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FORESTRY SCIENCE

Effect of chemical constituents on the energetic and physical properties of wood from forestry species

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ABSTRACT: Wood is an organic material and its energetic and physical properties are related to its chemical and anatomical constituents. This study evaluated the influence of the chemical constituents on the energetic and physical properties of *Parapiptadenia rigida* (Benth.) Brenan, *Peltophorum dubium* (Spreng.) Taub., *Eucalyptus grandis* W. Hill × *Eucalyptus urophylla* S.T. Blake (hybrid), and *Schizolobium parahyba* (Vell.) Blake an agroforestry system. Five trees of each species aged 9 years were sampled. Samples were collected at a diameter at breast height (DBH) of 1.30 m above the ground and were used to analyze the chemical, energetic, and physical properties of the wood. Chemical properties influence the energetic and physical properties of wood. We reported that the higher the lignin content in the wood, the greater the correlation with the fixed carbon content (0.76) and gross calorific value (0.65). High values of fixed carbon content increased the basic density of the wood (0.80). In contrast, the lower the lignin content in the wood, the greater the correlation with the extractive content (-0.76) and volatile material content (-0.74), and the higher the volatile material content, the lower the fixed carbon content (-0.98) and gross calorific value (-0.74).

Key words: lignin, biomass energy, Pearson's correlation.

Efeito dos constituintes químicos nas propriedades energéticas e físicas da madeira de espécies florestais

RESUMO: A madeira é um material orgânico e as suas propriedades energéticas e físicas estão relacionadas com os seus constituintes químicos e anatômicos. O presente estudo teve como objetivo avaliar a influência dos constituintes químicos nas propriedades energéticas e física da madeira de *Parapiptadenia rigida* (Benth.) Brenan, *Peltophorum dubium* (Spreng.) Taub., *Eucalyptus grandis* W. Hill × *Eucalyptus urophylla* S.T. Blake (híbrido) e *Schizolobium parahyba* (Vell.) Blake, provenientes de um sistema agroflorestal. Foram amostradas cinco árvores de cada espécie, com a idade de nove anos. Sendo coletadas amostras do diâmetro a altura do peito (DAP) à 1,30 m do solo, que foram utilizadas para análise das propriedades químicas, energéticas e física da madeira. As propriedades químicas influenciam nas propriedades energéticas e física da madeira. Quanto maior o teor de lignina na madeira maior será a correlação com o teor de carbono fixo (0,76) e de poder calorífico superior (0,65), assim como, elevados valores de teor de carbono fixo aumentam a massa específica básica da madeira (0,80). Em contrapartida, quanto menor o teor de lignina na madeira maior será a correlação com o teor de extrativos (-0,76) e teor de materiais voláteis (-0,74), sendo que, maiores valores de teor de materiais voláteis reduzem o teor de carbono fixo (-0,98) e o poder calorífico superior (-0,74) da madeira.

Palavras-chave: lignina, energia da biomassa, correlação de Pearson.

INTRODUCTION

Over the years, the demand for high-quality wood and the use of this material in various segments of the wood market have increased substantially. The need to meet this demand while simultaneously preserving the environment continues to be a priority for the global sustainability movement (MANGINI et al., 2023). Thus, species that show rapid growth and use new forms of cultivation stand out as alternatives for the timber market segment (ELOY et al., 2023).

Therefore, there is a growing interest in the implementation of agroforestry systems (SAFs) and there are considerable efforts to disseminate them in Brazil. SAFs are systems that introduce forestry components that interact with agricultural components in a consortium. They were developed with specific characteristics regarding the species used, which are adapted to the location, have productive potential, and interact with each other in a temporal arrangement that responds to planning over time, and a spatial arrangement of the components with spacing between plants according to the objectives and system functionality (SCHWERZ et al., 2018). Therefore, these systems are generally implemented using native and exotic species that

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have good technological characteristics and serve as sources of quality raw materials for various purposes.

The quality of wood intended for energy is the result of the combination of its properties, which vary depending on the species, location of planting, age, and physical, anatomical, and chemical compositions (SILVA et al., 2019). In general, the study of the chemical composition is an indispensable technological alternative with the potential to increase the yield and quality of biomass for energy purposes. The distribution of chemical compounds varies with wood tissue because of the anatomical structure of the plant. Each component is present in specific quantities and has well-defined characteristics that are influenced by the conditions to which the wood is subjected (SCHWERZ et al., 2020).

Wood is composed of cellulose, hemicellulose, and lignin, with chains composed exclusively of carbon, hydrogen, and oxygen. They also contain extractable accidental substances, called extractives, and a small fraction of inorganic substances distributed in various layers that constitute the cell wall. Lignin is the most important compound for producing energy from wood, as the energy yield is directly related to its levels present in the wood. It is a polymer with an aromatic and high-quality chemical structure and molecular mass, which makes it more thermally resistant when compared to cellulose and hemicelluloses (SANTOS et al., 2016).

Wood is an organic material and its chemical constituents are related to its energetic and physical properties. The study of the chemical composition of wood is essential for evaluating its energy potential, as well as for qualifying and quantifying the thermochemical properties of interest. Thus, this study evaluated the influence of the chemical constituents on the energetic and physical properties of wood from *Parapiptadenia rigida*, *Peltophorum dubium*, *Eucalyptus grandis* × *Eucalyptus urophylla*, and *Schizolobium parahyba* to better utilize the energy resources of wood from an agroforestry system.

MATERIALS AND METHODS

Description of the experimental site and sample collection

Wood from four forest species, *Parapiptadenia rigida* (Benth.) Brenan (Angico-vermelho), *Peltophorum dubium* (Spreng.) Taub. (Canafístula), *Eucalyptus grandis* × *Eucalyptus urophylla* (Eucalyptus hybrid), and *Schizolobium parahyba* (Vell.) Blake (Guapuruvu), were obtained from an agroforestry system characterized by having a planting spacing of 12.0 × 1.5 m (12.0 m between rows and 1.5 m between plants in the row), located in the municipality of Frederico Westphalen, Rio Grande do Sul (27°22”S, 53°25” W; 480 m altitude).

According to the Köppen classification, the region’s predominant climate is Cfa, characterized as sub-humid subtemperate, with an average annual temperature of 18.8 °C and an average coldest month temperature of 13.3 °C (ALVARES et al., 2013).

Discs measuring the diameter at breast height (DBH), 1.30 m above the ground, were collected from five 9-year-old trees of each species and were selected based on the average diameter of each individual (Table 1). Experiments were performed in the laboratories of the Universidade Federal de Santa Maria. Chemical analysis was carried out in the Madeira Chemistry Laboratory, while physical and energy analyses were carried out in the Forest Products Processing Laboratory on the Frederico Westphalen campus and in the Bromatology Laboratory.

Chemical, energetic, and physical characterization

The discs collected during sampling were marked in opposing wedges, two of which were intended for chemical and energetic analyses, and two for determining the basic density. The wedges intended for chemical and energy analyses were divided into sticks and sawdust using a Willey-type knife mill. The material was then classified using vibrating 40/60-mesh sieves. The ground materials from the five discs were mixed to generate a composite sample.

Chemical analyses were performed according to the technical standards for determining the wood ash content (TAPPI T211 om-93), total extractive content (TAPPI T264 cm-97), Klason lignin content (TAPPI T222 om-98), and holocellulose content (cellulose and hemicellulose), obtained from the difference given by equation 1.

$$HOLO = 100 - (AC + EXT + LIG) \quad (1)$$

Where HOLO is the holocellulose content (%), AC is the ash content (%), EXT is the total extractive content (%), and LIG is the lignin content (%).

For the energy analysis of the gross calorific value, a calorimetric bomb with an adiabatic operating principle was used in accordance with technical standard NBR 8633 (ABNT, 1984). For immediate chemical analysis, technical standard NBR 8112 (ABNT, 1986) was used, in which the levels of volatile materials, ash, and fixed carbon were obtained.

Table 1 - Diameter at breast height and average height of trees of the four forest species from an agroforestry system.

Species	------------------------DBH (m) ------------------------	--------------------------H (m) --------------------------
P. rigida	0.17	18.01
P. dubium	0.16	19.33
E. grandis × *E. urophylla*	0.34	26.99
S. parahyba	0.25	21.04

DBH = diameter at average breast height (1.30 m above the ground); H = average height.

For the physical analysis of basic density, two wooden wedges obtained during sampling were used. The procedures were performed in accordance with technical standard NBR 7190-1 (ABNT, 2022).

Experimental design and data analysis

The experiment was evaluated in a completely randomized design, with five replicates for each species and each tree considered as one replicate. The data were subjected to statistical analysis using Statistical Analysis System Software (SAS, 2003), which performed variance analysis (ANOVA) presupposition tests (F test), the Shapiro–Wilk test for normality, and the Bartlett test for homoscedasticity of variances. For significant variance analysis, multiple comparisons of means were performed using Tukey's test. Statistical significance was set at $P < 0.05$. These analyses were performed to identify the similarities and differences in the chemical, energetic, and physical properties of the wood between the species studied.

The functional relationship between the chemical, energetic, and physical properties was evaluated using the Pearson correlation test using all values of the analyzed variables. Statistical significance was set at $P < 0.05$. These relationships make it possible to evaluate whether variations in the chemical properties influence the energetic and physical properties of wood.

RESULTS AND DISCUSSION

The assumptions of ANOVA were met, validating the results obtained, and the analysis showed that all species were different in all energetic, chemical, and physical variables evaluated. The means of chemical variables demonstrated that the lignin content was the highest for *E. grandis* × *E. urophylla* (21.5%), which was not different from that of *P. dubium* and *S. parahyba*, whereas *P. rigida* (15.0%) had the lowest lignin content. In contrast, the opposite situation was observed for the extractive content; the highest average values were observed for *P. rigida* (19.8%). The lowest values were observed for *E. grandis* × *E. urophylla* (9.9%), which were not different from those of *S. parahyba*. *E. grandis* × *E. urophylla* also had the lowest ash content (0.63%). The holocellulose contents of *S. parahyba* (68.7%) and *E. grandis* × *E. urophylla* (68.0%) were higher than those of the other species (Figure 1).

The analysis of energetic properties showed that *E. grandis* × *E. urophylla* had the highest gross calorific value (4758 kcal kg^{-1}) and fixed carbon content (17.84%), which were not different from those of *P. dubium* and *P. rigida*. The lowest values were observed in *S. parahyba*. In contrast, for the volatile material, *S. parahyba* exhibited the highest average value (86.46%) compared to that of the other species.

The basic density was the highest for *P. rigida* (0.652 g cm^{-2}), followed that of by *E. grandis* × *E. urophylla* and *P. dubium*, which were not statistically different. The lowest values were observed for *S. parahyba* (0.277 g cm^{-3}).

When we analyzed the parameters for converting wood into energy, we consider the lignin content to be one of the main components; therefore, its content and type are important parameters. In general, conversion to energy is expected to increase with the proportion of total lignin and decrease with the lignin syringyl:guaiacyl ratio, because this would promote greater resistance to thermal degradation owing to the presence of more condensed structures (CASTRO et al., 2013).

Although, lignin begins to degrade at relatively low temperatures (approx. 150 °C), its decomposition is slower than that of cellulose and hemicelluloses, presenting greater resistance to thermal degradation (WANG & HOWARD, 2018). This energetic characteristic can be demonstrated from the correlation analysis of the lignin content of the wood, which varied positively with the gross calorific value (0.65) and fixed carbon content (0.76) (Table 2). This explains the fact that fuels with a

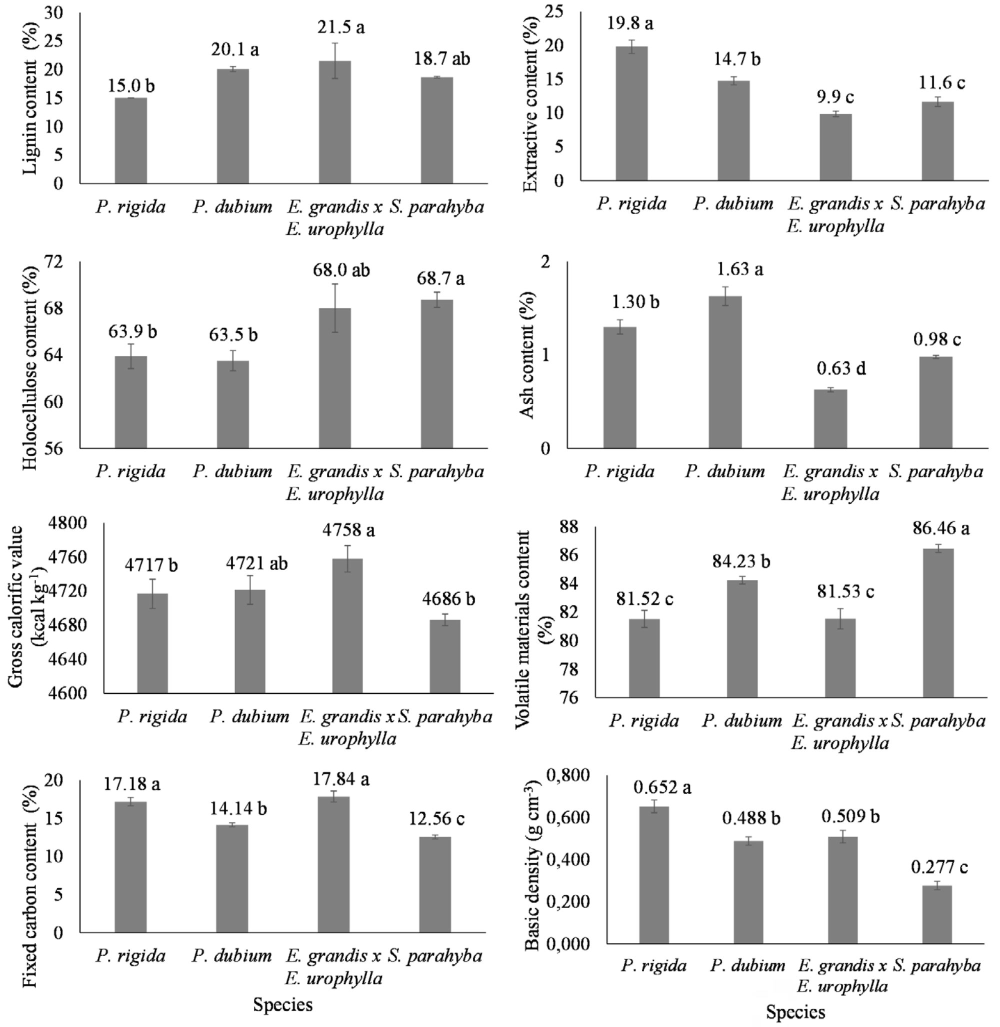

Figure 1 - Averages for the chemical and energetic properties of the four species in the agroforestry system.

Means followed by the same lowercase letters do not differ between species at the P < 0.05 level based on Tukey's test. Error bars identify the standard deviation.

high fixed carbon content burn more slowly, which is beneficial for the process (ELOY et al., 2016) as it implies a longer residence time in the burning devices compared to those with lower levels, contributing to greater energy efficiency (SILVA et al., 2015).

In contrast, lignin showed a negative correlation with extractive content (-0.76) and volatile material content (-0.74) (Table 2), which are properties that influence the thermal decomposition of wood. Volatile material positively affects ignition; the higher its value, the greater the reactivity, which determines the ease with which biomass burns. Thus, biomass with high levels of volatile material has a faster combustion, which is difficult to control. This reduces the residence time of the fuel in the combustion devices, which can lead to low energy efficiency (ELOY et al., 2017).

The wood with a higher fixed carbon content had a higher basic density, with a correlation of 0.80. Thus, these parameters can be used as indicators of direct combustion of wood. Similarly, regardless of the material used, the fixed carbon content was directly correlated with the gross calorific value (0.76). Therefore, it is expected that high lignin and fixed carbon contents imply high gross calorific value.

Table 2 - Pearson correlation of the chemical and energetic properties of the tested agroforestry system species.

Variables	-----EXT-----	----HOLO----	-----GCV-----	-----FCC-----	----VMC----	-----AC-----	-----BD-----
LIG	-0.76*	-0.11ns	0.65*	0.76*	-0.74*	-0.31ns	-0.36ns
EXT		-0.72*	-0.22ns	0.19ns	-0.32ns	0.66*	0.67*
HOLO			-0.10ns	-0.10ns	0.24ns	-0.74*	-0.61*
GCV				0.76*	-0.74*	-0.31ns	0.49ns
FCC					-0.98*	-0.33ns	0.80*
VMC						0.17ns	-0.88*
AC							0.24ns

LIG = lignin; EXT = extractives; HOLO = holocellulose; GCV = gross calorific value; FCC = fixed carbon content; VMC = volatile material content; AC = ash content; BD = basic density; * = Significant Pearson correlation ($P < 0.05$); ns = Non-significant Pearson correlation.

Regarding the extractive content, the presence of high values is advantageous for energy production (CASTRO et al., 2013), representing an important role in the thermal decomposition of wood because of the gross calorific value of these components. MEDEIROS et al. (2014) reported that the presence of extractives in wood is an important characteristic for charcoal production as it increases the basic density of wood, favoring the production of denser charcoal. Our results provided further support for their findings; a positive correlation was found between the extractive content and the basic density of wood (0.67) and ash content (0.66). In contrast, a negative correlation with the holocellulose content (-0.72) was observed.

The presence of holocellulose in large quantities is undesirable when the objective is to generate energy and, in particular, for the production of charcoal, because of its greater thermal instability during carbonization (COSTA et al., 2014). This is because the polysaccharides that form holocellulose contain more oxygen, and have simpler structures and a smaller number of C-C bonds when compared to lignin, thus exhibiting a greater tendency for thermal degradation (SILVA et al., 2014).

Analysis of ash content is important for the energy sector because high values in wood can damage furnaces and other equipment used for energy generation. A positive correlation was observed with the extractive content (0.66) and a negative correlation with the holocellulose content (-0.74). The ash content is related to the proportion of minerals in the wood, which remain as a residue after combustion, varying from 0.5% to over 5% (ELOY et al., 2017). The authors stated that low values were desirable because mineral oxides form scales on equipment and pipes when burned in furnaces, in addition to reducing fuel flammability.

CONCLUSION

The four studied forest species differed in all variables, with the main chemical properties influencing the energetic and physical properties of the wood. *E. grandis* × *E. urophylla* stood out, presenting high gross calorific value, lignin content, and fixed carbon content, and low values of extractive, volatile material, and ash contents.

The higher the lignin content in wood, the higher the fixed carbon content and gross calorific value; moreover, high fixed carbon content values increase the basic density of the wood. The lower the lignin content in wood, the higher the extractive and volatile material contents, and the higher the volatile material content, the lower the fixed carbon content and gross calorific value.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS’ CONTRIBUTIONS

All authors contributed equally to the collection, analysis, and interpretation of data, writing of the manuscript, and the decision to publish the results. All the authors critically reviewed and approved the final version of this manuscript.

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