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INFLUENCE OF TIME EXPOSURE TO SOIL ON THE PROPERTIES OF WOOD AND CHARCOAL FROM *Myracrodruon urundeuva* FR. ALL

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Resumo

Influência do tempo de exposição ao solo nas propriedades da madeira e carvão vegetal de Myracrodruon urundeuva Fr. All. A biomassa florestal possui grande potencial para a geração de energia, por conta disso é importante caracterizá-la e determinar quais propriedades da madeira são responsáveis pela qualidade energética e quais os fatores que a influenciam. O tempo de estocagem da madeira pode acabar tornando-a suscetível a alterações que podem afetar o seu desempenho, comprometendo a sua qualidade. Diante disso, o objetivo deste trabalho foi avaliar as propriedades da madeira e do carvão vegetal da espécie *Myracrodruon urundeuva* Fr. All. em função do tempo de exposição ao solo, visando a viabilidade para a produção energética. Foram confeccionados corpos de prova para instalação do experimento em campo durante 20 meses, sendo realizadas coletas a cada cinco meses para as análises das propriedades da madeira e do carvão vegetal. Nas propriedades da madeira foi observada uma redução na densidade básica (0,91 a 0,72 g.cm^{-3}) e holocelulose, consequentemente houve um aumento na perda de massa e solubilidade em NaOH, resultando assim na diminuição da densidade energética e no poder calorifico da madeira, entretanto obteve-se um aumento no teor de lignina que resultou no aumento do teor de carbono fixo e poder calorífico do carvão vegetal. Conclui-se que o tempo de exposição ao solo afetou de forma negativa as propriedades da madeira, porém as propriedades energéticas do carvão vegetal apresentaram resultados satisfatórios para a produção energética.

Palavras-chaves: Densidade básica, Perda de massa, Poder calorífico, Produção energética.

Abstract

Forest biomass has great potential for energy generation, so it is important to characterize it and determine which wood properties are responsible for its energy quality and what factors influence it. The storage time of the wood can make it susceptible to changes that can affect its performance, compromising its quality. Therefore, the objective of this study was to evaluate the properties of wood and charcoal from the species *Myracrodruon urundeuva* Fr. All. as a function of exposure time to the soil, aiming at viability for energy production. Test specimens were prepared for installation of the experiment in the field for 20 months, with collections being made every five months for analysis of wood and charcoal properties. In wood properties, a reduction in basic density (0.91 to 0.72 g.cm^{-3}) and holocellulose was observed, consequently leading to an increase in mass loss and solubility in NaOH, resulting in a decrease in energy density and calorific value of the wood. However, an increase in lignin content was obtained, resulting in an increase in fixed carbon content and calorific value of the charcoal. It is concluded that the exposure time to the soil negatively affected the wood properties, but the energy properties of the charcoal showed satisfactory results for energy production.

Keywords: Basic density, Mass loss, Calorific value, Energy production.

INTRODUCTION

Brazil is a world leader in charcoal production, primarily used in steelmaking as an energy source. According to data from Sindifer/IBÁ, charcoal production in key states such as Minas Gerais and Espírito Santo reached 3.6 million tons in 2021, showing a 9.4% increase compared to 2020 (IBÁ, 2022). The majority of charcoal production comes from planted forests, with the total planted tree area in 2021 reaching 9.93 million hectares, of which 75.8% (7.53 million hectares) is *Eucalyptus* (IBÁ, 2022), which is the main species used in the production of charcoal.

However, planted forests are still insufficient to meet the demand for raw materials in some states, leading to the exploitation of native forests. Tocantins's cerrado biome comprises 91% of the state, and it uses native wood for charcoal and firewood production, often clandestinely, resulting in deforestation. Sometimes, residues from clearing areas for agriculture or installing power lines are also utilized (TOCANTINS, 2014).

Myracrodruon urundeuva Freire Allemão (Aroeira) is a native cerrado specie with favorable characteristics for energy generation (firewood and charcoal), and it is also used for fence posts (SILVA *et al.*, 2018). The exploitation of native forests contributes to the disappearance of species with potential for the energy sector due to a lack of knowledge about the characteristics of many species, emphasizing the importance of studies on wood quality and properties (SIQUEIRA *et al.*, 2020).

Moreover, various factors can influence wood quality during harvesting, transportation, or storage until the final product. When wood is exposed to the soil, it is susceptible to attacks from various xylophagous organisms (fungi, bacteria, and insects) that feed on it, in addition to climatic conditions (solar radiation, rain, humidity) causing changes in the physical and chemical properties of the wood.

In this context, the study aimed to evaluate the energetic properties of wood and charcoal from the *Myracrodruon urundeuva* Fr. All. species based on the exposure time to the soil, aiming to assess its viability for energy production.

MATERIAL AND METHODS

The research was conducted at the Federal University of Tocantins, Gurupi Campus, in the Laboratory of Technology and Use of Forest Products. For the study, three trees of the species M. urundeuva were collected by simple random sampling method according to Wastowski (2018), originating from the residues of a clearing for the installation of an electrical network in the municipality of Gurupi, TO.

The trees were cut into logs from base to top, which were sent to the carpentry for the production of 2.5 x 2.5 x 30 cm test specimens, for installation of the experiment in the field and subsequent collection of samples for analysis. Before installation, the test specimens were dried in an oven at 103±2°C until constant mass and weighed to obtain the initial weight. Ten test specimens were preserved in the laboratory for analysis of unexposed wood (control).

The test specimens were placed in the area located at 11°44'44.3" South latitude and 49°02'59.1" West longitude on the university campus of Gurupi, divided into four lines with 10 test specimens each, buried vertically in the soil at a depth of 30 cm, undergoing climatic variations throughout the year. From the installation, every five months, 10 test specimens were removed from the field for laboratory analysis, thus four collections were carried out in total. Therefore, the treatments were divided as follows: T0: control, samples without soil exposure; T1: Samples with five months of soil exposure; T2: Samples with ten months of soil exposure; T3: Samples with fifteen months of soil exposure; T4: Samples with twenty months of soil exposure.

Figure 1. Woods of *M. urundeuva* before and after exposure to the soil.
Figura 1. Madeiras de *M. urundeuva* antes e depois da exposição ao solo.

After being removed from the soil, the test specimens underwent a thorough cleaning process to remove impurities, were dried in an oven at 103±2°C until constant mass, and were weighed to determine the mass loss

(%). To produce charcoal and the determination of basic density, the test specimens were transformed into blocks with dimensions of 2.5 x 2.5 x 5.0 cm.

For the determination of the wood's chemical properties (total extractives content, total lignin, holocellulose, and solubility in Sodium Hydroxide (NaOH) and moisture content, the blocks were transformed into sticks using a chisel and hammer, which were then turned into particles in the crusher (TRE-25, Tramontina, RS, BR) and the knife mill (SL - 30, Solab, SP, BR), and subsequently the wood particles were sieved (stainless steel 8" x 2", TPL - Tamis, SA, BR), with those that passed through the 40-mesh sieve and were retained on the 60-mesh sieve being selected for analysis.

The wood's basic density was determined according to standard NBR 7190 (2022). For this, 6 test specimens were used, left submerged in water in a vacuum pump process until fully saturated. After the saturation process, they were weighed on a hydrostatic balance to determine the saturated volume. Then they were placed in an oven to dry at 0% humidity at a temperature of 103°C ± 2°C until constant mass. The mass loss was calculated based on the initial and final mass values (determined by the exposure time) of each of the samples.

A determination of the moisture content, total extractives content, total lignin, holocellulose, and solubility in NaOH was carried out according to the methodologies presented by Wastowski (2018), with each analysis being performed in triplicate.

The determination of the immediate chemical analysis (ICA) of the wood was based on standard D1762 – 84 (ASTM, 2013), aiming to obtain the levels of volatile materials and ash, and by difference, fixed carbon, using 1.0000 g of particles retained on the 60-mesh sieve for each porcelain crucible. The elemental chemical analysis was determined using the values of fixed carbon and volatile materials of the wood, placed in estimation equations according to Parikh *et al.* (2007).

For the determination of the wood's energy density, the methodology proposed by Jesus *et al.* (2017) was used. The higher, lower, and net calorific values of the wood were estimated according to the proposal of the work by Ferreira *et al.* (2014), and the carbon stock of the wood was determined using the basic density and elemental carbon according to Protásio *et al.* (2013).

For the production of charcoal, wood pyrolysis was carried out using seven test specimens for each treatment, carbonized in a muffle-type electric furnace (Zezimaq, MG, BR) at 150°C for 1 hour, 200°C for 1 hour, 250°C for 30 minutes, 400°C for 30 minutes, 450°C for 30 minutes, 500°C for 30 minutes, 550°C for 30 minutes, and 600°C for 1 hour with adaptation for recovery of condensable and non-condensable gases.

After each carbonization, the gravimetric yields of charcoal obtained were determined through the percentage relationship between the dry mass of the charcoal and the mass of the wood, the yields of condensable gases or pyroligneous liquor obtained through the ratio between the mass of pyroligneous liquor obtained and the dry mass of the wood used in pyrolysis, and the yields of non-condensable gases through the difference between the total gravimetric yield in charcoal and the gravimetric yield in pyroligneous liquor.

For the determination of the immediate chemical analysis of charcoal, the charcoals from pyrolysis were crushed and sieved. The particles that passed through the 40-mesh sieve and were retained on the 60-mesh sieve were weighed 1.0000 g in each porcelain crucible. The same methodology as the wood's ICA was used as a basis, standard D1762 – 84 (ASTM, 2013). The fixed carbon stock of the charcoal (ECF) was determined according to Protásio *et al.* (2013).

The apparent density of the charcoal was determined according to standard NBR 9165 (ABNT, 1985). The higher heating value of the charcoal was estimated using the methodology proposed in works described by Vale *et al.* (2002). The energy density of the charcoal is calculated based on the value of the apparent density of the charcoal, multiplied by its higher heating value.

The experiment was conducted in a completely randomized design (CRD), with five treatments. The statistical programs used were Statgraphics Centurion XVI.I and SISVAR 5.6. After analysis of variance (ANOVA), the Tukey test ($p \leq 0.05$) was applied. The Excel® program was used to tabulate the data and determine the Standard Deviation (SD%), and Coefficient of Variation (CV%).

RESULTS

The physical and chemical properties of the wood showed significant differences among the treatments for all evaluated parameters (Table 1). The obtained coefficients of variation were low, demonstrating that the collected data is homogeneous. The average moisture content values varied over the exposure time, with T1 showing the highest average value compared to the other treatments. Regarding the wood's basic density, a significant reduction in its values can be observed over the months of exposure, with T4 having the lowest density (0.72 g cm^{-3}), coinciding with the highest mass loss value (27.34%).

Table 1. Physical and chemical properties of wood, mean values of moisture content (MC), basic density (BD), mass loss, extractive content, total lignin, holocellulose, and NaOH solubility of *M. urundeuva*.

Tabela 1. Propriedades físicas e químicas da madeira, médias dos teores de umidade (TU), densidade básica (Db), perda de massa, teores de extrativos, lignina total, holocelulose e solubilidade NaOH de *M. urundeuva*.

Treatments	**MC (%)**	**BD (g cm^{-3})**	**Mass loss (%)**	**Ext. content (%)**	**Total lignin (%)**	**Holocel. (%)**	**Solub NaOH (%)**
T0	7,29 ab (6,87)	0,91 a (2,17)	-	11,94 a (2,95)	20,37 c (0,69)	67,69 a (0,44)	19,01 d (2,35)
T1	7,81 a (1,06)	0,86 b (0,92)	8,19 c (7,98)	11,50 a (0,42)	20,29 c (3,34)	68,21 a (1,01)	20,16 c (1,26)
T2	6,81 b (0,66)	0,83 bc (2,89)	12,18 b (18,12)	10,60 b (1,66)	22,86 b (1,25)	66,54 b (0,47)	20,54 c (0,11)
T3	7,37 ab (1,60)	0,80 c (1,16)	13,24 b (6,05)	9,50 c (4,07)	24,16 a (2,02)	66,19 b (0,50)	21,37 b (0,10)
T4	7,13 b (1,66)	0,72 d (6,13)	27,34 a (7,41)	10,17 bc (2,88)	24,25 a (1,70)	65,66 b (0,43)	26,2 a (0,41)
Pr>Fc	*	*	*	*	*	*	*

Note: Means followed by the same lowercase letter in the column do not differ statistically (Tukey test – P≥0.05). Values in parentheses correspond to the coefficient of variation (%).

The total extractives content showed a significant difference in treatments T2 and T3, which decreased compared to the value found for the control (T0), although there was a slight increase in T4. For the total lignin content, the results obtained showed an increase during the months of exposure, where T4 (24.25%) was significantly higher than T0 (20.37%) and similar to T3 (24.16%). The holocellulose content for the control (T0) and T1 was significantly higher than T2, T3, and T4. The solubility in sodium hydroxide (NaOH) for T0 was significantly lower than the other treatments.

Through the elemental chemical analysis of wood, it is possible to quantify the elements present in fuels, where carbon (C) and hydrogen (H) are the main elements for energy generation (TAKAHASHI *et al.*, 2021). In Table 2, it is noted that the elemental chemical composition showed significant differences among the treatments.

Table 2. Elemental chemical composition, carbon (C), hydrogen (H), oxygen (O), and carbon stock (CS) of *M. urundeuva* wood.

Tabela 2. Composição química elementar, carbono (C), hidrogênio (H), oxigênio (O) e estoque de carbono (CS) da madeira de *M. urundeuva*.

Treatments	**C (%)**	**H (%)**	**O (%)**	**CS (kg.m^{-3})**
T0	47,93 a (0,12)	5,97 b (0,10)	44,26 b (0,13)	442,94 a (1,18)
T1	46,58 b (1,26)	6,00 b (1,06)	45,10 b (1,00)	413,45 b (0,10)
T2	46,15 b (0,10)	6,08 a (0,10)	46,13 a (0,10)	400,69 bc (0,10)
T3	46,14 b (0,12)	6,09 a (0,03)	46,30 a (0,10)	388,27 c (1,49)
T4	46,05 b (0,39)	6,10 a (0,10)	46,32 a (0,25)	341,7 d (3,17)
Pr>Fc	*	*	*	*

Note: Means followed by the same lowercase letter in the column do not differ statistically (Tukey test – P≥0.05). Values in parentheses correspond to the coefficient of variation (%).

Concerning the carbon content (C), there was a significant difference between the control (T0) and the other treatments. Although there was no statistical difference from T1 to T4, it is possible to observe a slight decrease in the percentage of C during the months of exposure (Table 2).

Observed in Table 2 the increase in hydrogen content (5.97 to 6.10%) and oxygen (44.26 to 46.32%), although in treatments T2, T3, and T4 the average values do not differ statistically at the 5% significance level for both elements. It is noted that the carbon stock (EC) showed a reduction during the exposure time, ranging from 442.94 to 341.7 kg.m $^{-3}$.

The energetic properties of wood (Table 3) showed significant differences among the analyzed parameters. According to the Tukey test at 5% probability, treatments T2, T3, and T4 did not show significant differences for the levels of volatile materials, fixed carbon, ash, and higher, lower, and net calorific values.

Table 3. Energetic properties of wood, volatile matter content (MC), fixed carbon content (FC), ash content (AC), higher heating value (HHV), lower heating value (LHV), useful heating value (UHV), and energy density (ED) of *M. urundeuva.*

Tabela 3. Propriedades energéticas da madeira, teor de materiais voláteis (MC), teor de carbono fixo (FC), teor de cinzas (AC), poder calorífico superior (HHV), poder calorífico inferior (LHV), poder calorífico útil (UHV) e densidade energética (ED) de *M. urundeuva.*

Treatments	**VM (%)**	**FC (%)**	**AC (%)**	**HHV (kcal.kg^{-3})**	**LHV (kcal.kg^{-3})**	**UHV (kcal.kg^{-3})**	**ED (kcal.cm^{-3})**
T0	82,62 c (0,39)	16,22 a (1,97)	1,16 a (0,77)	4447,13 a (0,34)	4123,13 a (0,37)	3778,83 a (0,80)	4.110,20 a (1,37)
T1	88,37 b (0,78)	10,00 b (5,23)	0,97 b (6,59)	4136,19 b (1,54)	3812,19 b (1,67)	3467,65 b (1,59)	3.671,36 b (1,0)
T2	93,12 a (0,10)	5,94 c (0,6)	0,94 bc (5,66)	3970,02 c (0,1)	3646,02 c (0,1)	3356,65 c (0,1)	3.446,52 c (0,98)
T3	93,49 a (0,27)	5,64 c (4,80)	0,86 bc (2,33)	3959,21 c (0,34)	3635,21 c (0,37)	3323,09 c (0,41)	3.331,85 c (1,28)
T4	94,07 a (0,83)	5,09 c (16,52)	0,84 c (6,93)	3933,75 c (1,07)	3609,75 c (1,16)	3309,55 c (1,11)	2.919,50 d (3,79)
Pr>Fc	*	*	*	*	*	*	*

Note: Means followed by the same lowercase letter in the column do not differ statistically (Tukey test – P≥0.05). Values in parentheses correspond to the coefficient of variation (%).

The volatile materials content of the wood (Table 3) increased during the exposure time, with T4 obtaining the highest value (94.07%) and the control T0 yielding the lowest result (82.62%), followed by T1 (88.37%). There was a reduction in the fixed carbon content of the wood during the exposure time, ranging from 16.22 to 5.09%. The same behavior was observed in the wood ash content (AC), which ranged from 1.16 to 0.84%. The average values of higher, lower, and net calorific values (Table 4) decreased over the exposure time, along with the energy density.

The average values of gravimetric yield in charcoal (Table 4) varied over the exposure time, with the control (T0) obtaining the highest yield, thus demonstrating that in the other treatments, the values decreased.

Table 4. Values of gravimetric charcoal yield (GCY), condensable gas yield (CGY), and non-condensable gas yield (NCGY).

Tabela 4. Valores do rendimento gravimétrico em carvão Vegetal (GCY), rendimento em gases condensáveis (CGY) e rendimento em gases não condensáveis (NCGY).

Pyrolysis Yields (600°C)	**Months**				
	T0	**T1**	**T2**	**T3**	**T4**
GCY (%)	35,11	26,26	29,21	28,88	29,40
CGY (%)	40,72	47,14	45,83	46,01	44,24
NCGY (%)	24,17	26,60	24,96	25,11	26,36

The yield of condensable gases (Table 4) showed higher values compared to the yield of charcoal and non-condensable gases, ranging from 40.72 to 47.14%, with T1 obtaining the highest value. Within the yield of non-condensable gases, T1 had the highest value at 26.60%.

Table 5 presents the average values of the energetic properties of charcoal, where significant differences were observed among the analyzed properties. The bulk density of charcoal showed a gradual decrease over the exposure time, ranging from 0.55 to 0.44 g.cm^{-3}. As for the volatile matter content of charcoal, there was a decrease in the values over time from 32.14 to 23.52%. The fixed carbon content of charcoal increased during the exposure time, ranging from 64 to 75%.

Table 5. Energetic properties of charcoal, mean values of bulk density (BD), volatile matter content (VM), fixed carbon content (FC), ash content (AC), higher heating value (HHV), fixed carbon stock (FCS), and energy density (ED) of *M. urundeuva*.

Tabela 5. Propriedades energéticas do carvão vegetal, média dos teores de densidade aparente (BD), materiais voláteis (VM), carbono fixo (FC), cinzas (AC), poder calorífico superior (HHV), estoque de carbono fixo (FCS) e densidade energética (ED) de *M. urundeuva.*

	Energetic Properties of Charcoal						
Treatments	**BD (g cm^{-3})**	**VM (%)**	**FC (%)**	**AC (%)**	**HHV (kcal.kg^{-1})**	**FCS (kg.m^{-3})**	**ED (kcal.cm^{-3})**
T0	0,55 a (2,96)	32,14 a (2,09)	64,90 d (1,21)	2,96 b (22,56)	7093,70 d (0,37)	317,34 c (2,41)	3.468,81 b (2,48)
T1	0,49 b (2,60)	26,29 b (3,01)	70,19 c (1,14)	3,52 a (2,88)	7269,74 c (0,37)	311,20 c (4,49)	3.222,72 c (4,04)
T2	0,49 b (13,20)	25,99 b (2,08)	71,67 b (1,12)	2,34 ab (13,20)	7318,9 b (0,37)	333,16 b (14,16)	3.404,910 b (13,51)
T3	0,47 bc (4,55)	26,11 b (2,46)	71,76 b (0,81)	2,13 bc (5,90)	7322,01 b (0,26)	348,96 b (5,19)	3.559,89 b (4,76)
T4	0,44 c (3,88)	23,52 c (1,01)	74,61 a (0,41)	1,87 c (4,80)	7416,70 a (0,14)	408,68 a (3,01)	4.062,53 a (2,97)
Pr>Fc	*	*	*	*	*	*	*

Note: Means followed by the same lowercase letter in the column do not differ statistically (Tukey test – P≥0.05). Values in parentheses correspond to the coefficient of variation (%).

In Table 5, the samples that showed the highest average ash content (3.52%) were from T1, and the lowest value (1.87%) was from T4. The lowest ash value coincided with the highest higher heating value. The higher heating value of charcoal ranged from 7,093 to 7,417 kcal.kg^{-1}, where its value increased over the exposure time, the same happened with the fixed carbon stock and energy density.

DISCUSSION

Even though the moisture content varied during the soil exposure time, it remained below 8% moisture, which according to COPAM 227 (2018) falls within the recommended range for energy generation, where the moisture content should be less than 40% for direct burning. The moisture content of the wood is a factor that influences the duration of wood carbonization, as the higher the moisture content, the more energy will be spent in the drying process.

According to the months of exposure, the basic density of the wood decreased, going from a high basic density (density above 0.72 g.cm^{-3}) to a medium density (0.50 to 0.72 g.cm^{-3}) in T4, according to the classification of the Brazilian Forest Service - SFB (2023). According to Carneiro *et al.* (2014), the basic density of wood is directly related to energy production, meaning that the higher the density, theoretically the greater the amount of energy stored per unit of mass. So, with the reduction in wood density, the bulk density of charcoal may decrease, which, depending on the conditions, may also result in a loss of energy density.

It is possible to observe an increase in mass loss over the exposure time as the wood loses basic density. According to the American Society for Testing and Materials (2005), *Myracrodruon urundeuva* wood can be classified as moderately resistant to decay, as the mass loss was less than 44% throughout the analyzed period.

The total extractives loss from the wood over the exposure time can be explained by the leaching of the extractives. However, in T4 there was a slight increase in the total extractives content, which may have occurred due to the degradation of structures during this period, which ended up being extracted by the solvents at the time of extraction, along with the total extractives. For charcoal production, low extractive contents are beneficial for energy generation, as they are degraded at low temperatures.

It is possible to observe an increase in the total lignin content, which is likely due to the greater attack of xylophagous organisms on the holocellulose, increasing the lignin content about the total mass, thus leading to a reduction in the holocellulose content in the exposed samples. Lignin accounts for the majority of carbon fixation in charcoal, contributing to an increase in calorific value. In this sense, it can be expected that there will be an increase in the amount of energy produced, according to the increase in lignin in the total wood mass.

According to Takahashi *et al.* (2021), the lower the holocellulose content, the greater the energy production, since cellulose and hemicelluloses are more thermally unstable compared to lignin. In charcoal production, wood with low levels of holocellulose is recommended, as high levels result in lower charcoal yield and higher percentages of condensable and non-condensable gases (SANTOS *et al.*, 2016).

It is noted that the wood underwent degradation over the exposure time, a strong indicator of this, in addition to the basic density and mass loss, is the increase in solubility in NaOH, which is due to the consumption of the wood's chemical constituents by xylophagous agents, with T4 showing the highest degree of deterioration due to the longer exposure time compared to the other samples.

When analyzing the elemental chemical composition of the wood, it is possible to observe a slight decrease in the percentage of carbon (C) during the months of exposure, which directly impacted the wood's carbon stock (CS). This loss may end up negatively influencing the calorific value of the wood due to the importance that carbon has in energy generation.

Although the hydrogen (H) content has increased, the oxygen (O) content has also increased, which would mean that while the hydrogen content is beneficial for energy generation, the oxygen content has the opposite effect, which can end up negatively affecting the energy properties of the wood.

The values of volatile materials in the wood increased as a result of the exposure time, which may be related to the increase in elemental oxygen, because the higher it is, the more rapidly the wood is consumed, resulting in a shorter energy production time.

The fixed carbon content of the wood decreased as the volatile materials content increased, as they are directly related, that is, the higher the volatile materials content, the lower the fixed carbon content will be. In addition, the reduction of elemental carbon in the wood also influenced the decrease in fixed carbon content. With this reduction, energy production is likely to be affected because the fixed carbon content influences the energy generation time.

Exposure time to the soil led to a reduction in the ash content of the wood, which is very beneficial for energy production, as the higher the ash content, the more energy is wasted in the combustion process since part of the released energy is absorbed by the fusion of inorganic materials (MACHADO *et al.*, 2014).

The higher heating value of the wood showed lower results during the exposure time compared to the control, the same was observed in the lower and useful heating values. A possible explanation for this fact is the high content of volatile materials, which reduced the fixed carbon content, in addition to the increase in elemental oxygen, these variables affected the higher heating value, which in turn affected the lower and useful heating values.

The higher heating value is the amount of energy released during the direct burning of wood, and it is considered one of the most important variables in the selection of species for energy purposes (CARNEIRO *et al.*, 2014).

The values of wood energy density decreased in the last treatments, this is because the wood's basic density and higher heating values were low, as both variables are directly related to energy density. Energy density determines the amount of energy stored per unit of mass.

The charcoal yield showed varied results over the months of exposure. It is possible to observe that the lowest value obtained coincides with the highest moisture content (TU), this is due to its removal during the carbonization process, which results in a decrease in charcoal yield and consequently an increase in condensable gas yield, which the liquid removed is added to its yield.

The results show that there was a reduction in charcoal yield when compared to the control, probably due to the loss of wood mass, however, T2 and T4 showed an increase compared to the others. Possibly due to the low moisture content in the two treatments and the differences in the wood's chemical composition, especially the lignin content. Lignin shows better resistance to thermal degradation compared to cellulose and hemicellulose, resulting in a higher gravimetric yield (LIN *et al.*, 2021).

It can be noticed that the condensable gas yield increased during the months of exposure when compared to the control, probably influenced by the moisture content.

The non-condensable gas yield showed higher results than the control in the months of exposure, due to the relationship between the yields, that is, the lower the charcoal yield, the higher the values of condensable and non-condensable gas yields.

The apparent density of the charcoal showed a gradual decrease over the exposure time, the same was verified for the wood's basic density, which is linked to the charcoal density. Density influences the productivity of charcoal kilns because, for a certain volume of the kiln, the higher the wood density, the greater the yield/weight ratio of the charcoal (FORTALEZA *et al.*, 2019).

The low volatile content of the charcoal obtained was due to the release of volatile materials present in the wood during carbonization. A high content of volatile materials is undesirable for steel mills, as this substance is part of the fuel that evaporates when heated to high temperatures and, after evaporation, mixes with atmospheric oxygen and burns, becoming more thermally unstable (JESUS *et al.*, 2017).

The high fixed carbon content obtained may be related to the lignin content, responsible for most of the carbon fixation in the charcoal during wood carbonization. The increase in lignin content in wood results in a higher fixed carbon content in the charcoal, resulting in a lower volatile content. According to Brand (2010), lower volatile levels tend to result in higher fixed carbon levels in the charcoal, which may require longer residence times in the kiln until complete combustion.

The ash content decreased in treatments T2, T3, and T4, which will have a positive effect on energy production. However, T1 showed a slight increase compared to the control. In some cases, the increase in ash may be caused by soil residues that were impregnated in the wood and were not consumed during carbonization. The ash content is considered low when below 4% according to Brand *et al.* (2013), which is a positive result for the use of wood energy in both firewood and charcoal production.

Although the ash content decreased over the exposure time, it can still be considered high for the SAA-40 resolution parameters, which stipulate that the ideal value for charcoal ash content is less than 1.5% (SÃO PAULO, 2015).

It is noted that the higher heating value of the charcoal increased with each treatment, the same behavior is observed in the fixed carbon content and energy density. The main factor responsible for this increase is the lignin content, which generated higher fixed carbon content through wood carbonization, resulting in a higher heating value, energy density, and carbon stock, as these parameters are related.

Although the apparent density of the charcoal is a variable that can affect the energy density and fixed carbon stock of the charcoal, the values obtained were not sufficient to negatively influence due to the higher percentage of fixed carbon present in the charcoal, which contributed to the increase of the charcoal's energy potential.

CONCLUSION

- The exposure time to the soil influenced the properties of both the wood and the charcoal, where the basic density, extractives content, and holocellulose decreased, consequently, there was an increase in mass loss, lignin content, and solubility in NaOH. This led to a reduction in the fixed carbon content, which contributed to the decrease in the energy potential of the wood.
- The energy properties of the charcoal showed good results.
- Analyzing the properties of the wood in general, it is possible to perceive that there were severe attacks in a short period, which makes it unfeasible for other purposes.
- It is recommended to produce charcoal after twenty months of wood exposure to the soil, as it presents the best energy potential for charcoal.

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