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Articles

Influence of basic density and chemical composition of wood on the carbonization process

Influência da densidade básica e da composição química da madeira para o processo de carbonização

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ABSTRACT

Charcoal production from wood of fast-growing species, *Eucalyptus* and native species, is one of the most important activities in the Brazilian forestry sector, and mainly supplies the steel sector. The objective of this work was to carry out a literature review on studies that relate the basic density and chemical composition of wood with the variables of the carbonization process and the characteristics of charcoal. The principle of exploratory study was used through a literature review. The main studies used in this research showed that *Eucalyptus* clones used in the charcoal industry showed a basic density between 330 and 600 kg/m³, fixed carbon content between 71.9 and 84.4% and a higher calorific value between 6996 cal/g and 8326 cal/g. Regarding the native species studied, these presented basic density varying between 364 and 1052 kg/m³, greater than the variation observed for *Eucalyptus*; fixed carbon content varying between 60.6 and 81.0%; and higher calorific value between 6248 cal/g and 7730 cal/g. The conclusion indicates necessity for more investment in wood quality analyzes to evaluate the carbonization process and charcoal quality, especially with wood from native species; among the characteristics of wood, basic density was the most used in the charcoal industry, while the holocellulose content and S/G ratio of lignin were rarely presented in research.

Keywords: Wood quality; Eucalyptus; Native species; Energy

RESUMO

A produção de carvão vegetal a partir de madeiras de eucalipto e espécies nativas é uma das mais importantes atividades do setor florestal brasileiro, e abastece principalmente o setor siderúrgico. O objetivo deste trabalho foi realizar uma revisão bibliográfica sobre estudos que relacionam a densidade básica e a composição química da madeira com as variáveis do processo de carbonização e com as características do carvão vegetal. Foi utilizado o princípio do estudo exploratório por meio de uma revisão de literatura. Os estudos utilizados nesta pesquisa apontaram que os clones de eucalipto utilizados na indústria de carvão vegetal apresentaram densidade básica entre 330 e 600 kg/m³, teor de carbono fixo entre 71,9 e 84,4% e poder calorífico superior entre 6996 cal/g e 8326 cal/g. Com relação às espécies nativas estudadas, estas apresentaram densidade básica variando entre 364 e 1052 kg/m³, maior que a variação verificada para o *Eucalyptus*; teor de carbono fixo variando entre 60,6 e 81,0%; e poder calorífico superior entre 6248 cal/g e 7730 cal/g. Conclui-se que é necessário mais investimento nas análises de qualidade da madeira para a avaliação do processo de carbonização e qualidade do carvão vegetal, principalmente com madeiras de espécies nativas; dentre as características da madeira, a densidade básica foi a mais utilizada nas indústrias de carvão vegetal, enquanto o teor de holocelulose e relação S/G da lignina foi pouco apresentada pelas pesquisas.

Palavras-chave: Qualidade da madeira; Eucalyptus; Espécies nativas; Energia

1 INTRODUCTION

Charcoal is the solid product of the carbonization of wood. It is an important renewable energy product used in many industrial applications and chains. Brazil is the world's leading producer, with output of 7.0 million metric tons in 2022 (INDUSTRIA BRASILEIRA DE ÁRVORES – IBÁ, 2023), mostly from wood harvested from planted forests. As an alternative to the use of coal, charcoal is an example of sustainability for the steel industry, making the nation a potential supplier of energy inputs to the rest of the world.

The carbonization process occurs through the thermal degradation of biomass submitted to a continuous supply of heat in a low-oxygen or oxygen-free atmosphere. Besides charcoal, carbonization results in a variety of other products: both liquid (pyroligneous liquor and tar) and gaseous (hydrocarbons and hydrogen) (Protásio *et al*., 2021). According to Pereira (2021), the variables of the carbonization process that directly impact the final characteristics of charcoal are the time and final carbonization temperature.

Furthermore, the quality of charcoal for industrial and domestic use can be assessed by determining its physical-chemical characteristics, such as apparent density and gravimetric yield, as well as immediate chemical analysis to ascertain the contents of fixed carbon, volatile materials and ash. Among these, apparent density stands out as the main characteristic used to determine the quality of charcoal, especially for application as a bioreducer in the steel industry, since higher apparent density indicates greater compressive strength and better performance in blast furnaces (Protásio *et al*., 2021).

Charcoal with higher than average apparent density releases more energy when burned, increasing the gravimetric yield, which is considered satisfactory between 30 and 35% (Rodrigues; Braghini Júnior, 2019).

The immediate chemical analysis of charcoal is also essential to determine its quality and efficiency as a fuel. The fixed carbon content, which corresponds to the percentage of carbon present in the charcoal, is one of the main indicators of this quality (Basso, 2017). Volatile materials, which include hydrogen, hydrocarbons, carbon monoxide and carbon dioxide, represent the fraction of residual volatile matter in charcoal. Although these volatile materials contribute to initial combustion, high content of ash, which is the residue of mineral oxides resulting from complete combustion, is considered undesirable (Lima, 2020).

With regard to the wood carbonization process, the appropriate selection of furnace characteristics (size, technology, reuse of byproducts, type of construction material, carbonization time) are also relevant factors that affect the quality of the charcoal produced. Monitoring the carbonization process and its control variables such as time, temperature and heating rate, when possible, allows further improvement in the quality of charcoal and the yield of the carbonization process.

Therefore, the characterization and quality of wood combined with a well-controlled carbonization process are essential for the production of high-quality charcoal. Here we report a literature review of the influence of the basic density and chemical composition of wood on the main variables of the carbonization process and the characteristics of charcoal.

2 METHODOLOGY

2.1 Search and selection of bibliographical material

Our exploratory literature review covered the period between 2000 and 2021 and was composed of scientific articles, master's dissertations and doctoral theses collected from Brazilian scientific periodicals (Revista Árvore, Cerne, Ciência Florestal, and Floresta e Ambiente) and the collections of theses and dissertations of Brazilian universities: Universidade Federal do Espírito Santo (UFES), Universidade Federal de Lavras (UFLA), Universidade Federal de Viçosa (UFV) and Escola Superior Luiz de Queiroz (ESALQ), employing the following keywords: carbonization, charcoal, pyrolysis and wood.

Next, we read and screened the scientific works considering as a selection criterion the bibliographies that addressed the quality of the wood (basic density and chemical composition) in relation to the carbonization process variables. At a third level of selection, we considered publications specifying the genera of the clones/species (Eucalyptus and Native) and other information about the cultivation of the trees (spacing, harvest age and location) and those clearly presenting the carbonization variables most commonly used by research institutions in Brazil. Based on these variables, we identified nine articles and four dissertations/theses.

2.2 Preparation of spreadsheets from the selected bibliographic material

The information extracted from the selected bibliographies was organized into spreadsheets containing the most relevant information for this study: (i) plantations (species/clone, age, spacing and location); (ii) wood characteristics (basic density and chemical composition); (iii) carbonization process variables (total carbonization time, final carbonization temperature and heating rate); and (iv) charcoal characteristics (yield, fixed carbon content, apparent density and higher heating value).

2.3 Relationships of wood quality, carbonization process variables and charcoal characteristics

To facilitate interpretation and discussion of the results, we ´ plotted correlation graphs between all selected variables: (i) basic density and chemical composition of the wood (contents of holocellulose. total lignin and extractives); (ii) carbonization process variables (total carbonization time, final carbonization temperature and heating rate); and (iii) characteristics of the charcoal (fixed carbon content, apparent density and higher heating value).

2.4 Comparison between the characteristics of charcoal and the carbonization process variables

To better understand the relationship between wood quality (basic density and chemical composition) in the carbonization process and charcoal quality among the selected studies, we prepared a comparative graph containing three different carbonization times for eucalyptus wood (240, 360 and 740 min) and three different times for native wood species (150, 240 and 330 min), considered extreme conditions at the same carbonization temperature of 450 °C. This comparison sought to illustrate under what conditions the other process variables (heating rate) should be changed, due to the variation in wood quality (basic density and chemical composition), and the reflection of this combination on the charcoal quality.

3 DEVELOPMENT

3.1 Assessment of information on the technological characterization of wood for charcoal production

In the first stage of material selection, we chose 26 articles and eight dissertations/ theses. In the second and third, more rigorous selection phases, we considered nine articles and four dissertations/theses, which in addition to the titles, were actually research studies with results and discussion related to wood quality (technological characterization) for charcoal production.

Based on these 13 selected works, we collected and tabulated data on 53 genetic materials (clones), of which 71.7% were related to the Eucalyptus genus (38 clones) and 28.3% belonged to native species (15 species), with all works being related to charcoal production.

An important aspect was the lack of information on planted forests. The age of the trees and the spacing used in the plantations were not reported in 0 and 32% of the eucalyptus works, respectively, and in 93 and 93% of the native works, respectively.

Since information on plantations is particularly important (tree age at harvest, spacing and origin), 75% of the works on eucalyptus plantations presented all such information, while only 20% of publications on native species satisfied this criterion.

In relation to the information on wood quality (basic density and complete chemical composition), all studies on eucalyptus clones and native species reported basic density and total contents of lignin, holocellulose and extractives. On the other hand, the studies did not present cellulose and hemicellulose content separately, and 100 and 62.5% of the studies on native species and eucalyptus clones did not present the S/G ratio of lignin, respectively.

With regard to information on wood quality (basic density and complete chemical composition), only 37.5% of the eucalyptus studies presented all the information, while none of the studies on native species were complete in this regard. This shows that greater investment is needed to perform wood quality analyses to assess the carbonization process, especially studies involving wood from native species.

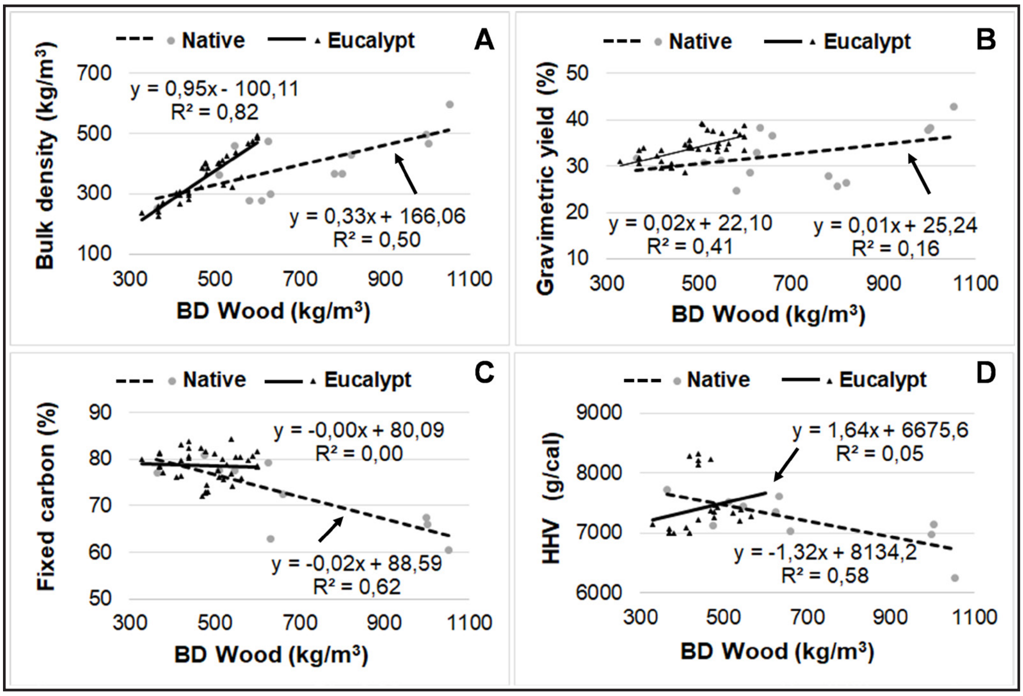
3.2 Influence of wood basic density on charcoal quality

Based on the works reviewed, the apparent density of eucalyptus charcoal ranged from 227 to 491 kg/m³, while the basic density ranged from 330 to 600 kg/m³, and the apparent density of charcoal from native species varied from 255 to 600 kg/m³, for a basic density range of 364 to 1,052 kg/m³ (Figure 1A). It is noteworthy that that wood from native species had greater variation of basic wood density than that presented for commercial species (eucalyptus). This is explained by the great diversity of native species with cultivation potential for charcoal production.

The apparent density of charcoal rose with the increase in the basic density of wood of both categories (eucalyptus clones and native species). Although the variables of the carbonization process were associated with the density of charcoal, a strong influence of the basic density of wood was observed. This was also observed by Frederico (2009) and Santos (2010), who found higher values of apparent density of charcoal of clones that had higher wood basic density.

According to Costa (2014), a strong correlation exists between the basic density of wood and the apparent density of charcoal. Hence, the denser the wood is, the denser the charcoal produced from it will be.

Figure 1 – Influence of the basic density of wood on the apparent density of charcoal (A); gravimetric yield of charcoal; (B); fixed carbon content; (C) and higher calorific value of native and eucalyptus (D)



Source: Authors (2024)

Regarding the gravimetric yield of charcoal, this increased with the increase in the basic wood density of both wood groups, and varied between 28.7 and 39.1% for the best eucalyptus clones and from 24.9 to 43.0% for the best native species, as shown in Figure 1B. Thus, the eucalyptus clones presented smaller variation in the gravimetric yield of charcoal than the variation presented by the native species.

According to Medeiros Neto *et al*. (2012), the use of denser wood enables greater mass production of charcoal, i.e., greater gravimetric yield of charcoal. However, it is important to consider that other factors, such as wood moisture and carbonization temperature, also influence the gravimetric yield (Oliveira *et al*., 2010).

The fixed carbon content of eucalyptus charcoal tended to remain constant as basic density increased, and varied from 71.9 to 84.4% for a basic density range of 330 to 600 kg/m³, as shown in Figure 1C. However, the fixed carbon content of charcoal from native wood species tended to decrease as basic density increased, and ranged from 60.6 to 81.0% for a basic density range of 364 to 1052 kg/m³.

This behavior can be explained by the fact that denser wood requires more drastic carbonization conditions and greater degradation of lignin, hence a decrease in the fixed carbon content of charcoal. Vital *et al*. (1994) found no positive correlation between the basic density of wood and the fixed carbon content of charcoal.

Thus, it is possible to note that eucalyptus charcoal has a higher fixed carbon content and less variation compared to charcoal from native species, due to greater control of the carbonization process because of the lower heterogeneity of the wood species.

Finally, the higher heating value (HHV) of eucalyptus charcoal showed an increasing trend with rising basic wood density, and varied between 6,996 and 8,326 cal/g, for basic density variation between 330 and 600 kg/m³, as shown in Figure 1D. According to Silva *et al*. (2011), wood with higher density is more suitable for the manufacture of charcoal, since it tends to have a greater higher heating value per unit volume.

However, the higher heating value of charcoal from native wood species showed a decreasing trend as the wood basic density increased, and varied between 6,248 and 7,730 cal/g for a basic density variation between 364 and 1052 kg/m³. The reason is that denser wood requires more extreme carbonization conditions, reduction in fixed carbon content (lignin degradation) and consequent decrease in higher heating value.

Becaue of the importance of wood basic density, industrial units producing charcoal prefer to work with wood having medium to slightly high density in order to optimize the performance of carbonization furnaces, aiming to increase the yield and efficiency of charcoal production.

3.3 Effect of the chemical composition of wood on the quality of charcoal

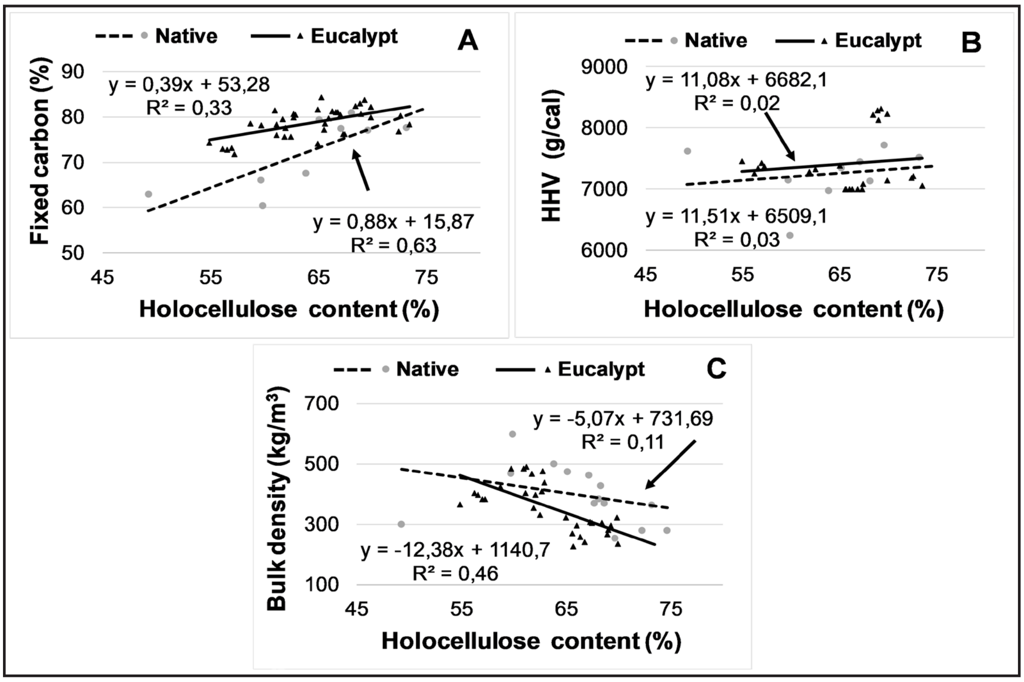
The chemical composition of wood has a strong influence on the carbonization process and the quality of charcoal. The fixed carbon content of eucalyptus charcoal ranged from 71.9 to 84.4%, for a variation in the holocellulose content of wood between 54.9 and 73.5%, and the fixed carbon content of charcoal from native species ranged from 60.6 to 81.0%, for a variation in the holocellulose content of the wood between 49.3 and 74.6% (Figure 2A).

The fixed carbon content of the charcoal had an increasing trend as the holocellulose content of the wood increased for both wood categories. The carbohydrates in the wood also contribute to the increase in the fixed carbon content of the charcoal, especially when produced at shorter times and lower temperatures, which result in less carbon being released in the form of volatile materials.

With regard to the higher hating value of charcoal, both wood types had a rising trend as the holocellulose content of increased, ranging from 6,996 to 8,326 cal/g for eucalyptus and from 6,248 to 7,730 cal/g for native species (Figure 2B).

With respect to the higher heating value of charcoal, both categories had an increasing trend as the holocellulose content of the wood rose, ranging from 6,996 to 8,326 cal/g for eucalyptus clones and from 6,248 to 7,730 cal/g for wood from native species (Figure 2B). The apparent density of eucalyptus and native charcoal showed a decreasing trend as the holocellulose content of the wood increased, varying from 227 to 491 kg/m³ for eucalyptus and from 255 to 600 kg/m³ for native wood (Figure 2C). This can be explained by the volatilization of most of the chemical compounds of the wood during carbonization, always producing a less dense charcoal. Understanding this relationship is very useful to adjust the parameters of industrial processes to enable the selection of species for charcoal production, since the density of the charcoal affects not only its quality, but also the yield of furnaces.

Figure 2 – Influence of the holocellulose content of native and eucalyptus wood on the fixed carbon content (A); higher heating value (B); and apparent density of charcoal (C)

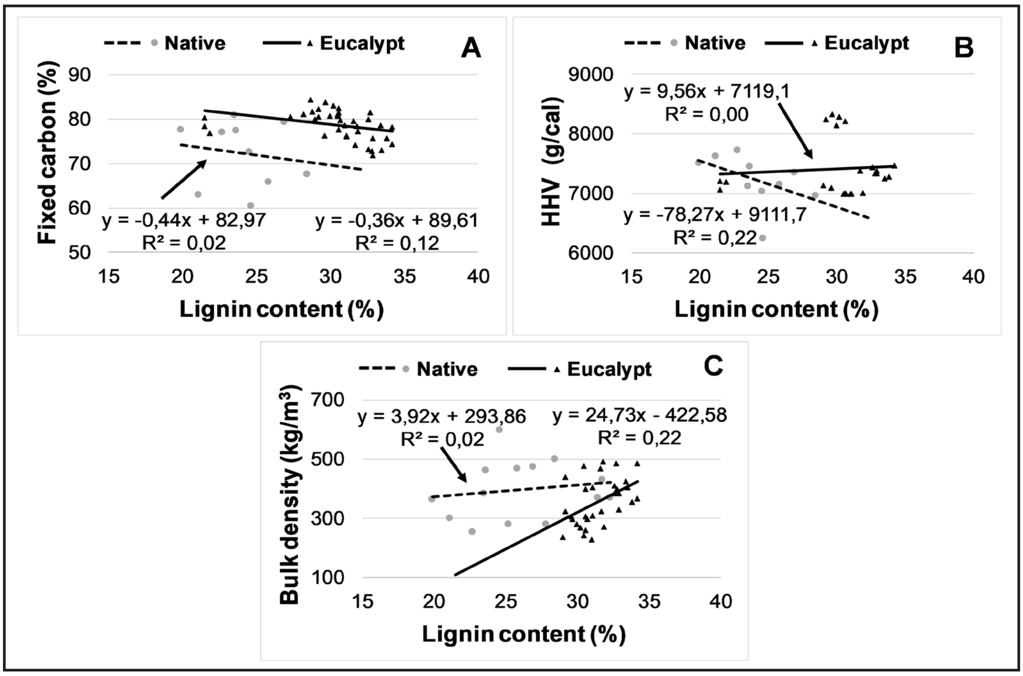


Source: Authors (2024)

For both wood groups, the fixed carbon content of the charcoal had a decreasing trend as the wood lignin content increased (Figure 3A). For wood from eucalyptus clones, the fixed carbon content of the charcoal varied between 71.9 and 84.4% for a variation in the lignin content between 21.5 and 34.2, while the fixed carbon content of the charcoal from native species varied between 60.6 and 81.0% for a variation in the lignin content between 19.9 and 32.3%.

The lignin content had a negative impact on the fixed carbon content, contrary to what was expected. This can be explained by the fact that carbonization conditions have to be more drastic for denser woods (Figure 1C), which consequently have higher lignin contents (Figure 3A). Higher carbonization temperatures lead to greater degradation of carbohydrates and lignin, even though lignin is more resistant to thermal degradation.

Figure 3 – Influence of lignin content of wood from native species and eucalyptus clones on fixed carbon content (A); higher heating value (B); and apparent density of charcoal (C)



Source: Authors (2024)

The higher heating value (HHV) of eucalyptus charcoal had a slight upward trend with increasing lignin content of the wood, and varied between 6,996 and 8,326 cal/g for a lignin content variation between 21.5 and 34.2%, as shown in Figure 3B. According to Santana (2009), the higher heating value of charcoal is greater in the presence of higher lignin and extractives content of the wood, since these compounds contain lower percentages of oxygen than do polysaccharides.

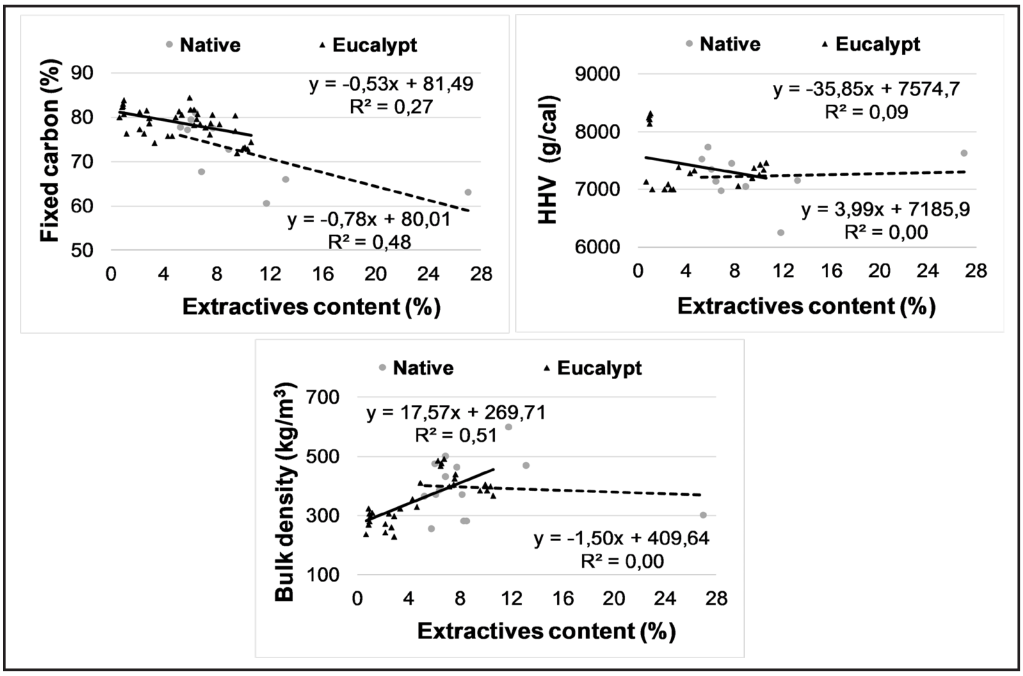
However, the higher heating value of charcoal from native species had a decreasing trend as the lignin content of the wood increased, and varied between 6,248 and 7,730 cal/g for a variation in lignin content between 19.9 and 32.3%. The reason was that wood from native is generally much denser than eucalyptus wood and requires more drastic carbonization conditions (higher temperature and longer time), and consequently produces charcoal with less stored energy.

The apparent density of eucalyptus and native charcoal had an increasing trend as the lignin content of the wood increased, ranging from 227 to 491 kg/m³ for eucalyptus and from 255 to 600 kg/m³ for native species (Figure 3C). This can be explained by the thermal stability of lignin in relation to carbohydrates. Since lignin is much more thermally stable, wood with higher levels of this compound retain a greater amount of mass in the charcoal.

Vale, Dias and Santana (2010) evaluated the relationships between the chemical, physical and energy properties of wood from five Cerrado species and found a significant and directly proportional relationship between the lignin content of the wood and the apparent density of charcoal.

The fixed carbon content of charcoal had a decreasing trend as the extractives content of the wood increased, a pattern observed in a similar manner for both types. The fixed carbon content of eucalyptus charcoal varied between 71.9 and 84.4% for a variation in the extractives content of wood between 0.9 and 10.6%, and the fixed carbon content of charcoal from the native species varied between 60.6 and 81.0% for a variation in the extractives content of the wood between 5.3 and 27.0% (Figure 4A). Vale, Dias and Santana (2001) stated that the presence of compounds originating from extractives decreases the fixed carbon content of charcoal because they are compounds that are mostly volatilized during the thermal process, mainly in wood with higher extractives content.

Figure 4 – Influence of the extractives content of native and eucalyptus wood on the fixed carbon content (A); higher heating value (B); and apparent density of charcoal (C)



Source: Authors (2024)

With regard to the higher heating value of eucalyptus charcoal, a decreasing pattern was observed as the extractives content of the wood increased, with variation from 6,996 to 8,326 cal/g, as shown in Figure 4B. This can be attributed to the propensity of extractives to be volatilized during the carbonization process, which can have an adverse impact on the quality of the resulting charcoal, leading to a product with reduced fixed carbon content, and consequently a higher heating value.

In contrast, the higher heating value of native charcoal increased slightly with the increase in the extractives content of the wood, ranging from 6,248 to 7,730 cal/g to (Figure 4B). Frederico (2009) stated that depending on the resistance to thermal degradation of the extractives present in the wood, a higher percentage of extractives may contribute to increase the calorific value of charcoal. Extractives in native wood are found in greater quantities and with greater diversity, which may explain this different trend from that presented by wood from eucalyptus clones.

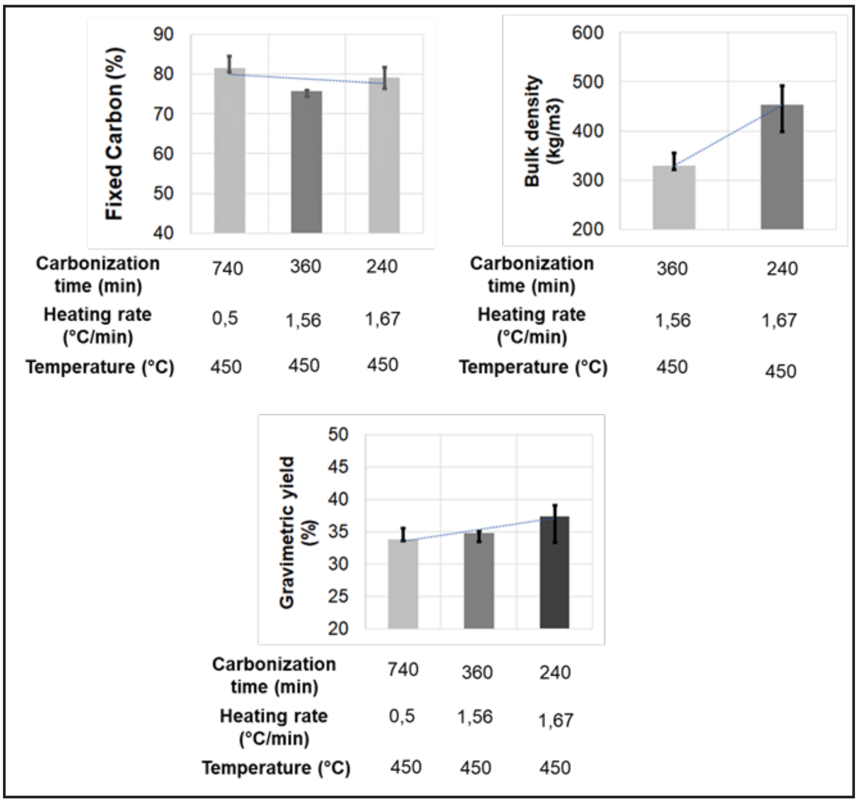
Finally, the apparent density of eucalyptus charcoal increased with rising extractives content, ranging from 227 to 491 kg/m³. For native wood species, the apparent density of charcoal decreased with increasing extractives content, ranging from 255 to 600 kg/m³ (Figure 4C). Some of the extractives from the wood, especially wood with high extractives content, tend to remain in the charcoal and contribute positively to its density. However, this pertains to wood with higher densities and more drastic carbonization conditions, and therefore lower densities of the charcoal produced.

4 Analysis of the parameters of the carbonization process on the quality of charcoal

Carbonization parameters are defined according to the quality of charcoal to meet the specifications of a given product. The information on eucalyptus wood in the scientific works used in this review to compare the parameters of the carbonization process indicated, in most cases, carbonization times of 240, 360 and 740 minutes; heating rates of 0.5, 1.56 and 1.67 °C/min; and a final temperature of 450 °C in all cases.

From these data it was possible to observe that for eucalyptus wood, the fixed carbon content was higher when extreme conditions were used, i.e., longer carbonization time (740 min) associated with lower heating rate (0.5 °C/min); and shorter carbonization time (240 min) associated with a faster heating rate (1.67°C/min), as shown in Figure 5A, i.e., longer carbonization times associated with a slower heating rate enabled a more stable thermal decomposition process and more efficient release of volatile compounds, while promoting a more effective retention of structural carbon in the form of charcoal.

Figure 5 – Influence of carbonization parameters (time, heating rate and final temperature) on the quality of charcoal from eucalyptus wood: fixed carbon content (A), apparent density of charcoal (B) and gravimetric yield (C)



Source: Authors (2024)

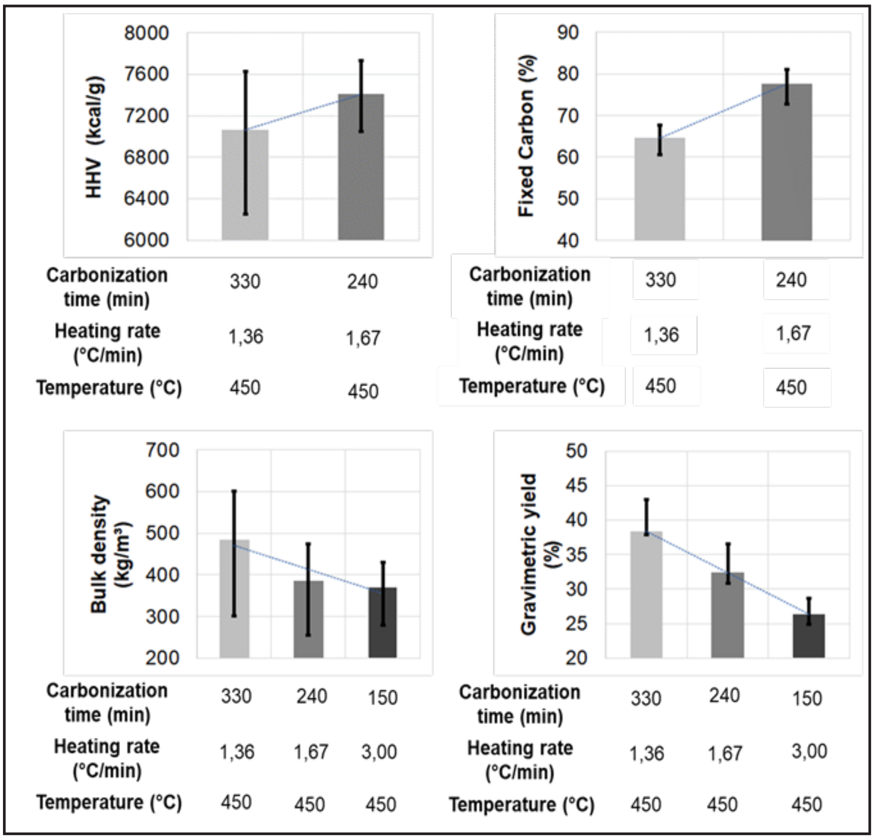
The apparent density and gravimetric yield of charcoal were higher with a shorter carbonization time (240 min) associated with a faster heating rate (1.67 °C/min), which produced denser charcoal (453 kg/m³) and higher gravimetric yield (37.4%).

The values of the higher heating value of charcoal from eucalyptus wood were mainly absent in the literature consulted, so it was not possible to carry out this assessment.

The information on native wood species from the scientific works considered in this study to compare the parameters of the carbonization process indicated, for the most part, carbonization times of 150, 240 and 330 minutes, heating rates of 1.36 1.67 and 3.0 °C/min, and temperature of 450 °C. In the case of eucalyptus wood, the carbonization times had less variation and shorter values, while the heating rates were higher.

We observed that for wood from native species, the higher heating value of charcoal was greater when using the shortest carbonization time (240 min) associated with the fastest heating rate (1.67°C/min), as shown in Figure 6A, while the lowest value was found when combining longer carbonization time and slower heating rate (330 minutes and 1.36°C/min). This demonstrates that different wood species can produce charcoal with a greater higher hearing value as long as specific process conditions are used.

Figure 6 – Influence of carbonization parameters on the quality of charcoal from native wood species: higher calorific value (A), fixed carbon content (B), apparent density of charcoal (C) and gravimetric yield (D)



Source: Authors (2024)

The fixed carbon content of native charcoal had similar behavior regarding the higher hearing value. It was greater with a faster heating rate (1.67 °C/min) and shorter carbonization time (240 min), as shown in Figure 6B. Thus, conditions involving a faster heating rate and shorter carbonization time may be more favorable for obtaining charcoal with a higher fixed carbon content, and consequently a greater higher heating value.

Finally, the apparent density and gravimetric yield of charcoal from native species behaved similarly, i.e., the highest apparent density of charcoal (484 kg/m³) and the highest charcoal yield (38.4%) were associated with the longest carbonization time (330 min) and slowest heating rate (1.36 °C/min), for the temperature of 450 °C, as shown in Figures 6C and 6D, respectively.

This behavior can be attributed to a longer and less drastic carbonization process (slower heating rate), resulting in a process with less gas release and a heavier charcoal with a greater content of volatile materials, which are important parameters to increase density and yield.

4 CONCLUSIONS

In relation to the wood:

- Basic density, total lignin content and extractives content were the parameters most frequently considered in the scientific literature consulted, while holocellulose content and lignin S/G ratio were less frequently reported.

- There was a substantial difference in the number of studies investigating native wood species in relation to eucalyptus, with the vast majority of studies focusing on the latter wood.

In relation to the carbonization process:

- The final temperature was a practically fixed variable (450 °C), while the total carbonization time and heating rate varied according to the quality of the wood (native species and eucalyptus clones).

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