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BIOENERGY POTENTIAL OF 30-YEAR-OLD *Balfourodendron riedellianum* (Engl.) Engl. AND 32-YEAR-OLD *Peltophorum dubium* (Spreng.) Taub. WOOD FROM HOMOGENEOUS PLANTATIONS[1]

POTENCIAL BIOENERGÉTICO DAS MADEIRAS DE *Balfourodendron riedellianum* (Engl.) Engl. AOS 30 ANOS E *Peltophorum dubium* (Spreng.) Taub. AOS 32 ANOS PROVENIENTES DE PLANTIOS HOMOGÊNEOS

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ABSTRACT - Scientific knowledge of native species in different plantations is important for encouraging sustainable forest management policies, especially if a particular species is at risk of extinction, such as *Balfourodendron riedelianum*. In this context, studies on energy characteristics of native wood are scarce. Thus, we aimed to determine Higher Heating Value - HHV and Wood Density - DE of 30-year-old *B. riedelianum* of 32-year-old *Peltophorum dubium* from different origins: *B. riedelianum* from Alvorada do Sul, Bauru and Gália and *P. dubium* from Alvorada do Sul and Bauru. We selected these species because they belong to different successional groups. *B. riedelianum* is late secondary, and *P. dubium* is a pioneer species. We observed medium basic density for *P. dubium* and high density for *B. riedelianum*. Density was higher for both species from Alvorada do Sul. The correlation between HHV and DE showed a significant positive relationship, but only in Bauru provenance. Despite differences between analyzed properties, both species have favorable values for use in bioenergy.

Keywords: Canafístula; Pau-marfim; Native planting; Wood quality.

RESUMO - O conhecimento científico de espécies nativas em diferentes plantios é importante para o incentivo de políticas de manejo florestal sustentável, especificamente se uma determinada espécie possui risco de extinção, como *Balfourodendron riedelianum*. Nesse contexto, estudos sobre as características energéticas da madeira nativa são escassos. Desta forma, objetivamos avaliar o Poder Calorífico Superior - PCS e a Densidade da Madeira - DE de *Balfourodendron riedelianum* aos 30 anos e *Peltophorum dubium* aos 32 anos de idade de diferentes procedências. *B. riedelianum*: Alvorada do Sul, Bauru and Gália. *P. dubium*: Alvorada do Sul e Bauru. Selecionamos essas espécies por pertencerem a diferentes grupos sucessionais, sendo *B. riedelianum*, uma secundária tardia e *P. dubium*, uma pioneira, determinando o potencial dessas espécies como matéria prima para bioenergia. Observamos média densidade básica para a espécie *P. dubium* e alta densidade para *B. riedelianum*. A densidade foi maior para ambas espécies na procedência de Alvorada do Sul. A correlação entre PCS e DE mostrou relação significativa positiva apenas na procedência de Bauru. Apesar de haver diferenças entre as propriedades analisadas, em síntese, ambas espécies apresentam valores favoráveis para serem empregadas para fins energéticos.

Palavras-chave: Canafístula; Pau-marfim; Plantio de nativas; Qualidade da madeira.

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1 INTRODUCTION

The global demand for energy has increased significantly in the last decades, but most of the additional demand is still being supplied by use of fossil fuels (Empresa de Pesquisa Energética, 2018). Therefore, the incentive for, as well as intensification of, renewable sources becomes essential, among which biomass stands out as one of the most relevant and promising alternatives in Brazil.

In Brazil, 42.9% of the energy matrix comes from renewable sources from which biomass accounts for almost 10% (Empresa de Pesquisa Energética, 2018). According to data from Indústria Brasileira de Árvores - IBÁ (IBÁ, 2019), the area with forests planted for industrial purposes in Brazil totaled 7.83 million in 2018, which contributed 91% of all wood produced for industrial purposes and 6.9% of industrial GDP in the country. About 6.3 million hectares are covered by *Eucalyptus* spp. plantations intended mainly for energy uses and paper production, since *Eucalyptus* species are dedicated for both purposes, with few studies addressing wood quality of native species for energy uses (IBÁ, 2019).

It is estimated that around 40 to 60% of total volume of native tree species is used in processing of log, while the remainder is transformed into waste, most of which is not used commercially (Monteiro et al., 2012). Among the main uses of waste generated from native species, we can mention energy generation by direct burning or waste transformation into briquettes, pellets or charcoal (Moutinho et al., 2016).

One of the ways to achieve sustainable use of native woods is through species selection for forest management. This practice can provide information on economic activities in native forests of all Brazilian biomes, a key point for regulating the sustainable use of forestry resources, including waste (Gasson et al., 2018).

The growth and development of a species with potential energy use, as well as wood features, can be different according to edaphic and climatic conditions, and each country, or even region, must develop strategies independent of biomass production or management programs for more appropriate use of timber resources (Mola-Yudego et al., 2017).

Forest biomass is an important source of energy, as it is very abundant. It is an alternative source of energy that offers significant economic and environmental advantages, as it contributes to reducing dependence on petroleum-derived fuels (Chaves, 2016). According to the principles of sustainable development, the use of forest-based biomass for energy is recognized as a measure to mitigate global warming, as it replaces fossil fuels and reduces the emission of greenhouse gases (Staples et al., 2017).

In selecting native species for energy use, Karsten et al. (2014) recommend studying silvicultural methods, intensity of exploitation, cutting cycles and characteristics of biomass to be used. Specifically, *B. riedelianum* was listed by the International Union for the Conservation of Nature (IUCN, 2015) as an endangered species owing to intensive exploration for wood resources in the Atlantic Forest biome, highlighting the importance of characterizing wood properties and incentivizing planting and reforestation with species appropriate for bioenergy uses (Carvalho, 2004; Aguiar et al., 2019).

For most forest species, Silva et al. (2009) expect a positive relationship between higher heating value and wood density based on lignin and cellulose content. However, wood density is influenced by several factors and varies significantly according to age, place of origin, spacing, growth rate between genera and species (Valério et al., 2008).

In this context, present study evaluated Higher Heating Value - HHV and Wood Density - DE of two native wood species of interest, *Balfourodendron riedelianum* and *Peltophorum dubium*, in a homogeneous plantation at the Forestry Institute, Brazil. *Balfourodendron riedelianum* (Engl.) Engl., Rutaceae (pau-marfim) is a native, nonendemic species of Brazil with geographical distribution in midwestern, southeastern and southern Brazil, as well as the Cerrado and Atlantic Forest (Pirani, 2017). *Peltophorum dubium* (Spreng.) Taub, Fabaceae (canafístula) is also a native species, not endemic to Brazil, with geographical distribution in northeastern, midwestern, southeastern and southern Brazil, as well as the Caatinga, Cerrado, Atlantic Forest and Pantanal (Silva, 2017).

B. riedelianum and *P. dubium* are important for logging purposes. As such, it is essential to establish the bioenergy values of these native species in order to make planting decisions and apply the resource correctly. We selected these species because they belong to different successional groups and because few studies have reported the properties of these species for energy uses. *B. riedelianum* is late secondary (Durigan and Nogueira, 1990), and *P. dubium* is a pioneer species (Lorenzi, 2002). Thus, our objective was to determine Higher Heating Value and Wood Density of these species as raw materials for bioenergy.

2 MATERIAL AND METHODS

2.1 Provenances of the seeds and planting area

In 1983, seeds of *B. riedelianum* from open-pollinated plants were collected in three natural populations (provenances) in the states of São Paulo and Paraná municipalities, Alvorada do Sul (AS), state of Paraná; Bauru (BA) and Gália (GA), state of São Paulo. Seedlings were grown from seeds planted in 1984 at the Luiz Antônio Experimental Station - LAES in the municipality of Luiz Antônio. The plantation was established in six blocks in linear plots of six plants at a spacing of 3 m × 3 m (Gurgel-Garrido et al., 1997).

In 1981, seeds of *P. dubium* from open-pollinated plants were collected in two natural populations (provenances) in AS and BA. Seedlings were grown from the seeds planted in 1982 at LAES. The plantation was established in six blocks in linear plots of six plants at a spacing of 3 m × 2 m (Gurgel-Garrido et al., 1997). Geographic location, climate and soil data from the four areas are presented in Table 1.

Tabela 1. Geographic location, climatic and soil data in the provenances of *B. riedelianum* (Alvorada do Sul-PR, Bauru-SP and Gália-SP) at 30-years-old and *P. dubium* (Alvorada do Sul-PR and Bauru-SP) at 32-years-old and data from the municipality of Luiz Antônio-SP.

Table 1. Localização geográfica, dados climáticos e de solo das procedências de *B. riedelianum* (Alvorada do Sul-PR, Bauru-SP e Gália-SP) aos 30 anos e *P. dubium* (Alvorada do Sul-PR e Bauru-SP) aos 32 anos e dados do município de Luiz Antônio-SP.

Area and Geographic location	**Luiz Antônio (21º40'S, 47º49'W)**	**Alvorada do Sul (22º46'S, 51º13'W)**	**Bauru (22°18'S, 49°03'W)**	**Gália (22º17'S, 49º33'W)**
Köppen climate classification	Cwa	Cfa	Cwa	Cwa
Mean precipitation (mm)*	1340	1368	1296	1395
Mean temperature (ºC)*	23.5	22.1	22.5	22.0
Mean minimum temperature (ºC)	16	16	17.2	15.6
Mean maximum temperature (ºC)	30	28.4	27.8	28.5
Altitude (m)	550	320	530	650
Soil type and characteristic**	Dark Red Latosol. Medium texture, clayey or very clayey. High fertility. Low water- holding capacity.	Red nitosol. Clayy texture to very clayey. Medium to high fertility. High water-holding capacity.	Red Argisols. Medium texture to coarse. Low fertility. Low water-holding capacity.	Red Yellow Latosol. Medium texture. Low fertility. Low water-holding capacity.

* Data of mean annual precipitation and temperature from January 1975 to December 1985 (ANA, 2017.
* Dados de precipitação média anual e temperatura de Janeiro de 1975 a Dezembro de 1985 (ANA, 2017).
** Data of Luiz Antônio, Alvorada do Sul, Bauru and Gália (Assad et al., 2020; Galão, 2017).
** Dados de Luiz Antônio, Alvorada do Sul, Bauru e Gália (Assad et al., 2020; Galão, 2017).

It should be noted that Assad et al. (2020) and Galão (2017) studied wood quality without evaluating wood energy characteristics.

2.2 Sampling

In 2013, 36 *B. riedelianum* trees were collected and randomly selected, 12 from each source. A 1.3 m trunk was removed from the base of each tree, and a central board was cut to obtain samples, resulting in the study of Assad et al. (2020).

Also, in 2013, we selected 30 *P. dubium* trees at random, 15 from each source. A 1.3 m trunk was removed from the base of each tree, and a central board was cut to obtain specimens, resulting in study of Galão (2017). Samples close to the bark were removed for Higher Heating Value - HHV and determination of Wood Density - DE. Tree height and Diameter at Breast Height - DBH (1.3 m from the ground) are shown in Table 2.

Table 2. Tree height and mean DBH from *B. riedelianum* (Alvorada do Sul-PR, Bauru-SP and Gália-SP) at 30-years-old and *P. dubium* (Alvorada do Sul-PR and Bauru-SP) at 32-years-old.

Tabela 2. Altura da árvore e DAP médio de *B. riedelianum* (Alvorada do Sul-PR, Bauru-SP e Gália-SP) aos 30 anos e *P. dubium* (Alvorada do Sul-PR e Bauru-SP) aos 32 anos.

Balfourodendron riedelianum			
	Alvorada do Sul	Bauru	Gália
Height (m)	15.64	15.95	16.24
DBH (cm)	15.19	16.48	16.36
Peltophorum dubium			
	Alvorada do Sul	Bauru	
Height (m)	16.9	15.9	
DBH (cm)	15.9	15.6	

2.3 Wood Density

Wood Density - DE was determined according to Glass and Zelinka (2010) by evaluating the mass and volume at 12% Moisture Content - MC. Specimens of 3 x 2 x 2 cm were conditioned at constant temperature and MC (21ºC and 65%MC, respectively), and under these conditions, mass was determined with an analytical balance. The volume was estimated with a caliper rule used to measure their dimensions.

2.4 Higher Heating Value

The same samples used in wood density determination were fragmented into smaller pieces with a hammer and chisel and milled in a micro mill. Higher Heating Value - HHV was determined after thermal rectification with dry samples. To perform the analysis, the isoperibolic method was used with an IKA C200 calorimeter, according to American Society for Testing and Materials - ASTM, D5865-98 (ASTM, 1998).

2.5 Energy Density

Energy Density - ED of wood was calculated by multiplying Higher Heating Value by Wood Density with values expressed in ($kJ.m^3$).

2.6 Data Analyses

We initially undertook descriptive statistical analysis and used Box Plot graphics to detect outliers. Thus, values 1.5 times higher than the 3rd quartile and values 1.5 times lower than the 1st quartile were excluded from the analysis. Normality tests were performed to check the distribution of data, and when a normal distribution was not observed, data were square root-transformed. Then, for *B. riedelianum*, a parametric analysis of variance (one-way analysis of variance) (ANOVA) was performed. Tukey's test was used to identify pairs of significantly different means. For *P. dubium*, t test was used to identify pairs of significantly different means. Linear regressions between Wood Density and Higher Heating Value were also performed.

3 RESULTS

In *B. riedelianum*, higher HHV values occurred in Gália and Bauru provenaces, and in *P. dubium*, HHV was higher in Bauru. The lowest HHV values occurred in Alvorada do Sul in both species. Wood Density was higher in Alvorada do Sul in *B. riedelianum* and did not differ in *P. dubium*. We observed that for *P. dubium* it has lower values of Energy Density. The values found for *B. riedilianum* were higher, with no significant differences for the origins (Table 3).

Table 3. Median values of Higher Heating Value - HHV, Wood Density - DE, (apparent density at 12% moisture content) and Energy Density - ED from *B. riedelianum* (Alvorada do Sul-PR, Bauru-SP and Gália-SP) at 30-years-old and *P. dubium* (Alvorada do Sul-PR and Bauru-SP) at 32-years-old.

Tabela 3. Valores médios de Poder Calorífico Superior - HHV, Densidade da Madeira - DE e Densidade Enegética - ED de *B. riedelianum* (Alvorada do Sul-PR, Bauru-SP e Gália-SP) aos 30 anos e *P. dubium* (Alvorada do Sul-PR e Bauru-SP) aos 32 anos.

Balfourodendron riedelianum			
	Alvorada do Sul	Bauru	Gália
HHV (kJ.kg^{-1})	19167 b	19414 a	19318 a
*DE (g.cm^{-3})	0.90 a	0.84 b	0.84 b
ED (kJ.m^{3})	16384 a	16025 a	15844 a
Peltophorum dubium			
	Alvorada do Sul	Bauru	
HHV (kJ.kg^{-1})	19300 b	19609 a	
*DE (g.cm^{-3})	0.61 a	0.63 a	
ED (kJ.m^{3})	13036 a	12442 b	

Source: *DE for *B. riedelianum* (Assad et al., 2020) and *P. dubium* (Galão, 2017).
Fonte: *DE para *B. riedelianum* (Assad et al., 2020) e *P. dubium* (Galão, 2017).
The difference between provenances in the same row is represented by distinct letters differing statistically (P <0.05) by Tukey's test in *B. riedelianum* and t test in *P. dubium*.
A diferença entre procedências na mesma linha é representada por letras distintas que diferem estatisticamente (P<0.05) pelo teste de Tukey em *B. riedelianum* e test t em *P. dubium*.

HHV was significantly related to density in *B. riedelianum*. However, a negative relationship was observed in Bauru and a positive one in Alvorada do Sul. No significant relationships were observed in *P. dubium* (Figures 1 and 2).

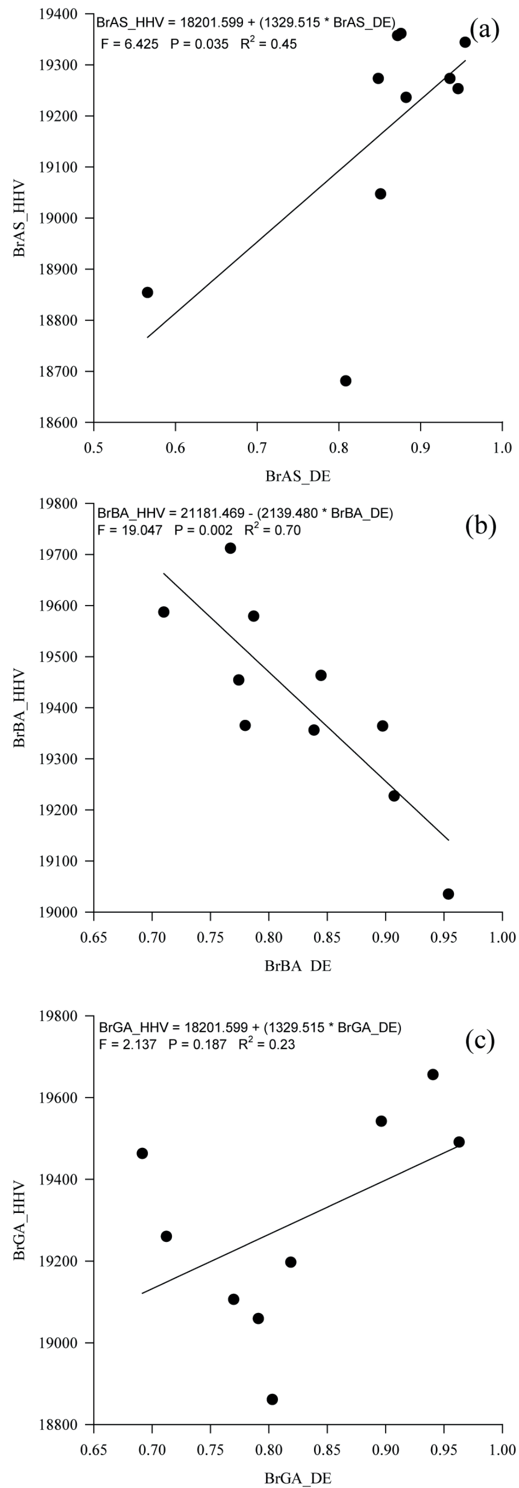

Figure 1. Relationships between HHV as a function of Wood Density - DE of *Balfourodendron riedelianum* at 30-years-old: (a) Alvorada do Sul; (b) Bauru; (c) Gália.

Figura 1. Relações entre HHV em função da Densidade da Madeira - DE de *Balfourodendron riedelianum* aos 30 anos de idade: (a) Alvorada do Sul; (b) Bauru; (c) Gália.

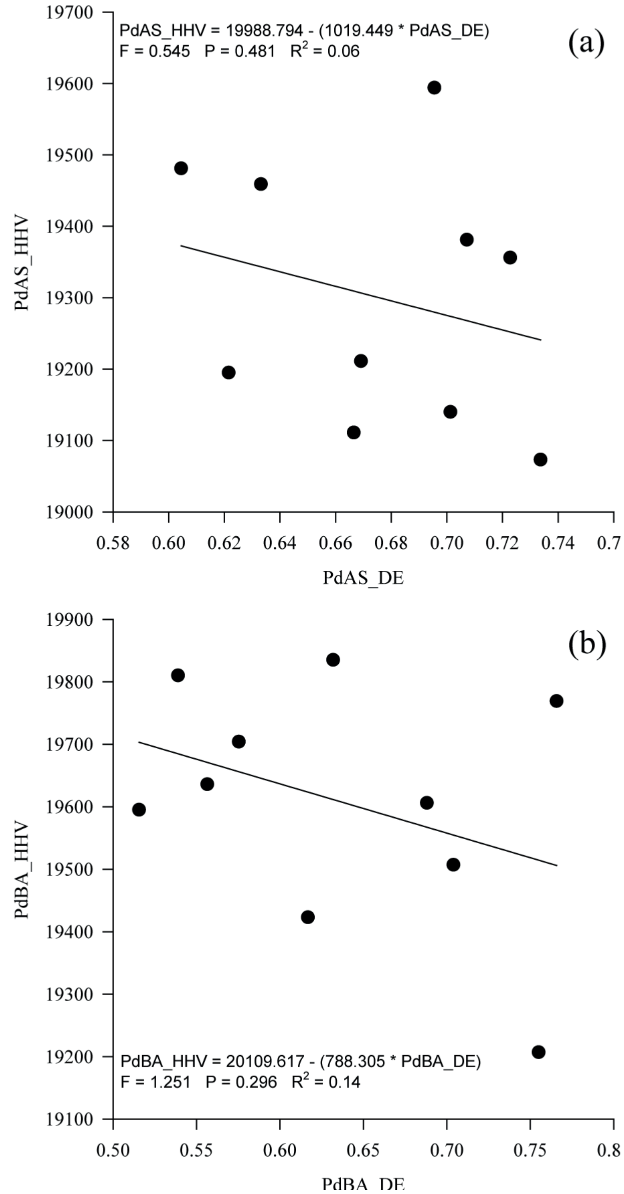

Figure 2. Relationships between HHV as a function of Wood Density - DE of *Peltophorum dubium* at 32-years-old: (a) Alvorada do Sul; (b) Bauru.

Figura 2. Relações entre o HHV em função da Densidade da Madeira - DE de *Peltophorum dubium* aos 32 anos de idade: (a) Alvorada do Sul; (b) Bauru.

4 DISCUSSION

It is expected that higher density wood will present HHV, but this was not observed in our study because *P. dubium* has lower densities and higher HHV, specifically *P. dubium* from Bauru (Table 3). However, wood properties, such as chemical composition, vary, depending on genetic factors, edaphoclimatic conditions, silvicultural treatments and age (Oliveira et al., 2012). In addition, quality and quantity of charcoal basically depend on physical and chemical wood characteristics and the production process. Therefore, it is necessary to understand these characteristics of trees from different origins and the correlations between them (Pereira et al., 2013).

Quirino et al. (2005) reported basic density values of 108 Brazilian forest species, ranging from 0.20 to 1.08 $g.cm^{-3}$, with potential for energy generation. In the present study, density values of two species were similar to those other studies. Vivian et al. (2010), evaluating the wood physical properties of *P. dubium*, found a density of 0.64 $g.cm^{-3}$. For *B. riedelianum*, Lopes (2017) reports an average value of 0.84 $g.cm^{-3}$.

Araújo (2002) proposes different classes for Wood Density, including low, i.e., those with values below 0.550 $g.cm^{-3}$; medium density, i.e., those with corresponding values between 0.550 to 0.720 $g.cm^{-3}$; and high density, i.e., those with values greater than 0.730 $g.cm^{-3}$. Based on this information, *B. riedelianum* wood is considered to have high density in three provenances, and *P. dubium* wood is considered to have medium density, according to the classification proposed by Araújo (2002).

According to Vieira (2012), low density wood tends to be less efficient in the wood burning process, resulting in rapid thermal transformation in less time. For this reason, it is recommended to use wood with higher densities, as they represent greater mass per unit volume.

Wood Density is directly related to energy production; thus, the higher the density, the greater the energy amount stored per cubic meter. Therefore, this characteristic is very important in the selection of species for direct wood burning. In addition, higher wood density results in higher coal densities and strength, as well as a greater amount of dough, reducing production costs and increasing coal production units and high ovens (Brito, 1993).

Vale et al. (2002) recommend the use of wood with density above 0.65 $g.cm^{-3}$ in order to generate energy from biomass. *Balfourodendron riedelianum* has density values in three provenances that meet the requirements of Vale et al. (2002), while *P. dubium* wood from two provenances are below those requirements (Table 3).

Studying different *Eucalyptus* sp. clones, Protásio et al. (2013) and Carneiro et al. (2014) report wood density ranging from 0.45-0.56 $g.cm^{-3}$, emphasizing that *Eucalyptus* species is widely used in Brazil for bioenergetic uses. However, for *B. riedelianum* and *P. dubium*, we observed densities higher than those reported in the literature for some *Eucalyptus*. This result suggests that the two studied species can be used for the production of charcoal and bioenergy and reinforces the need for studies related to genetic improvement of species for their bioenergetic use.

When it comes to wood quality for energy uses, density is the main parameter that indicates the suitability of wood. It is a complex variable, as it results from a combination of several factors, such as fiber size, wall thickness, vessel dimensions and fiber dimensions of anatomical elements and proportion of heartwood and sapwood (Silveira et al., 2013).

Carneiro et al. (2016) evaluated energy characteristics in *Eucalyptus* clones in three cities in the State of Minas Gerais. They report that edaphoclimatic characteristics influence wood quality and, consequently, energy characteristics and total charcoal produced.

Marques et al. (2020) studied five Cerrado species and reported HHV ranging from 18710 to 19300 $kJ.kg^{-1}$. Such studies show that it is possible to use wood waste from native species for energy, using wood residues after sawing processes for other uses.

Santos et al. (2013) evaluated eight forest species from Caatinga originating from a management plan for energy production. They report HHV values ranging from 18585 to 20179 $kJ.kg^{-1}$. The authors indicate that Wood Density, HHV and Wood Volumetric Productivity are essential metrics for determining potential bioenergetics use in the case of wood originating from forest with no waste management plan.

Studies with forest residues of native species from the Amazon have shown that raw material has potential use in biogenergy. Moutinho et al. (2016) studied forest residues from a second cut cycle and reported basic density ranging from 0.33 to 0.98 $g.cm^{-3}$ and HHV ranging from 19309 to 20058 $kJ.kg^{-1}$, excellent values industrial energy use, and both are well within the values observed for *B. riedelianum* and *P. dubium*.

Energy Density measures the potential of a given volume of biomass for generating energy (Rodrigues and Rousset, 2009). Based on this characteristic, *B. riedelianum* wood shows no difference among provenances, despite otherwise satisfactory results, while Energy Density in *P. dubium* was higher in Alvorada do Sul. Energy Density, associated with Wood Density and HHV, can also be used as a characteristic for species selection for energy uses.

In general, positive relationships between HHV and Wood Density are expected. However, Quirino et al. (2005), analyzing higher heating value and basic density of 108 forest species, report that the highest calorific value does not necessarily correspond to species with the highest basic density. Thus, other wood characteristics can influence HHV, e.g., chemical components. Vidaurre et al. (2012) report that 1) density is not directly related to the amount of energy contained in wood and 2) no clear relationship can be established between basic density and calorific value. The authors report that higher density correlates with greater amont of energy contained per unit of volume, which stimulates the interest in denser wood for burning.

In our study, we observed a negative relationship in BA and positive relationship in AS between HHV and density in *B. riedelianum*. In addition, *P. dubium* has higher HHV values, even with lower density when compared to *B. riedelianum*, which reinforces the idea that other wood characteristics, besides the density, should be investigated when selecting suitable wood for energy. Castro (2011) mentions that numerous factors influence the relationship between HHV and density, e.g., tree age, genetic and environmental factors, silvicultural practices, and tree sampling.

5 CONCLUSIONS

Our results suggest that both species have potential for energy uses since HHV values are within the expected range for that purpose. In addition to Wood Density, we emphasize that other characteristics, such as Energy Density, must be analyzed as part of the process for choosing species for energy purposes. Specifically, in our study, *P. dubium* had higher HHV values, even though it presented lower density when compared to *B. riedelianum*. Additionally, the behavior between the two species was reflective of the different energy density results.

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