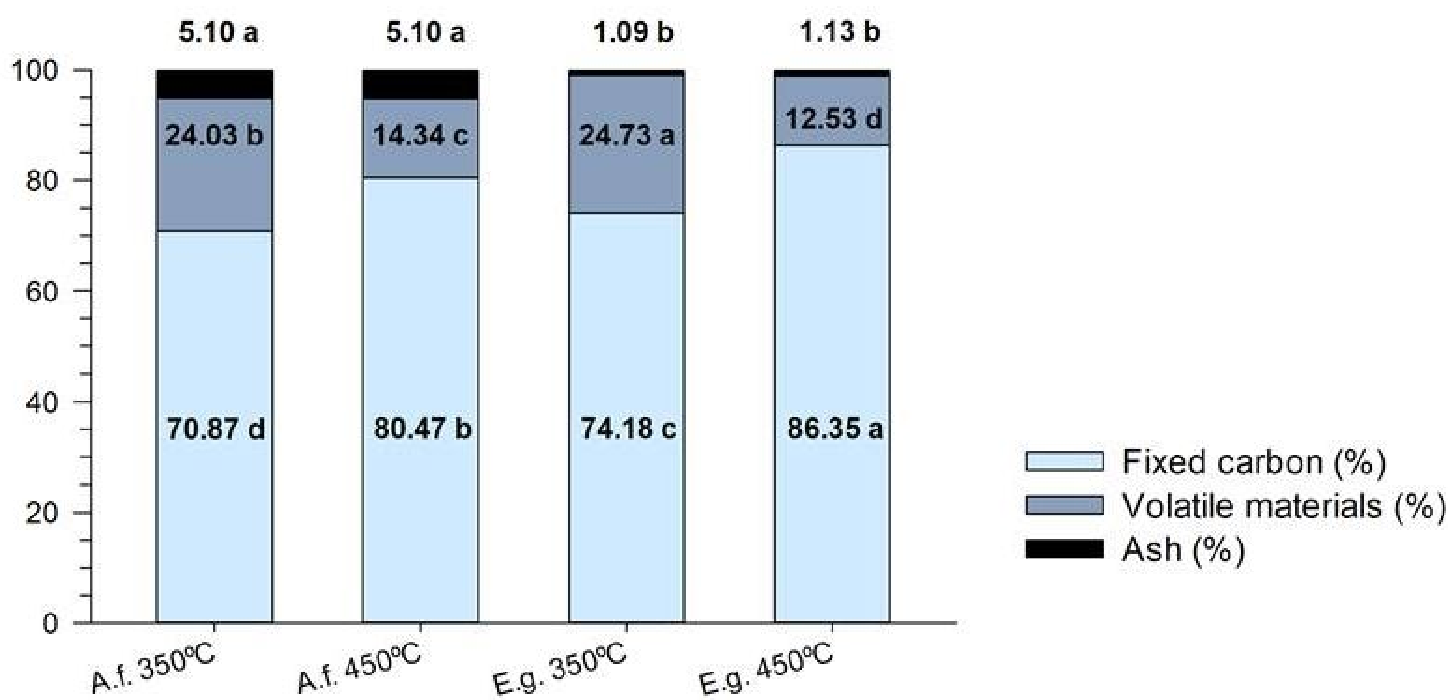

Figure 1

Immediate chemistry of *Astronium fraxinifolium* and *Enterolobium gummiferum* charcoal at two final temperatures.

Where: A.f.= *Astronium fraxinifolium*; E.g. = *Enterolobium gummiferum*. Averages followed by the same letter between treatments do not differ statistically by the Kruskal-Wallis test at 5% of significance.

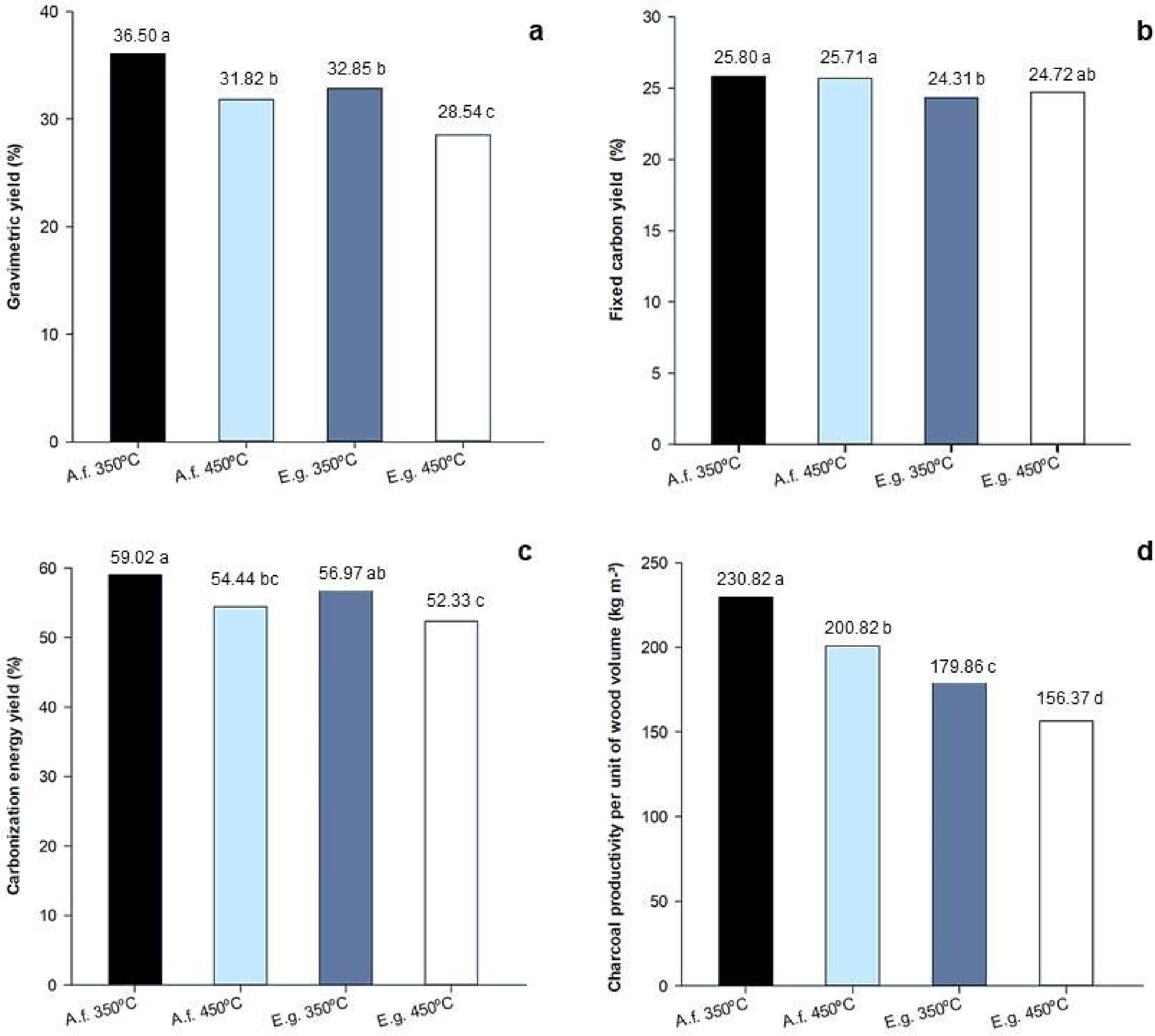

Figure 2

Average values for gravimetric yield (a), fixed carbon yield (b), energy yield of carbonization (c), and charcoal productivity per unit of wood volume (d) of *Astronium fraxinifolium* and *Enterolobium gummiferum* at two final carbonization temperatures.

Where: A.f.= *Astronium fraxinifolium*; E.g. = *Enterolobium gummiferum*. Averages followed by the same letter in each graph do not differ statistically by Tukey's test at 5% of significance.