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ENERGY POTENTIAL OF *PROSOPIS JULIFLORA* WOOD IN BRAZILIAN CAATINGA BIOME

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Prosopis juliflora (SW.) DC, an invasive exotic plant with energy potential was introduced in rural areas in northeastern Brazil as animal food and timber use. The objective was to evaluate the energy potential of wood from *P. juliflora* for charcoal production and quality of this plant material, based in the PMQ 3-03 standard, produced in the Caatinga biome, semiarid region of Sergipe, Brazil. Basic density and moisture along the trunk, immediate chemical analysis, structural chemical analysis, higher calorific value wood of gravimetric yield, immediate chemical analysis, bulk density, and higher calorific value of the charcoal of this plant were determined. The volatile material content, fixed carbon, ash, lignin, holocellulose, extractives, and calorific value of *P. juliflora* wood were 76.61%, 22.28%, 1.11%, 32.55%, 66.52%, 0.83% and 19.70 MJ/kg, respectively. Values of gravimetric performance, pyroligneous liquid, non-condensable gases, volatile materials, fixed carbon, ash, bulk density, calorific value of *P. juliflora* charcoal were 37.95%, 33.96%, 28.08%, 29.60%, 68.19%, 2.20%, 204 kg m^{-3} and 27.47 MJ kg^{-1}, respectively. The values of wood and charcoal of *P. juliflora* indicate its potential for energy production with its properties gathering the PMQ 3-03 standard for domestic use in rural properties.

Keywords: Bioenergy, carbonisation, charcoal, conservation, rural sustainability

INTRODUCTION

In Northeast of Brazil, forest system represents about 9.78% of 9.0 million hectares in the country, being the second largest consumer of charcoal with 12.2%, after the Southeast region with 76.1% (IBÁ 2022). The firewood and charcoal demand is high in the Northeast (Coelho Junior et al. 2018, Dias Junior et al. 2018, Fonseca et al. 2020). In the semiarid of this region, especially in those invaded by exotic species, forest management can generate wood and energy resources (Friedler et al. 2011, Nascimento et al. 2014). This is necessary to meet the firewood demand features for domestic use in rural communities (Medeiros Neto et al. 2014, Morais et al. 2018), in accordance to regulate the cutting and marketing wood control (Mendonça et al. 2020).

The vegetation of the Caatinga is characterised by twisted deciduous herbaceous species, cacti and, in particular, thorny deciduous shrubs and trees, covering 4322 species, 744 of which have been identified as endemic to this biome. This vegetation has been grazed, cut down or removed, resulting in environmental degradation and the regeneration of trees in places where desertification processes are underway (Figueiredo et al. 2012, Forzza et al. 2010). Illegal logging and firewood extraction and inadequate management threaten the only unique Brazilian biome, the Caatinga (Medeiros Neto et al. 2014, Pandey et al. 2019). The use of *Prosopis juliflora* (Sw.) DC. (Fabales: Fabaceae) wood, known as mesquite, can be an economical and conservation alternative (Pegado et al. 2006, Nogueira Júnior et al. 2016, Morais et al. 2018). *Prosopis juliflora* is plant exotic species introduced in the 1940s in northeastern Brazil from Peru to produce forage and wood (Nogueira

Junior et al. 2019). The quick growth and high reproductive rate (Sato 2013) and adaptation to edaphoclimatic conditions (Nogueira Junior et al. 2019, Fonseca et al. 2020) allow this plant to extend deforested areas avoiding the native species regeneration affecting the forest ecosystem dynamic, forest conservation and sustainability of forest management techniques (Pegado et al. 2006, CBD 2010, Tadese et al. 2021).

The basic wood density for energy production purposes must be high (Protásio et al. 2021). For *P. juliflora*, this parameter was from 0.78 g cm^{-3} to 1.2 g cm^{-3} in semi-arid areas of northeastern Brazil and plantations from 5–10 year-old in India (Gomes et al. 2007, Saraswathi & Chandrasekaran 2016, Fonseca et al. 2020) classified its wood as high density (Csanády et al. 2015). *Prosopis juliflora* wood is widely used to produce stakes for fences in semi-arid region of Northeast Brazil (Nogueira Junior et al. 2016). The calorific value determines the energy capacity by the amount of heat given off in its complete combustion per mass unit is high for mesquite (Medeiros Neto et al. 2014, Lungulease et al. 2020) from 16.75 to 20.93 MJ kg^{-1} (Chava et al. 2016).

The energy potential of *P. juliflora* increases the need to define regions suitable for the growth and management of this invasive plant to generate income and Caatinga's biodiversity conservation (Nascimento et al. 2014, Al-Assaf et al. 2020). In addition, charcoal production with quality for domestic use, increases the importance of *P. juliflora* wood for rural sustainability in the Northeast region of Brazil.

São Paulo is the only Brazilian state with minimum quality standards for charcoal for domestic use through the Resolution No. 40 SAA (December 14, 2015) called PMQ 3-03 (SAA 2015). The lack of legislation in other states allows the production of low quality charcoal and reduces the introduction of improvements in the production chain and in the traceability of this product (Brand et al. 2015, Anater et al. 2019).

The objective of this research was to evaluate the energy potential of *Prosopis juliflora* (Sw.) DC. wood for charcoal production in the Caatinga biome from semi-arid region (Sergipe, Brazil) and quality standards of this product using the PMQ 3-03 standard. Additionally, the study aimed to focus on controlling this invasive species by producing charcoal in areas already established by its presence, avoiding the need to open new areas

MATERIAL AND METHODS

Figure 1 presents an illustrative diagram outlining the sampling and analyses conducted in the study of *Prosopis juliflora*. The diagram highlights the sampling points at the base, middle, and top of the trees, along with the various analyses performed to characterise the wood and charcoal of *P. juliflora*.

Origin, collection and sampling of *P. juliflora* wood

Two trees with circumference at breast height (CBH) above 15 cm — a measure commonly found in specimens used for charcoal production — and an average commercial height of 8.76 m were randomly selected in a private area, where the wood of the species was already being exploited. A cutting permit was required for the felling of these trees. While we acknowledge that the number of trees used may be limited in fully representing the species' variability, these samples provided valuable preliminary data for the study.

The private area is located in the municipality of Nossa Senhora da Glória, within the Caatinga biome (Sergipe state, Brazil; 10°13'S, 37°25'13"W and 291 m) (Rocha et al. 2021). This region is semi-arid with hypoxerophilic Caatinga vegetation; 700–800 mm rainfall and 24.2 °C mean annual temperature (Governo do Estado de Sergipe 2010). The heights corresponding to the base, middle and commercial top of *P. juliflora* trees were measured with a measuring tape.

The trees selected were harvested and the discs removed from the base, middle and top of the commercial height. Wood density and moisture were evaluated at each axial position sampled at the Wood Chemical Analysis Laboratory of the Department of Forest Sciences at the "Universidade Federal de Sergipe".

Chemical analysis, calorific value and carbonization were performed on composite samples of discs from different longitudinal sections of trees at the Chemistry, Cellulose

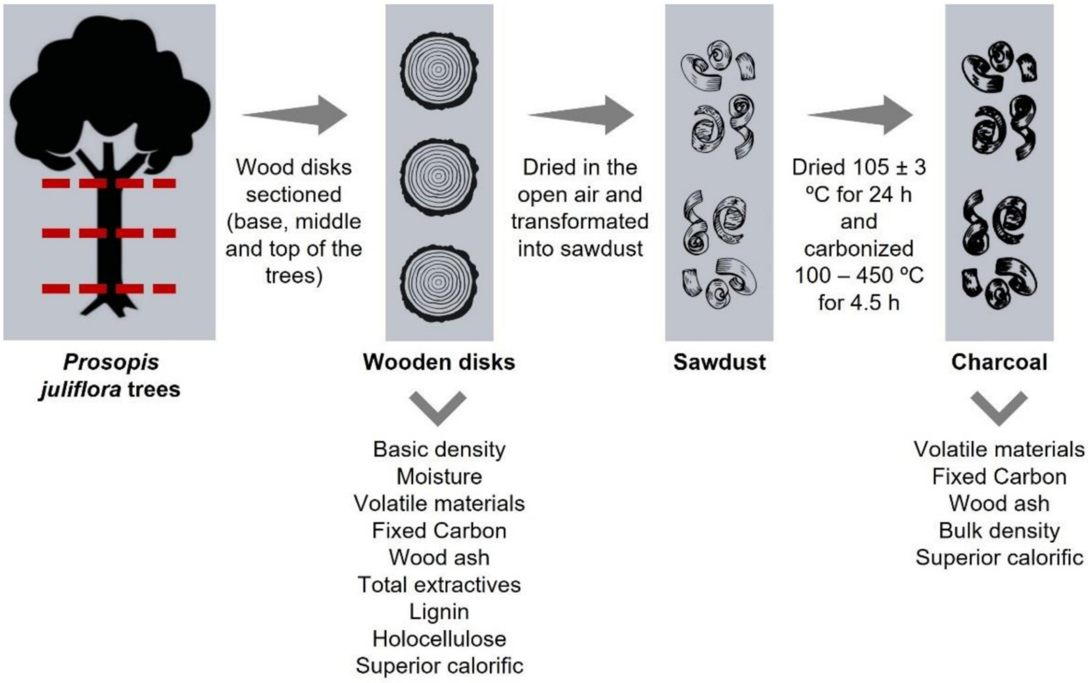

Figure 1 Illustrative diagram of the sampling and analyses conducted in the study of *Prosopis juliflora*. The diagram shows the sampling points at the base, middle, and top of the trees and the analyses performed for the characterization of *P. juliflora* wood and charcoal

and Energy II Laboratory of the Department of Forestry Sciences of the "Escola Superior de Agricultura, Luiz de Queiroz" in Piracicaba, São Paulo State, Brazil.

Characterisation of the *P. Juliflora* (Sw.) DC. Wood

Wooden disks were removed from the base, middle and top of the trees to determine its moisture and density. The basic density of *P. juliflora* wood was determined by the relation between the dry weight and the saturated volume of the samples by the water immersion method, according to NBR 11941 (ABNT 2003). Wood moisture was determined according to equation (1).

$$U = [(mu - ms)/ms] \times 100 \quad (1)$$

where U = wood moisture (%), mu = wet mass of wood (g) and ms = anhydrous mass of wood.

The contents of volatile materials, fixed carbon and wood ash were obtained according to NBR 8112 (ABNT 1986). The content of total extractives, lignin and holocellulose, were obtained according to TAPPI T 222 om-98 (2002), TAPPI T 204 cm-97 (1997) and TAPPI T 19 om-54 (2002) standards, respectively. The superior calorific value was determined in a calorimetric pump (adiabatic) model IKA 600 according to ABNT NBR 8633 (ABNT 1984).

Prosopis juliflora charcoal properties

Prosopis juliflora wood disks were sectioned along the tree trunk (base, middle and top), dried in the open air, transformed into sawdust, which passed through the 40 mesh sieve and was retained on the 60 mesh sieve, was then homogenized and dried in an oven at a temperature of 105 ± 3 °C for 24 h.

The dry sawdust was carbonised in an electric oven (muffle), coupled to a condenser, with a heating rate of 1.67 °C min^{-1} and an initial temperature of 100 °C to a maximum of 450 °C, stabilised in the latter for a period of 60 minutes for the carbonisation time of 4.5 hours. The vapors/gases were conducted to a condenser and the pyroligneous liquid collected in kitasato flask. Non-condensable gases were combusted at the outlet of the condensing system.

The gravimetric and pyroligneous liquor yields were determined by the ratio of these parameters with the dry mass of wood used and those of non-condensable gases, by difference, subtracting the gravimetric yield and pyroligneous liquor yields. The sum of the gravimetric yields, pyroligneous liquor and non-condensable gases was 100%. The contents of volatile materials, ash and fixed carbon were obtained according to ABNT NBR 8112 (ABNT 1986).

Bulk density was determined by the mass of *P. juliflora* charcoal in a known volume of an 80 ml Becker and expressed in kg m^{-3}. The superior calorific value of *P. juliflora* charcoal was calculated according to the norm for wood.

The physical and chemical characteristics *P. juliflora* charcoal were compared with Resolution No. 40 SAA (December 14 2015) called PMQ 3-03, which defines the minimum quality standards for this product for domestic use. The charcoal bulk density must be greater than 200 kg m^3 and the fixed carbon and ash contents greater than 73% and lower than 1.5%, respectively (SAA 2015).

Statistical analysis

Data on variables of wood basic density and moisture of wood were subjected to one-way analysis of variance (ANOVA) and Tukey's HSD test ($P < 0.05$) using the Statsoft 7.0 software (STATSOFT 2007).

RESULTS AND DISCUSSION

The basic density of *P. juliflora* wood at the base, middle and top of the total height of the trunk was 0.96, 0.86 and 0.78 g cm^{-3}, respectively (Figure 2). Variations in basic wood density of *P. juliflora* with higher values at the base and lower one at the top of the trunk are similar to those reported for *Eugenia rostrifolia* (Candaten et al. 2020) and *Maclura tinctoria* (Coldebella et al. 2018) and can be explained by the increase in the proportion of juvenile wood and cellular lumen in the base-to-top direction (Vidaurre et al. 2011). Basic wood density of *P. juliflora* was similar to that of other species of this genus, such as *Prosopis alba*, *Prosopis kuntzei*, *Prosopis nigra* and *Prosopis ruscifolia*, of 0.61 g cm^{-3}, 0.97 g cm^{-3}, 0.79 g cm^{-3} and 0.65 g cm^{-3}, respectively (Pometti et al. 2009), being classified as high to very high (Csanády et al. 2015). The basic density of *P. juliflora* wood is suitable to produce charcoal as a denser and more resistant material, with higher energy (Carneiro et al. 2017, Pereira et al. 2016, Ramos et al. 2019), than the wood from three clones of *Eucalyptus* sp. to produce charcoal, 0.45 g cm^{-3} to 0.56 g cm^{-3} (Carneiro et al. 2014). Species of the *Eucalyptus* genus are among the most cultivated and used in charcoal and energy production in Brazil, particularly due to their

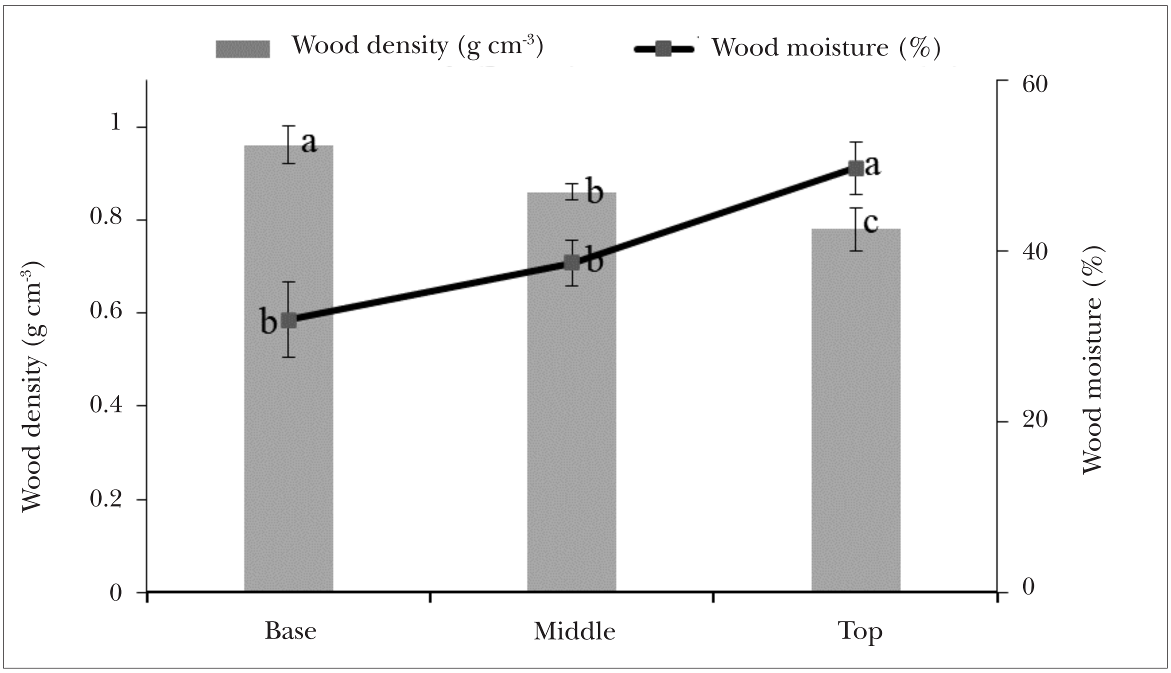

Figure 2 Basic wood density and moisture at the base, middle and top of *Prosopis juliflora* trunks Means followed by the same letter column do not differ by Tukey test ($P < 0.05$)

Table 1 Properties of *P. juliflora* wood

	VM (%)	A (%)	FC (%)	Extractives (%)	Lignin (%)	Holocellulose (%)	HHV (MJ kg^{-1})
Average	76,61	1,11	22,28	0,83	32,55	66,62	19,70
Maximum	78,05	1,38	25,39	0,87	32,63	69,21	19,87
Minimum	73,23	0,87	20,98	0,77	29,95	66,50	19,53
SD	1,96	0,25	1,78	0,03	2,09	2,09	0,24
CV	2,56	22,50	7,98	4,18	6,41	3,14	1,22

SD = standard deviation, CV = coefficient of variation; VM (%) = volatile matter content, A (%) = ash content, FC (%) = fixed carbon content, HHV = Higher heating value

rapid growth and high productivity. Therefore, their performance in terms of wood and charcoal production can serve as a relevant comparative parameter to assess the energy potential of other species, such as *P. juliflora*.

The moisture content of *P. juliflora* wood at the base, middle and top of the trunk samples was 31.91%, 38.58% and 49.71%, respectively (Figure 2). The increase in wood moisture of *P. juliflora* from the base to the top of the trunk is similar to that reported for *Aspidosperma pyrifolium*, *Auxemma oncocalyx*, *Mimosa caesalpiniifolia*, *Mimosa ophthalmocentra* and *Mimosa tenuiflora* in the Caatinga (Batista et al. 2020). The humidity of *P. juliflora* wood is above 30%, the maximum recommended for carbonisation, and, therefore, it must be subjected to adequate drying, improving its energy potential and reducing CO_2 emissions in steel and domestic processes (Zanuncio et al. 2015, Canal et al. 2016, Protásio et al. 2021).

Table 1 shows the levels of volatile materials, fixed carbon and wood ash from *P. juliflora*. The volatile materials and fixed carbon contents of *P. juliflora* wood were lower and higher than those of this species cultivated in India, 81.5 and 17.2%, respectively (Chandrasekaran et al. 2019). The higher fixed carbon content improves the energy characteristics, increasing the calorific value (Marques et al. 2020). High volatile values facilitate ignition, but difficult in controlling burning and reduce energy efficiency, in addition to increasing charcoal friability (Fonseca et al. 2020, Chandrashekar et al. 2021, Kiflie et al. 2021). It is important to balance this parameter with the fixed carbon content in the wood ensuring easier ignition and increasing residence time in burning appliances (Siqueira et al. 2020). The ash content of *P. juliflora* wood is in the recommended range, around 1% to reduce the frequency of furnace cleaning and damage to equipments (Pereira et al. 2013, Medeiros Neto et al. 2014, Chavan et al. 2016).

The contents of lignin, holocellulose and total extractives of *P. juliflora* they are in Table 1. The lignin and holocellulose contents of *P. juliflora* were lower and greater than that of this plant cultivated in India, 28% and 72%, respectively (Chandrasekaran et al. 2019) and those of in natural wood briquettes of this plant, 28% and 70.1% respectively (Kumar & Chandrashekar 2020). The wood chemical composition of this plant is high in lignin and low levels of holocelluloses, the latter not being resistant to thermal degradation indicates adequacy for energy pr oduction (Santos et al. 2016, Marques et al. 2020). The lignin content was adequate and must be at least 28% for charcoal production (Pereira et al. 2013) because the thermal degradation rate of this material is lower than that of other remaining components during and after pyrolysis (Medeiros et al. 2019). The greater thermal stability of lignin is due to its more complex chemical structure with aromatic rings and greater binding capacity, difficulty degradation, even at high temperatures (Quan et al. 2016, Jayakishan et al. 2019). The lignin content with the gravimetric yield, thermal stability and carbon contents increase its importance (Santos et al. 2016, Carneiro et al. 2017). The lignin and holocellulose contents of *P. juliflora* were similar to those of four clones of *Eucalyptus* hybrids at seven years old, 32% and 65%, respectively, indicating the energy potential of the wood of this plant (Santos et al. 2016). The total extractive contents of *P. julifora* were close to 1% for this plant (Nath et al. 2020) and generally degraded in the initial stage of combustion (Soares et al. 2014, Hamada et al. 2017).

Table 1 shows the superior calorific value of *P. juliflora* wood. The superior calorific value of *P. juliflora* was lower, 23.65 MJ kg^{-1} in the northeastern semiarid region, with wood density of 1.2 g cm^{-3} (Fonseca et al. 2020), but it is in the indicated range, 16.75 MJ kg^{-1} at 20.93 MJ kg^{-1} (Chavan et al. 2016) above that of *E. dunii*, *E. globulus*, *E. grandis*, *E. phaotrica*, *E. viminalis*, and *E. robusta* at 19.68 MJ kg^{-1}, 19.55 MJ kg^{-1}, 19.44 MJ kg^{-1}, 19.39 MJ kg^{-1}, 18.71 MJ kg^{-1}, and 19.48 MJ kg^{-1}, respectively (Juizo et al. 2017). The calorific value was similar to those of *Handroanthus impetiginosus* and *Poincianella pyramidalis* native to the Caatinga (Medeiros Neto et al. 2014).

Table 2 shows the values of gravimetric yield in charcoal, pyroligneous liquids and non-condensable gases of *P. juliflora* charcoal. The gravimetric charcoal yield of *P. juliflora* was similar to that of this plant carbonised at 400 °C and higher than that at 700 °C (Chandrashekar et al. 2021), which may be due to the increase volatilisation and degradation of wood components as temperature increase (Kiflie et al. 2021). The gravimetric charcoal yield of *P. juliflora* was lower than the 45.05% of this plant at a lower final carbonisation temperature (Fonseca et al. 2020) with a reduction in the fixed carbon content and an increase in the volatile content. The carbonisation temperature is important because the relationship of the gravimetric yield in charcoal of *Eucalyptus urograndis*, carbonised at the final temperatures of 380 °C, 430 °C and 480 °C, varied from 30.22% to 35.53%, inversely with the final temperature. (Silva & Ataíde 2019). The higher carbonisation yield of *P. juliflora*, even at lower temperatures, indicates the potential of wood from this plant as an energy source in relation to *E. urograndis*. The yield in pyroligneous liquids is in the range of that obtained from charcoal of a hybrid of *Eucalyptus grandis* × *Eucalyptus camaldulensis*. However, as expected, non-condensable gases were lower (Rocha et al. 2017), being by-products of the carbonization process (Protásio et al. 2020).

Table 2 shows the values of contents of volatile materials, fixed carbon and ash in *P. juliflora* charcoal. The volatile material contents of *P. juliflora* charcoal are in the ideal range for domestic use, 20–30% and higher than that for industrial metallurgical use, 10–15% (Chandrasekaran et al. 2019, 2021). Volatile materials, fixed carbon and ash values in the charcoal in this plant were 31.71%, 66.34% and 1.56%, respectively, from a very high density material, 1.2 g cm^{-3}, but with lower release of volatiles and ash and fixed carbon content (Fonseca et al. 2020). With the latter directly influencing the productivity in kilns (Chandrasekaran et al. 2019, Siqueira et al. 2020). The contents of volatile materials, fixed carbon and ash in *P. juliflora* charcoal were similar to those of this product from this plant commercialised in north-central Mexico, with materials of different masses and geographical origin (Montelongo et al. 2020), confirming the potential of *P juliflora* charcoal. The ash content of *P. juliflora* was higher than that of a clone of *Eucalyptus* (Rocha et al. 2017) and its charcoal is suitable for domestic use in barbecue grills, which must be lower than 5% for ash to maintain its calorific value (Dias Júnior et al. 2020). The ash content in charcoal varies with the plant and volatile materials and its quantify

Table 2 Properties of *P. juliflora* charcoal

	CGY (%)	PLY (%)	NCGY (%)	VM (%)	A (%)	FC (%)	HHV ($MJ.kg^{-1}$)
Average	37.96	33.97	28.09	29.60	2.20	68.19	27.46
Maximum	38.28	34.99	29.44	35.54	2.52	70.29	28.18
Minimum	37.63	32.94	26.73	27.47	1.96	62.50	26.38
SD	0.46	1.45	1.92	3.43	0.21	3.29	0.72
CV	1.21	4.27	6.82	11.58	9.34	4.82	2.63

SD = standard deviation, CV = coefficient of variation; CGY = charcoal gravimetric yield, PLY = pyroligneous liquid yield, NCGY = non-condensable gases, VM = volatile matter content, A = ash content, FC = fixed carbon content, HHV = higher heating value can increase the emission of polycyclic aromatic hydrocarbons (HPA) harming human health (Shikorire et al. 2019), mainly due to the risk of inhaling smoke while using this material.

The bulk density of *P. juliflora* charcoal was 204 kg m^{-3}. Bulk density of *P. juliflora* charcoal was greater than that of chips from *Eucalyptus* spp., 186 kg m^{-3} (Pedrazzi et al. 2010) and lower than that of different brands of charcoal, 228 kg m^{-3} to 270 kg m^{-3}, sold in Cuiabá, Mato Grosso, for cooking food. This parameter should be as high as possible to reduce the frequency of system replenishment (Costa et al. 2017).

Table 2 shows the values of superior calorific value of charcoal from *P. juliflora.* The superior calorific value of *P. juliflora* was greater than the 23.65 MJ kg^{-1} of this plant at a final carbonisation temperature of 450 °C (Fonseca et al. 2020). The observation can be explained by the wood used and the chemical composition of the biomass with low volatile contents and high fixed carbon increasing the value of this parameter (Ozyuguran et al. 2018, Dias Junior et al. 2020, Souza et al. 2021). The production of charcoal needs final pyrolysis temperature of 400 °C and 600 °C, 27.6 MJ kg^{-1} and 32.3 MJ kg^{-1}, respectively, for *P. juliflora* wood (Chandrashekaran et al. 2021).

The volatile materials, fixed carbon and charcoal ash contents of *P. juliflora* are in the Table 2. Bulk density of *P. juliflora* charcoal was 204 kg m^{-3}, with the standard recommendation, which must be greater than 200 kg m^{-3}, but the contents of volatile materials, fixed carbon and ash were greater than 23.5%, lower than 73% and greater than 1.5%, respectively, of those recommended for domestic use according to the PQM 3-03 standard (São Paulo 2015). However, this can be adequate by raising the final carbonisation temperature of this wood to increase and reduce fixed carbon and volatile materials, respectively. However, these values ranged, for this plant, from 22.55% to 15.24% of volatile materials and 74.63% to 80.74% of fixed carbon at a final temperature of 400 °C to 600 °C (Chandrashekar et al. 2019) and from 72.50% to 79.91% for fixed carbon at a final temperature of 400 °C to 700 °C (Chandrashekar et al. 2021). Bulk density and volatile materials, fixed carbon and ash contents indicate the potential of *P. juliflora* to produce quality charcoal for domestic use, as the PQM 3-03 standard does not define the final carbonisation temperature.

The density, fixed carbon, calorific value and ash of wood and charcoal of *P. juliflora*, grown in degraded soils (Singh et al. 2014) increase its potential to generate energy. The charcoal parameters of this plant are superior to those of eucalyptus and similar to those of native species from the Caatinga, despite the higher ash content, but below the maximum accepted for domestic use (Batista et al. 2020).

CONCLUSION

The basic density, immediate and structural analysis and the calorific value of the wood and the gravimetric yields, immediate analysis and the calorific value of *P. juliflora* charcoal indicate its potential to generate. The ash content of *P. juliflora* charcoal was higher than that of species used for energy purposes with breeding programs already established, but lower than the maximum indicated, 5%, for domestic use, reducing its use for this purpose. The adjustment to the PQM 3-03 standard is possible with the increase in the final carbonisation temperature, improving the quality of *P. juliflora* charcoal, as its volatile materials and fixed carbon values show potential for domestic use in rural properties. *Prosopis juliflora* may be an alternative for to generate energy by reducing the use of native plants from the Caatinga Biome of Northeast Brazil.

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