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ENERGY QUALITY OF WOOD AND CHARCOAL FROM *Eucalyptus* spp. STORED OUTDOORS

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Resumo

Qualidade energética da madeira e do carvão vegetal de Eucalyptus spp. estocada ao ar livre. O objetivo deste trabalho foi avaliar o comportamento da madeira de *Eucalyptus* spp. estocada ao ar livre durante o período de quatro meses, visando a qualidade energética da madeira e do carvão vegetal. Durante o período de 4 meses foram coletadas amostras a cada mês para a realização das análises da madeira e do carvão vegetal. As análises incluíram a avaliação das propriedades físicas, químicas e energéticas da madeira, bem como as propriedades do carvão vegetal. Durante a estocagem, a madeira apresentou perdas em massa (0,22 a 1,39 %) e densidade básica (0,75 a 0,64 g/cm³), em todos os meses de tratamento, porém até o terceiro mês apresentou aumento no teor de lignina total devido às perdas em holecelulose. Mesmo com as perdas de massa e holocelulose, ocorreu aumento energético para a madeira. Para o carvão vegetal houve um aumento até o terceiro mês para carbono fixo e poder calorífico. Conclui-se que até o terceiro mês de tratamento a madeira teve um desempenho positivo para a geração de energia e no quarto mês apresentou menor densidade básica e aparente, estoque de carbono e densidade energética, resultando na diminuição do potencial energético. A recomendação a partir do presente estudo, é que a madeira de *Eucalyptus* spp. apresentou boa resistência à estocagem ao ar livre com boa qualidade até três meses, a partir disso começou a apresentar perdas significativas.
Palavras-chave: Carvão vegetal; perda de massa; propriedades da madeira; propriedades energéticas.

Abstract

The objective of this study was to evaluate the behavior of *Eucalyptus* spp. wood stored outdoors over a period of four months, focusing on the energy quality of the wood and charcoal. During the four months, samples were collected each month to analyze the wood and charcoal. The analyses included the assessment of the physical, chemical, and energetic properties of the wood, as well as the properties of the charcoal. During storage, the wood exhibited mass losses (0.22 to 1.39%) and basic density (0.75 to 0.64 g/cm³) in all treatment months; however, until the third month, there was an increase in total lignin content due to losses in holocellulose. Despite the losses in mass and holocellulose, there was an increase in energy for the wood. For the charcoal, there was an increase in fixed carbon and calorific value until the third month. It is concluded that until the third month of treatment, the wood showed positive performance for energy generation. In contrast, in the fourth month, it exhibited lower basic and apparent density, carbon stock, and energy density, resulting in decreased energy potential. The recommendation from this study is that *Eucalyptus* spp. wood demonstrated good resistance to outdoor storage with good quality for up to three months; beyond that, it began to show significant losses.
Keywords: Charcoal; mass loss; wood properties; energetic properties.

INTRODUCTION

The Brazilian energy matrix in 2022 was composed of 47.4% of renewable energy sources, according to the Energy Research Company (EPE), which makes it one of the cleanest in the world with lower gas emissions, in which sugarcane biomass (15.4%), hydraulics (12.5%), wind (2.3%), firewood and charcoal (9.0%) stand out. solar (1.2%), bleach, and other renewables (7.0%) (BEN, 2023). Although hydraulic energy represents 12.5% of the Brazilian energy matrix, water accounts for 61.9% of the electricity generated in Brazil in 2022; for this reason, the Brazilian energy matrix is considered one of the most renewable in the world (BEN, 2023).

Therefore, forest biomass has favorable properties for the generation of renewable energy, mainly due to its versatility, rapid growth, and biodiversity. In 2022, Brazil reached 9.94 million hectares of planted forests, a growth of 0.3% compared to the previous year, where 11% of this planted area is attributed to charcoal production (IBÁ, 2023).

Brazil leads the global ranking of charcoal producers, being an important raw material for other chains, replacing inputs of fossil origin, reducing GHG emissions in steel mills and other industries that use charcoal as an energy source. *Eucalyptus* is mainly used in planted forests and the so-called energy forests, formed by species with fast growth, high productivity and high calorific value, used exclusively for energy generation.

For energy production, factors such as humidity affect direct burning and charcoal production, directly influencing the wood's calorific value and carbonization time, resulting in a longer stay and energy expenditure in removing water from the wood to start burning. For this reason, drying the wood for energy production is ideal, mainly done outdoors in the field after harvest, for the loss of part of the free water present in the wood (MAYER *et al*., 2020).

According to Brand *et al*. (2014), storage is one of the stages of biomass processing that contributes significantly to improving biomass's energy quality. Drying mainly helps in the loss of moisture; however, it is important to determine the storage time of the wood, as very long periods make the wood vulnerable to loss of mass and energy due to the attack of xylophagous organisms.

In this context, it is important to carry out studies that demonstrate the changes that storage causes in biomass and whether these changes are beneficial or harmful to its quality. Therefore, the present work aims to analyze the behavior of *Eucalyptus* spp. wood stored outdoors during the period of 4 months, thus making a comparison of its energy gains and losses for wood and charcoal, determining the optimal storage time.

MATERIAL AND METHODS

The research was carried out at the Laboratory of Technology and Use of Forest Products of the Federal University of Tocantins (UFT), Gurupi Campus. The wood used was collected in a 10 spp. Com-year-old *Eucalyptus* plantation, located in Formoso do Araguaia, TO. The samples for the installation of the experiment were obtained from logs of 10 trees randomly collected in the planting area. The specimens were sent to the carpentry shop to obtain the specimens with dimensions of 2.5x2.5x30 cm (Width x Thickness x Length). Before being installed in the field, the specimens were dried in an oven at 103±2°C until constant weight to determine the loss of wood mass. 10 samples were reserved as a control for the initial analyses.

For the installation of the experiment, 40 samples were used, taken to the field to be stored outdoors in an area of the UFT on the Gurupi campus, being divided into four equal parts, referring to each treatment, five of each treatment were directly in contact with the ground, and another five were suspended. Thus, it was divided into: Control = samples without exposure to soil; T1 = samples with one month of exposure; T2 = samples with two months of exposure; T3 = samples with three months of exposure; T4 = samples with four months of exposure.

After the installation of the experiment, the samples were collected every month until the four months of exposure to time and soil were completed. The samples were carefully cleaned in each collection to avoid soil remnants and other incrustations and dried in an oven at 103 ±2°C to a constant mass. For the analyses, the specimens were transformed into 2.5 x 2.5 x 5.0 cm (W x H x L) blocks, used to determine basic density and produce charcoal. The blocks were transformed into sticks, then crushed in a mill and sieved to obtain particles that passed through the 40 mesh sieve and were retained in the 60 mesh sieve for the wood's physical, chemical, and energetic analysis.

Wood properties

The basic density of the wood was determined according to the NBR 7190 (2022) standard. The mass loss of wood stored outdoors was determined by the gravimetric method, using the mass on a dry basis as a reference (0% moisture content). In each month of exposure, the mass loss was calculated according to Equation 1:

$$ML=\left(\frac{IW\text{-}FW}{IW}\right)\times 100$$

Em that: ML = mass loss (%), IW = initial weight of the Madeira sample (g), FW = final weight of the Madeira sample (g).

Determining the contents of total extractives, total lignin, holocellulose, and solubilities in cold water, hot water, and NaOH was carried out according to the methodologies presented by Wastowski (2018). The elemental chemical analysis was determined according to Parikh *et al*. (2007). The wood's immediate chemical analysis (ICA) was determined according to the D1762 – 84 standard (ASTM, 2013) to obtain the contents of volatile materials and ashes and, by difference, fixed carbon. The energy density of the wood was determined using the methodology proposed by Jesus *et al*. (2017). The wood's upper, lower, and useful calorific value was determined according to the proposal in the work of Ferreira *et al*. (2014). The carbon stock of the wood was obtained as used by Protásio *et al*. (2013).

Properties of charcoal

The carbonization was carried out in a muffle furnace adapted for the capture of condensable gases. 10 specimens were used in each treatment, with a final temperature of 500ºC and a heating rate of 5ºC per min. The apparent density of charcoal was determined using the NBR 9165 standard (ABNT, 1985). The immediate chemical analysis of charcoal followed the same methodology used for the ICA of wood, standard D1762 – 84 (ASTM, 2013). The higher calorific value of charcoal was estimated using the methodology described by Vale *et al*. (2002). The fixed carbon stock of charcoal (FCS) was obtained according to the work of Protásio *et al*. (2013). The energy density of charcoal was determined through the charcoal's bulk density multiplied by the charcoal's higher calorific value.

Statistical analysis

The experiment was carried out in a completely randomized design (DIC). Initially, the normality of the data was tested. Once normality was verified, analysis of variance (ANOVA) was performed, and finally, the Tukey test was applied to compare the means at the level of 5% significance. The statistical programs used were Statgraphics Centurion XVI.I and SISVAR 5.6.

RESULTS

Wood properties

Table 1 shows the mean values of basic density (BD) and mass loss of *Eucalyptus* spp. wood stored for 4 months. Tukey's test ($p \geq 0.05$) shows a significant difference in the physical properties of the wood in relation to the storage time. In the basic wood density, the mean values of the control of T1, T2, and T3 did not differ statistically by the Tukey test ($p \geq 0.05$), while T4 presented the lowest value (0.64 g/cm3). Regarding the loss of wood mass, the average values found increased during the storage time, ranging from 0.22 to 1.39%, where the highest result was obtained in T4 (Table 1).

Table 1. Average basic density (BD) and mass loss of *Eucalyptus* spp.
Tabela 1. Médias da densidade básica (BD) e perda de massa de *Eucalyptus* spp.

Treatments	BD (g/cm³)	Mass loss (%)
Control	0,75 a (3,72)	-
T1	0,73 a (3,67)	0,22 d (14,56)
T2	0,71 a (2,62)	0,64 c (16,04)
T3	0,71 a (6,23)	0,83 b (18,26)
T4	0,64 b (6,90)	1,39 a (23,22)
Pr>Fc	*	*

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

Table 2 shows the average values of total extractives, total lignins, holocellulose, solubilities, and percentage of *Eucalyptus* spp. wood elements stored for 4 months. Tukey's test shows a significant effect ($p \geq 0.05$) on the parameters evaluated, in relation to the storage time, except for the hydrogen content (H). The coefficients of variation obtained were considered low, thus demonstrating the precision of the experiment. The content of total extractives of *Eucalyptus* spp. wood increased up to T3, which presented the highest value with 13.35%, while T4 presented the lowest result (10.16%) among the storage time (Table 2).

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Table 2. Average contents of total extractives, total lignins, and holocellulose, solubilities of *Eucalyptus* spp. wood.
Tabela 2. Médias dos teores de extrativos totais, ligninas totais e holocelulose, solubilidades da madeira de *Eucalyptus* spp.

Chemical Properties of Wood											
Treatments	**Total Ext. (%)**	**Insoluble Lig. (%)**	**Soluble Lig. (%)**	**Total Lig. (%)**	**Hol. (%)**	**Solubility in cold water (%)**	**Solubility in hot water (%)**	**Solub NaOH (%)**	**C (%)**	**H (%)**	**O (%)**
Control	6,99 d (2,20)	22,24 b (1,11)	0,94 c (2,89)	23,65 b (1,18)	76,35 a (0,36)	5,54 b (3,82)	7,08 c (1,16)	23,77 c (1,77)	49,25 a (0,24)	5,98 a (0,11)	43,96 c (0,26)
T1	11,16 b (0,99)	23,49 a (5,98)	1,47 b (3,28)	24,96 ab (5,44)	75,04 ab (1,81)	4,25 c (15,77)	8,12 b (2,87)	36,42 b (0,45)	49,58 a (0,24)	5,97 a (0,10)	43,73 c (0,24)
T2	13,09 a (0,87)	23,91 a (5,19)	1,47 b (2,58)	25,38 ab (4,83)	74,62 ab (1,64)	6,61 a (1,43)	7,84 b (1,26)	37,19 b (0,17)	49,49 a (0,22)	5,97 a (0,13)	43,73 c (0,27)
T3	13,35 a (0,61)	23,91 a (3,49)	3,53 a (3,30)	27,44 a (3,42)	72,56 b (1,29)	6,78 a (1,06)	9,74 a (3,84)	40,36 a (1,18)	48,39 b (1,18)	6,06 a (0,54)	45,14 a (1,23)
T4	10,16 c (2,06)	22,24 b (13,40)	3,27 a (6,32)	23,93 b (2,75)	76,16 a (0,89)	5,89 ab (3,24)	9,84 a (2,77)	41,29 a (0,71)	48,46 b (0,17)	6,03 a (0,09)	44,77 b (0,19)
Pr>Fc	*	*	*	*	*	*	*	*	*	ns	*

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 (%).

It is noted that for the levels of lignin, whether insoluble, soluble, or total, the values increased up to T3, presenting the highest results with 23.91, 3.53, and 27.44%, respectively. The holocellulose content showed a reduction in the average values found, where T3 obtained the lowest result (72.56%), while T4 obtained the highest value (76.16%) between the storage time (Table 2).

The values found for solubility in cold water ranged from 4.25 to 6.78%, in which the lowest value found was in T1 and the highest mean values in T2 and T3 treatments. As for the solubility in hot water, the values ranged from 7.08 to 9.84%. For sodium hydroxide (NaOH) solubility, the results ranged from 23.77 to 41.29%, where the lowest value was that of the control followed by T1 (36.42%), while the highest values were found in the T3 and T4 treatments.

Table 2 presents the average values for elemental carbon, hydrogen, and oxygen of *Eucalyptus* spp. wood stored for four months. By Tukey's test, the evaluated parameters present significant values at the level of 5% probability in relation to the storage time. The coefficients of variation presented were considered low and less than 1%, thus demonstrating the accuracy of the experiment.

Among the elemental components of the wood, the Control, T1, T2, and T3 did not present significant differences according to Tukey's test (P≥0.05). Elemental carbon showed a trend of reduction with storage time, with the lowest result in T3 (48.39%). For elemental hydrogen, the values increased, with the highest value obtained in T3 (6.06%). Elemental oxygen values increased up to T3 (45.14%), but T4 decreased in relation to the previous treatment (Table 2).

Table 3 presents the average values of *Eucalyptus* spp. Note by the Tukey test (p≥0.05) significant effect between the evaluated parameters regarding the storage time.

Table 3. Average values of volatile matter content (VM), fixed carbon content (FC), ash content (AC), higher calorific value (HCV), lower calorific value (LCV), useful calorific value (UCV), carbon stock (CS) and energy density (ED) of *Eucalyptus* spp. wood.

Tabela 3. Valores médios do teor de materiais voláteis (VM), teor de carbono fixo (FC), teor de cinza (AC), poder calorífico superior (HCV), poder calorífico inferior (LCV), poder calorífico útil (UCV), estoque de carbono (CS) e densidade energética (ED) da madeira de *Eucalyptus* spp.

Treatments	Energy Properties of Wood							
	VM (%)	FC (%)	AC (%)	HCV (Kcal/Kg)	LCV (Kcal/Kg)	UCV (Kcal/Kg)	CS (Kg/m³)	ED (Kcal/cm³)
Control	79,02 b (0,83)	20,87 b (6,12)	0,11 ab (12,63)	4707,77 a (0,65)	4383,77 a (0,70)	3940,79 b (0,74)	371,32 a (3,78)	3549,74 a (3,92)
T1	77,53 c (0,81)	22,36 a (2,83)	0,12 ab (30,01)	4786,49 a (0,63)	4462,49 a (0,68)	4247,67 a (1,33)	361,74 b (3,68)	3492,23 a (3,73)
T2	77,70 c (0,85)	22,20 a (2,91)	0,10 b (29,73)	4770,99 a (0,63)	4462,49 a (0,67)	4268,06 a (1,62)	351,47 b (2,45)	3387,79 ab (2,19)
T3	83,86 a (3,79)	16,00 c (19,91)	0,14 a (25,71)	4452,16 b (3,33)	4128,16 b (3,59)	3794,57 c (4,19)	345,40 b (5,72)	3176,84 b (5,37)
T4	83,99 a (0,55)	16,37 c (2,78)	0,14 a (30,89)	4498,21 b (0,47)	4174,21 b (0,51)	3798,51 c (0,51)	310,73 c (6,99)	2884,37 c (7,17)
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 (%).

It can be observed that for the content of volatile materials, there were no significant differences between T1 and T2 and between T3 and T4. The highest average obtained among the storage months was for T4, with an average value of 83.99%, and the lowest was 77.53% for T1. In the fixed carbon content, T1 had the highest average with 22.36%, and the lowest was 16% in T3. The highest ash content was obtained in T3 and T4, both with 0.14%, and the lowest value was obtained in T2, with 0.10%.

It is observed that for the higher calorific value of *Eucalyptus* spp. wood, the values found between the control, T1 and T2, and between T3 and T4, do not differ statistically by Tukey's test at the significance level of 5%. The highest value was obtained for T1 with 4786.49 kcal/kg, and the lowest value with 4452.16 kcal/kg was found in T3 (Table 3). For the lower calorific value of the wood, the highest value was found in T1 and T2, with 4462.49 kcal/kg, and the lowest value was obtained by T3 with 4128.16 kcal/kg (Table 4). For the useful calorific value, the highest mean values were obtained at T1 and T2 (4247.67 and 4268.06 kcal/kg, respectively), and the lowest mean values at T3 and T4 (3794.57 and 3798.51 kcal/kg, respectively) (Table 3).

Regarding the carbon stock of the wood, the one that presented the highest average value was the control (371.32 kg/m³), followed by T1 (367.74 kg/m³), while the lowest value was found in T4 with 310.73 kg/m³. With the storage time, the energy density of *Eucalyptus* spp. wood decreased, where the highest value found was for the control with 3549.74 kcal/cm³, followed by T1 with 3492.23 kcal/cm³, while the lowest values found were 3176.84 kcal/cm³ in T3, followed by T4 with 2884.37 kcal/cm³.

Pearson's correlation between wood properties

In Figure 1, it is possible to observe that the solubility in NaOH presented a positive correlation with the mass loss (0.70) obtained negative correlation results with the basic density (-0.60), fixed carbon (-0.40), higher calorific value (-0.50), carbon stock (-0.50) and energy density (-0.60). The basic density of wood had a positive correlation with fixed carbon (0.60), higher calorific value (0.60), energy density (0.90), carbon stock (0.90), and carbon (0.60), while it showed a negative correlation with mass loss (-0.90).

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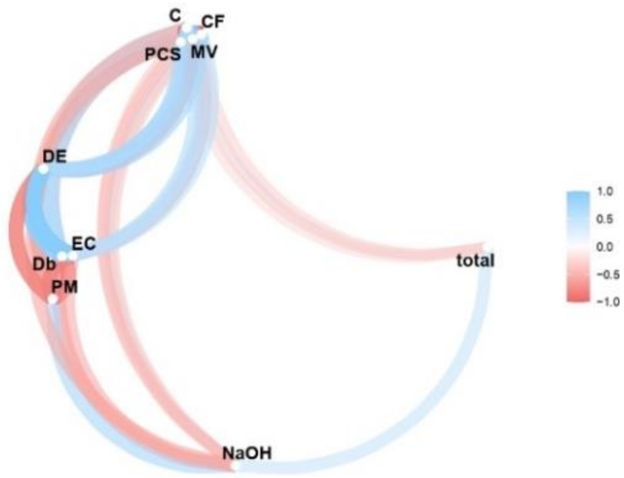

Figure 1. Correlation between wood parameters: energy density (ED), carbon stock (CS), higher heating value (HHV), carbon (C), fixed carbon (FC), volatile materials (VM), mass loss (ML), basic density (BD), solubility in sodium hydroxide (NaOH).

Figura 1. Correlação entre os parâmetros da madeira: densidade energética (DE), estoque de carbono (EC), poder calorífico superior (PCS), carbono (C), carbono fixo (CF), materiais voláteis (MV), perda de massa (PM), densidade básica (Db), solubilidade em hidróxido de sódio (NaOH).

The loss of wood mass obtained a negative correlation with fixed carbon (-0.50), carbon (-0.60), higher calorific value (-0.60), carbon stock (-0.80), and energy density (-0.80). The content of volatile materials showed a negative correlation with fixed carbon (-1.0), carbon (-1.0), carbon stock (-0.60), higher calorific value (-1.0), and basic density (-0.70). The fixed carbon and carbon content were positively correlated with the higher calorific value (1.0), carbon stock (0.60), energy density (0.7), and each other (1.0). The higher calorific value of wood obtained a positive correlation with carbon stock (0.60) and energy density (0.70), and carbon stock with energy density correlated positively with each other (Figure 1).

Properties of charcoal

Table 4 presents the mean values for the bulk density (BD), volatile material content (VM), fixed carbon content (FC), ash content (AC), higher calorific value (HCV), carbon stock (CS) and energy density (ED) of *Eucalyptus* spp charcoal. The parameters analyzed showed a significant difference at 5% probability by Tukey's test concerning the storage time.

Table 4. Average apparent and energetic density, immediate chemical analysis, higher calorific value, and carbon stock of charcoal produced with *Eucalyptus* spp. wood.

Tabela 4. Média da densidade aparente e energética, análise química imediata, poder calorífico superior e estoque de carbono do carvão produzido com a madeira de *Eucalyptus* spp.

Treatments	Energy properties of charcoal						
	BD (g/cm³)	VM (%)	FC (%)	AC (%)	HCV (Kcal/Kg)	CS (Kg/m³)	ED (Kcal/cm³)
Control	0,62 a (5,35)	33,56 a (1,64)	66,02 e (0,85)	0,42 a (6,10)	7130,94 e (0,26)	407,70 a (5,18)	4404,30 a (4,83)
T1	0,53 b (5,90)	22,23 c (6,02)	77,45 b (1,73)	0,32 b (5,74)	7511,17 c (0,59)	409,41 a (5,58)	3971,87 b (5,10)
T2	0,52 b (5,85)	18,20 d (3,36)	81,52 b (0,72)	0,28 c (21,76)	7646,51 b (0,26)	424,34 a (6,08)	3979,60 b (6,50)
T3	0,47 bc (8,80)	13,64 e (6,46)	86,21 a (1,06)	0,15 d (26,58)	7802,65 a (039)	406,13 a (8,70)	3676,24 c (8,57)
T4	0,44 c (8,12)	26,77 b (1,70)	73,03 d (0,69)	0,20 cd (21,11)	7364,1 d (0,23)	318,46 b (8,16)	3210,99 d (8,25)
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 (%).

For the apparent density of charcoal, the highest average value was obtained for the control (0.62 kg/m3), followed by T1 (0.53 kg/m3). The lowest value was found in T4 with 0.44 kg/m3. The content of volatile materials presented the highest result for the control (33.56%) and the highest values among the stored woods, which were found in T4 and T1 (26.77 and 22.23%), while the lowest results were found in T3, followed by T2 (Table 4).

Regarding the fixed carbon content, the highest value obtained was in T3 and T2 (86 and 81.5%), while the lowest value obtained was by the control with 66.02%. However, the lowest value obtained among the stored wood was for T4, with 73%, followed by T1, with 77%. For the ash content, the average values found ranged from 0.15 to 0.42%, where the highest value found was in the control, followed by T1 with 0.32%, while the lowest average value was obtained by T3 (Table 4).

The mean values of higher calorific values ranged from 7802.65 to 7130.94 kcal/kg, where T3 obtained the highest value, while the control found the lowest value, followed by T4 with 7364.10 kcal/kg. Regarding the carbon stock by Tukey's test at the level of 5% significance, the control and the treatments T1, T2, and T3 did not present significant differences between them, ranging from 406 to 424 kg/m3. Among the treatments, T4 presented the lowest result, with 318.46 kg/m3. The energy density of charcoal ranged from 4404.00 to 3210.99 kcal/cm3, while the control obtained the highest average value and the lowest average value obtained by T4.

DISCUSSION

Wood properties

The basic density of the wood showed losses during the storage time (Table 1), although it was not significant until the T3 treatment. However, it obtained a reduction in T4, which may result from the decrease in the energy density of the wood and the apparent density of charcoal. According to the Brazilian Forest Service - SFB (2024), the basic density of wood is classified as heavy wood when greater than 0.72 g/cm³, medium density values between 0.50 and 0.72 g/cm³ and light density values below 0.50 g/cm³.

Taking this classification into account, the Control and T1 (0.75 and 0.73 g/cm³, respectively) are considered to be of high density, while T2, T3 and T4 (0.71, 0.71 and 0.64 g/cm³, respectively) are considered to be of medium density. The basic density is an extremely important parameter to be considered, as it interferes with the amount of mass available for energy generation.

As can be seen in Table 1, the samples under treatment showed mass loss each month, being more significant in T4, thus compromising the quality of the wood and, consequently, of the charcoal. The loss of mass is an indication that there was leaching of extractives and degradation of wood by attack by xylophagous organisms (termites and/or fungi), mainly by fungi, which was proven by the analysis of solubility in NaOH that increased with the passing of the months of exposure, evidencing the consumption of wood, especially holocellulose, where it reduced until the T3 treatment. In contrast, in the T4 treatment, there was an increase in the result, thus demonstrating that until the third month of stock, holocellulose was more attacked. This attack resulted in the reduction of holocellulose molecules by the microorganisms, making them more soluble in NaOH (ARAUJO *et al*., 2021).

The mean levels of total extractives increased during the months of treatment, as can be seen in Table 2. This result may be related to the degradation of wood structures that occurred during the exposure time, in which these degraded structures were solubilized in the extraction process with solvents, interfering in the values of total extractives, thus causing an increase in the percentage.

In the T1 treatment, the percentage of total lignin did not change compared to the control. However, the holocellulose content decreased, which increased the percentage of total lignin, even though the mass did not change. This relationship was observed until the T3 treatment, which shows that during this storage time, only holocellulose was attacked. In the T4 treatment, holocellulose stopped being attacked, and lignin began to be consumed, thus causing the percentage of holocellulose to increase.

Lignin is one of the most important components in energy generation with biomass, as it is more thermally resistant than holocellulose (WATKINS *et al*., 2015). It takes longer to deteriorate when subjected to high temperatures, causing the wood to burn more slowly and release energy for longer, in addition to contributing to carbon fixation (Table 2).

The results obtained for solubility in cold and hot water showed an increasing trend compared to the Witness, which shows that the wood lost extractives during the storage time. In addition, the solubility in NaOH showed the same upward trend, where T4 (41.29 %) showed a higher degree of degradation, i.e., it underwent a more severe attack by xylophagous organisms, especially fungi. This result and the loss of mass and decrease in basic density are strong indicators of attack (Table 2).

The elemental carbon content of the control up to the T2 treatment presented values of 49%, while in the T3 and T4 treatments, it increased to 48% (Table 2). The energy potential is expected to decrease slightly over the months. Carbon content is a very important parameter for direct burning and charcoal production because it is fully consumed in direct burning. In contrast, charcoal production is converted into fixed carbon, which is mainly responsible for the energy stored in coal (CARNEIRO *et al*., 2014).

The elemental hydrogen content was statistically equal during the four months (Table 2), not significantly influencing the characteristics of the wood during the four months of exposure. Even in small amounts in wood, hydrogen releases more energy than carbon during combustion. However, during the production of charcoal, as the wood is thermally degraded, there is a concentration of carbon and a decrease in hydrogen content (CARNEIRO *et al*., 2014).

Table 2 shows that elementary oxygen has increased in the last two months, which negatively impacts energy potential because, unlike carbon and hydrogen, oxygen does not generate energy, meaning less stored energy (CARNEIRO *et al*., 2014).

The volatile material content of the wood showed an increase from T3 to T4, which consequently resulted in a decrease in the fixed carbon content, as they are inversely proportional, i.e., the higher the volatile material content, the lower the fixed carbon content. In addition, high levels of volatile materials cause wood to be consumed more quickly, so samples from T3 to T4 will degrade quickly, eventually generating energy for a shorter period, while in T1 and T2, they tend to generate energy for a longer time, as they have higher fixed carbon levels (Table 3) (FELÍCIO *et al*., 2023).

It is observed that the ash content of the wood presented values below 1% during the storage time, which is a beneficial factor for energy generation because, according to Brand (2013), the ash content must be less than 5% to be considered a positive point in the energy use of wood, both in the form of firewood and in the production of charcoal (Table 3).

Regarding the calorific value of the wood, both the lower, upper, and useful ones showed a reduction in the last two months of storage, with greater evidence in T4 due to the loss of fixed carbon also in this same time of exposure (Table 3).

In the last two months (T3 and T4), there was also an apparent drop in the values of carbon stock and energy density of wood, with greater evidence in T4. This was due to losses in lignin content, elemental and fixed carbon content, and calorific value, in addition to the basic density of the wood, which are parameters that directly influence these characteristics (FELÍCIO *et al*., 2023). The carbon stock determines the amount of carbon available per unit of mass for energy generation, so when this mass is reduced, the total amount of carbon consequently decreases. The same goes for energy density, which, with the loss of basic density, decreases the amount of energy stored by mass moisture, thus influencing the burning yield (FELÍCIO *et al*., 2023).

Pearson's correlation between wood properties

The correlation between NaOH solubility and mass loss shows that when the wood is attacked by xylophagous organisms and is consumed, it loses mass due to the degradation of its constituents, i.e., the higher the solubility in NaOH, the greater the mass loss due to the influence between the parameters. The increase in solubility in NaOH results in a negative correlation with the basic density due to the loss of mass, which reduces the amount of energy by volume, thus affecting the higher calorific value and consequently the energy density, fixed carbon, and carbon stock, this by having a negative influence on these properties.

The basic density, as seen in Figure 1, presents a positive correlation with fixed carbon, higher calorific value, energy density, carbon stock, and elemental carbon. This is due to the influence that each parameter exerts on the other; when the basic density is high, the more volume per unit mass it has for energy generation; consequently, there will be more fixed carbon and carbon, which will result in a higher calorific value and energy density.

The fixed carbon and carbon content correlated positively with the higher calorific value, carbon stock, energy density, and each other because carbon is the main element responsible for energy generation.

Properties of charcoal

Table 4 shows the mean values of the apparent density of charcoal, in which they suffered losses over the months of treatment, with greater evidence at T4. The decrease in the bulk density of charcoal is related to the loss in the basic density of the wood and the loss of mass. With the loss of coal density, even with a gain in calorific value up to T3, there were losses in energy density, being higher in T4. This indicates that, although there were gains in lignin content and carbon fixation up to T3, the loss of the basic density of the wood and the consequent loss in the density of the charcoal ended up affecting this property, causing energy losses over time of exposure (SILVA *et al*., 2018).

The levels of volatile materials of charcoal show a tendency to decrease from T1 to T3 and increase in T4 (26.77%). Possibly in the fourth month, due to the wood structures being compromised by degradation, its components were more easily volatilized in carbonization (Table 4).

The fixed carbon content is directly related to the charcoal's volatile material content and calorific value. That is, the higher the fixed carbon content, the lower the percentage of volatile materials present in the charcoal and consequently the greater the energy efficiency of the charcoal, a fact observed in Table 4 where the fixed carbon values increased, while the volatile material reduced until the T3 treatment, the same was found in the work of Dias Júnior *et al*. (2015), who studied seven genetic materials of *Eucalyptus* and all of them showed high levels of fixed carbon and low levels of volatile materials. In T4, it showed a drop in carbon fixation, going against the values of total lignin. As a result, this month saw a significant drop in coal's calorific value, carbon stock, and energy density.

In Table 4, the values obtained for the ash content during the treatment were considered low, which is a common characteristic among the species of *Eucalyptus* spp., all of which are less than 1%, where according to Santos (2016), the ash content of charcoal should be less than 1% for use in the steel industry, to avoid pollution and reduction of calorific value, in addition to reducing possible damage to the equipment used during carbonization.

The values of higher calorific value of charcoal presented in Table 4 gradually increased until T3. Which T4, there was a decrease from 7802.6 Kcal/Kg in T3 to 7364.1 kcal kg in T4. This can be explained by wood's lower lignin and fixed carbon content, which are the main responsible for generating energy from biomass (FELÍCIO *et al*., 2023).

Table 4 shows that the carbon stock of charcoal increased up to T2, decreasing drastically from T3 to T4, which can be explained by the decrease in the apparent density of charcoal, which is directly linked to this parameter (PROTÁSIO *et al*., 2013). In the same way, charcoal's energy density results are directly related to its apparent density and calorific value, as previously demonstrated (Table 4). In this sense, the significant loss of the apparent density of charcoal in the last months of treatment caused the energy density of charcoal to decrease, thus causing a considerable loss of energy (PROTÁSIO *et al*., 2015).

CONCLUSION

The analyses carried out allowed us to conclude that:

- Wood stored outdoors showed mass loss in all treatments, being higher in the four-month exposure treatment;
- In addition to a lower basic density and lignin content, it consequently resulted in a decrease in the energy density of the wood;
- Until the third month of treatment, *Eucalyptus* spp. wood had positive results. From the fourth month of treatment, the wood showed negative results, with significant losses that compromised the quality of the wood and charcoal;
- Showed loss of bulk density, higher calorific value, carbon stock, and energy density in the treatment from the fourth month of exposure;
- It is possible to conclude that the quality of the wood was maintained until the third month of outdoor stock, starting a significant loss, especially in energy quality, from the fourth month onwards.

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