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ENERGY CHARACTERISTICS OF WOOD AND CHARCOAL OF SELECTED TREE SPECIES IN MEXICO

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ABSTRACT

This study determines the main energy characteristics of wood and charcoal within five tree species of the forest of Ixtlán de Juárez, Oaxaca, México: *Alnus acuminata, Arbutus xalapensis, Myrsine juergensenii, Persea longipes* and *Prunus serotina*. Basic density, moisture content, charcoal yield, volatile material, ash content, high heating value, fixed carbon and fuel value index were determined for each one. The average results of the species are in the range of 0.372 to 0.498 $g \cdot cm^{-3}$ for wood density; 26.19 to 34.12% for charcoal yield; 77.29 to 83.66% for wood volatile matter and 28.40 to 34.25% for charcoal volatile matter; 0.56 to 1.50% for wood ash and 1.13 to 4.83% for charcoal; 19.50 to 24.99 $MJ \cdot kg^{-1}$ for high heating value of wood and 29.38 to 32.11 $MJ \cdot kg^{-1}$ for charcoal. It was determined that these species provide a good alternative for burning wood and charcoal. Additionally, these remain untapped resources in the Sierra Juárez region, meaning that awareness and inclusion in management plans could be of relative importance to the development of the forestry sector.

KEYWORDS: Fixed carbon, ash content, yield, high heating value.

INTRODUCTION

One of the greatest discoveries of humanity was the use of fire, which has been around us for 1.5 million years (Risbrudt 2005, Gowlett 2016). At present, the consumption of wood as an energy source has increased worldwide (Agostinho-Da Silva et al. 2014). In Mexico, an increase in fuel production of 6.4% and 5.5% in the form of firewood and charcoal respectively, was reported between 2013 and 2014 which represents 12.4% of the national volume of timber forest production (SEMARNAT 2014).

One of the fuels derived from forest biomass is charcoal, which is produced in the absence of air when the wood is subjected to temperatures ranging from 400 to 700°C (Soto and Núñez 2008). At these temperatures there is a complex combination of pyrolysis products from cellulose, hemicelluloses and extractives (Mohan et al. 2006) and as a result the porous material with high carbon content is obtained. In relation to wood, charcoal has a higher calorific value and is not attacked by biological agents, so it is considered a better quality fuel (Marcos 1989). Such quality is evaluated based on the moisture content, fixed carbon, percentage of ash and amount of volatile materials emitted during combustion (FAO 1983).

In the community of Ixtlán de Juárez, Oaxaca, the use of wood as a fuel plays an important role as an energy source. *Quercus* is being the preferred genus species for its high basic density and energy quality (Ruiz-Aquino et al. 2015). In this community, oak charcoal is produced in brick kilns, with an approximate production of 140,000 kg per month. However, derived from the silvicultural system that is used in forest areas of timber production (strip clear cutting), the various broadleaved species that are felled to stimulate the growth of pine without there being a final destination until now (STF 2015). Therefore, this paper evaluates the energy properties of wood and charcoal of five hardwood species: *Alnus acuminata* subsp. arguta (Schltdl.) Furlow, *Arbutus xalapensis* Kunth, *Myrsine juergensenii* (Mez) Ricketson & Pipoly, *Persea longipes* (Schltdl.) Meisn. and *Prunus serotina* Ehrh.; for its inclusion as biofuels in the form of firewood and its transformation into charcoal to obtain a more efficient fuel.

MATERIALS AND METHODS

Study area

This study was carried in the pine-oak forest of the community of Ixtlán de Juárez, Oaxaca. This community has a communal surface of 19,310 ha and is located between geographic coordinates: 17°18'16" and 17°30'00" N, 96°31'38 " and 96°22'00" W (Castellanos-Bolaños et al. 2008). On average, the medium annual temperature is 20°C and rainfalls varies between 800 and 1200 mm per year, in the pine-oak forest where is a humic acrisol soil (Ah) of medium salty texture with a very rich layer of organic matter on the surface (Rainforest Alliance 2006).

Tree selection and sample preparation

The selection of trees was based on a directed sampling whereby two trees were taken per species with the following criteria: health, vigour, lack of bifurcation and representative of the study area, from 20 to 30 cm in diameter at breast height and with heights between 10 and 15 m. Logs of 2.5 m in length were taken from each tree and a slice of 2 cm was cut on each side. Moreover, the sapwood and heartwood were separated. To determine the ash and volatile content, the material of the two slices was splintered.

It was mixed and ground in a Wiley-type mill, subsequently sieved in No. 40 and 60 mesh, and used the material that was retained in the 60 mesh (Honorato-Salazar et al. 2015).

Wood basic density

Twelve wooden cubes of 2 cm per side were prepared for each species and the wood basic density was determined in samples of sapwood and heartwood of each species by ASTM D143-94: 2007.

Elaboration and yield of charcoal

Charcoal was elaborated on a laboratory scale with 12 cubes of wood per species, 1.5 cm per side; these were introduced in metal tubes of 3 cm in diameter by 11 cm of length. The cylinder with the wooden cubes (3 to 5 cubes) was subjected to combustion in a Thermolyne® digital furnace at a temperature of 450°C ± 10° C for 30 minutes. The yield was evaluated by Eq. 1 (Vogel and Wolf 1986, Heya et al. 2014).

$$Yield = \left(\frac{Anhydrous\ charcoal\ weight}{Anhydrous\ wood\ weight}\right) \times 100 \quad (\%) \tag{1}$$

Energy characterization of wood and charcoal

The moisture content of the wood and charcoal was determined with ASTM D1762-84: 2007. The material was conditioned in the laboratory environment and then used in an electric furnace at 105°C.

Volatile matter was determined by ASTM E872-82: 2006 at temperature of 950ºC.

Ash content was determined according to ASTM D1102-84 R07: 2007. The sample was used without volatile material in a furnace at 600°C for 6 h. Ash content was calculated to the anhydrous weight of the initial sample.

High heating value (HHV) was determined in samples (1.5 cm^3) of sapwood and heartwood of wood and charcoal by using flat jacket calorimeter 1341 (Parr USA).

According to Purohit and Nautiyal (1987) the high heating value, normal density and ash content are related by means of the fuel value index (FVI) by Eq. 2; where HHV: High heating value ($MJ \cdot kg^{-1}$), ND: Normal density ($kg \cdot m^{-3}$), AC: Ash content ($g \cdot g^{-1}$), MC: Moisture content.

$$\text{FVI} = \frac{HHV \times ND}{AC \times MC} \tag{2}$$

Statistic analysis

In order to determine differences between species and by type of wood (sapwood and heartwood), the analysis of variance of two factors was carried out followed by a comparison of means with the method of minimum significant difference. The statistical package SAS® Version 9.0 (SAS Institute Inc. 2002) was used. The level of significance (α=0.05) was selected.

RESULTS AND DISCUSSION

Wood basic density

The wood basic density varied in interval 0.372 $g \cdot cm^{-3}$ (*P. longipes* heartwood) to 0.498 $g \cdot cm^{-3}$ (*P. serotina* sapwood) with an average of 0.435 $g \cdot cm^{-3}$ (Fig. 1). With the exception of *A. acuminata* and *A. xalapensis*, the rest of the species showed no statistical differences between types of wood (sapwood and heartwood). The basic density in the sapwood presented slightly higher values, which coincides with Goche-Télles et al. (2000) who mention that the basic density of wood tends to increase from the centre to the periphery, due to the existence of an immature or juvenile heartwood present in the central part of the tree and this characteristic is structurally related to age (Daniel et al. 1982). Based on wood density classification of Vignote-Peña and Martínez-Rojas (2006), the wood of the five species of the present study is classified as Light (<500 kg·m^{-3}).

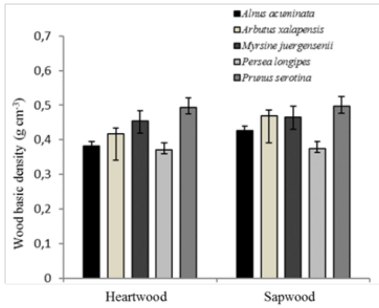

Fig. 1: Wood basic density of five tree species.

In general, the basic density is a variable attribute because they can change according to the geographical area and the climate (Ordóñez-Díaz et al. 2015). Likewise, specimens of the same species developed in a specific site, but under different external factors such as light, humidity, altitude, temperature and interventions in growth create variations in terms of their density in wood (Dalla-Salda et al. 2009, Goche-Télles et al. 2011). The anatomical structure also has a marked influence due to the greater or lesser proportion of juvenile wood (Carmona-Cerda 2015).

Charcoal yield

The highest yield of charcoal was obtained with wood of *P. serotina* (34.12%). This species was statistically superior to the others (Tab. 1). The yield may vary due to factors such as equipment, processes, temperature and rate of heating, physical characteristics and chemical composition of the species and moisture content (Demirbas 2004). According to Rivera and Uceda (1987), a higher yield is related to a higher extractive content.

Tab. 1: Charcoal, moisture content, yield and volatile matter of five tree species.

Tree species		**Moisture content (%)**	**Charcoal yield (%)**	**Volatile matter (%)**	
				Wood	**Charcoal**
A. acuminata	Sapwood	1.45 (0.34)**a**	26.30 (0.92)**a**	82.08 (0.77)**a**	32.56 (0.82)**a**
	Heartwood	1.73 (0.22)**a**	26.08 (1.32)**a**	83.15 (0.53)**a**	32.72 (1.94)**a**
	Average	1.59 (0.31)**A**	26.19 (1.09)**A**	82.61 (0.84)**C**	32.64 (1.42)**B**
A. xalapensis	Sapwood	2.32 (0.58)**a**	30.06 (0.96)**a**	80.71 (1.66)**a**	28.16 (4.01)**a**
	Heartwood	2.33 (0.80)**a**	27.80 (0.90)**b**	80.71 (1.49)**a**	28.63 (1.16)**a**
	Average	2.32 (0.65)**B**	28.93 (1.47)**B**	80.71 (1.50)**B**	28.40 (2.82)**A**
M. juergensenii	Sapwood	3.70 (0.49)**a**	27.57 (0.72)**a**	84.08 (2.21)**a**	34.90 (1.54)**a**
	Heartwood	3.65 (0.25)**a**	26.71 (0.72)**a**	83.24 (1.82)**a**	33.59 (5.61)**a**
	Average	3.67 (0.36)**C**	27.14 (0.82)**A**	83.66 (1.98)**C**	34.25 (3.98)**B**
P. longipes	Sapwood	3.46 (0.20)**a**	30.01 (0.28)**a**	79.17 (2.19)**a**	31.03 (2.90)**a**
	Heartwood	3.44 (0.32)**a**	29.46 (0.84)**a**	75.41 (4.07)**b**	34.09 (1.99)**a**
	Average	3.45 (0.25)**C**	29.73 (0.67)**B**	77.29 (3.69)**A**	32.56 (2.86)**B**

P. serotina	Sapwood	2.15 (1.02)**a**	31.55 (1.08)**a**	81.51 (1.10)**a**	27.28 (1.16)**a**
	Heartwood	2.52 (0.65)**a**	36.69 (1.29)**b**	78.56 (1.40)**b**	29.72 (1.23)**a**
	Average	2.33 (0.82)**B**	34.12 (2.92)**C**	80.03 (1.96)**B**	28.50 (1.71)**A**

Values in parentheses represent the standard deviation. Equal upper case letters in each column represent statistical equality per species ($p \geq 0.05$). Equal lower case letters in each column represent statistical equality between sapwood and heartwood within each species ($p \geq 0.05$).

The yield of the five species, with the exception of *P. serotina* (34.12%) is within the interval reported by Heya et al. (2014) for five species (20.96-30.15%). It should be noted that, as in the present study, in the one conducted by Heya et al. (2014), charcoal was elaborated on a laboratory scale in a furnace at a controlled temperature. However, under real conditions, the main problem is the low carbonization yield because there are no regulations in the charcoal production process (Bustamante-García et al. 2013). Moreover, the yield may be affected by the species, dimensions of the firewood or the type of kiln (Carrillo-Parra et al. 2013).

Moisture content

The analysis of variance of the moisture content in charcoal showed no statistical differences between type of wood of the five species ($p>0.05$) (Tab. 1). The comparison test of means of moisture content between species indicates: *A. acuminata* was statistically lower to the rest of species. Based on the moisture content, *A. acuminata* is more efficient as a fuel, because the net calorific value increases with lower moisture content. In all studied species, the moisture content was less than 5%. In general, moisture contents of less than 8% are required to reduce the consumption of material to evaporate the water and also with these values a charcoal less susceptible to attack by biological agents is obtained (Heya et al. 2014).

Volatile matter

On average, the volatile content for sapwood and heartwood of the five species was 80.86% (Tab. 1). It has been reported that species with less volatile content are better as fuels because they promote cleaner combustion (Heya et al. 2014).

By wood type, statistical differences were found between sapwood and heartwood of *P. longipes* ($p=0.0017$) and for *P. serotina* ($p=0.0121$). By species, the volatile contents were significantly higher in *A. acuminata* and *M. juergensenii* 82.61 and 83.66%, respectively.

A high emission of volatiles in combustion leads to deterioration of air quality and contributes to the generation of pollutants that can have negative repercussions on ecosystems and even on human health (Querol 2008).

In the volatile matter of charcoal, no statistical differences were found by type of wood (sapwood-heartwood) ($p> 0.05$) (Tab. 1). Volatile matter range was from 27.28 to 34.9% with an average of 31.27%. However, when making a general comparison between the volatile material of wood and charcoal, an increase of 158.6% of volatile was observed in wood combustion compared to charcoal of the five species.

In the present study, in relation to the percentage of volatile content, a charcoal of *A. xalapensis* and *P. serotina* presents an advantage from the energy point of view, since its combustion is slower and cleaner. On the other hand, the content of volatiles in charcoal of *A. acuminata*, *P. longipes* and *M. juergensenii* could increase the ignition ease and the speed of combustion. However, these samples would cause the liberation of tars and emission of fume (Bustamante-García et al. 2014). High amounts of volatile matter indicate that a heterogeneous carbonization process is carried out at low temperatures (Siddique 2008).

Ash content

The ash content (Tab. 2) fluctuates within the reported interval for sapwood hardwoods from the state of Michoacán, Mexico (0.25-3.54%) and also for heartwood (0.22-2.10%) (Martínez-Pérez et al. 2015). With the exception of *P. longipes,* ash results are within the interval (0.10-1.0%) mentioned in the literature for temperate hardwoods (Fengel and Wegener 2003).

The ash content is an important parameter to consider for the selection of a biomass fuel. Under this criterion the wood of *A. xalapensis* could be considered as of better quality. Conversely, high ash content causes problems because its accumulation obstructs the flow of combustion gases inside biomass boilers (Werkelin et al. 2011) as well as causing corrosion, erosion and abrasion (Melissari 2012).

Tab. 2: Ash content and fixed carbon in wood and charcoal of five tree species.

Tree species		Ash content (%)		Fixed carbon (%)	
		Wood	**Charcoal**	**Wood**	**Charcoal**
A. acuminata	Sapwood	0.63 (0.04)**a**	2.29 (0.11)**a**	17.29 (0.78)**a**	65.15 (0.91)**a**
	Heartwood	0.62 (0.06)**a**	2.10 (0.08)**a**	16.24 (0.51)**a**	65.18 (1.99)**a**
	Average	0.62 (0.05)**a,B**	2.19 (0.14)**B**	16.76 (0.83)**A**	65.16 (1.48)**B**
A. xalapensis	Sapwood	0.62 (0.09)**a**	1.09 (0.22)**a**	18.68 (1.64)**a**	70.75 (4.23)**a**
	Heartwood	0.50 (0.08)**a**	1.68 (0.32)**a**	18.80 (1.48)**a**	69.69 (1.45)**a**
	Average	0.56 (0.10)**A**	1.38 (0.41)**A**	18.74 (1.49)**B**	70.22 (3.07)**C**
M. juergensenii	Sapwood	0.87 (0.06)**a**	2.29 (0.12)**a**	15.05 (2.19)**a**	62.81 (1.67)**a**
	Heartwood	0.72 (0.07)**b**	2.30 (0.00)**a**	16.04 (1.86)**a**	64.11 (5.62)**a**
	Average	0.79 (0.10)**C**	2.29 (0.08)**B**	15.55 (2.00)**A**	63.46 (4.00)**A,B**
P. longipes	Sapwood	1.56 (0.24)**a**	4.98 (1.02)**a**	19.27 (2.17)**a**	63.99 (3.49)**a**
	Heartwood	1.44 (0.15)**a**	4.68 (1.27)**a**	23.15 (3.98)**b**	61.23 (1.30)**a**
	Average	1.50 (0.19)**D**	4.83 (1.11)**C**	21.21 (3.67)**C**	62.61 (2.89)**A**
P. serotina	Sapwood	0.73 (0.14)**a**	1.06 (0.06)**a**	17.76 (1.08)**a**	71.66 (1.18)**a**
	Heartwood	0.63 (0.05)**a**	1.20 (0.00)**a**	20.82 (1.38)**b**	69.08 (1.23)**a**
	Average	0.68 (0.11)B	1.13 (0.08)**A**	19.29 (1.99)**B**	70.36 (1.77)**C**

The values in parentheses represent the standard deviation. Equal upper case letters in each column represent statistical equality per species ($p \geq 0.05$). Equal lower case letters in each column represent statistical equality between sapwood and heartwood within each species ($p \geq 0.05$).

No statistical differences were found in the charcoal ash content by type of wood (sapwood-heartwood) ($p > 0.05$) (Tab. 2). On average 2.37% of ash was obtained for the five species. The low content of ash in charcoal of *P. serotina* and *A. xalapensis* allows to perceive interesting possibilities of application from the energetic point of view.

In addition, it is an approximate measurement of the mineral salts and other inorganic substances in wood (Rowell et al. 2005). Likewise, the results obtained show that the five species comply with the values allowed by the German standards < 6% (DIN 51749: 1989) as well as with the European <8% (EN 1860-2: 2005). With the exception of *P. longipes*, four remaining species meet the standards of the Japanese market < 4% (Carrillo-Parra et al. 2013). Values lower than 5% of ash content indicate that the combustion energy is obtained from carbon and that the inorganic elements of the ash do not contribute to the heat released by combustion (Carrillo-Parra et al. 2013).

Fixed carbon

Fixed carbon (FC) of *P. longipes* was significantly higher than that of the other species. However, the preference of people in the use of firewood species is related to attributes and characteristics such as the availability of timber resources as well as economic and energy implications (Aguirre-Cortés et al. 2018). Ruiz-Aquino et al. (2015) conducted a study in the same area and reported 14.7% and 16.5% of fixed carbon for *Q. laurina* and *Q. crassifolia*, respectively, and emphasize the importance of two species as good fuels in the study area.

In relation to the FC of charcoal, no differences were found by type of wood (sapwood and heartwood) (Tab. 2). However, when comparing the FC content of wood and charcoal, it was observed that FC content increases to 262% in compared to wood. Fixed carbon is related to volatile material, and it is possible to increase it to meet with international standards to 75% (NBN M11-001: 1984), 78% (DIN 1749:1989) and 75% (EN 1860-2:2005) if the process of charcoal elaboration is controlled (e.g. process of carbonization is controlled by the temperature inside the kiln) (Márquez-Montesino et al. 2001, Carrillo-Parra et al. 2013).

Fuel value index

In relation to the Fuel Value Index (FVI), the same tendency was observed in wood and charcoal, with the highest values for *A. xalapensis* and *P. serotina* (Tab. 3).

Tab. 3: Fuel value index and high heating value of wood and charcoal of five tree species.

Tree species		Fuel value index		High heating value ($MJ \cdot kg^{-1}$)	
		Wood	**Charcoal**	**Wood**	**Charcoal**
A. acuminata	Sapwood	27295.45 (1011.16)**a**	8515.07 (170.07)**a**	20.15 (0.198)**a**	32.21 (0.59)**a**
	Heartwood	25299.41 (4687.63)**a**	7980.97 (345.57)**a**	20.17 (0.065)**a**	32.01 (0.24)**a**
	Average	26297.43 (3396.98)**B**	8248.02 (381.08)**B**	20.16 (0.141)**B**	32.11 (0.45)**D**
A. xalapensis	Sapwood	30947.88 (4366.96)**a**	20420.56 (3915.45)**a**	20.07 (0.171)**a**	31.32 (0.45)**a**
	Heartwood	34592.65 (8599.43)**a**	14395.77 (3457.60)**b**	20.19 (0.193)**a**	31.05 (0.57)**a**
	Average	32770.26 (6775.33)**C**	17408.16 (4722.51)**C**	20.13 (0.185)**B**	31.19 (0.51)**B,C**
M. juergensenii	Sapwood	20955.47 (1829.85)**a**	9711.79 (484.20)**a**	19.45 (0.145)**a**	31.49 (0.24)**a**
	Heartwood	25020.83 (2890.36)**a**	9047.50 (86.91)**a**	19.56 (0.06)**a**	31.21 (0.30)**a**
	Average	22988.15 (3134.77)**B**	9379.65 (479.95)**B**	19.50 (0.121)**A**	31.35 (0.29)**C**
P. longipes	Sapwood	9698.66 (1710.06)**a**	4098.42 (896.02)**a**	19.71 (0.299)**a**	29.48 (0.61)**a**
	Heartwood	10148.31 (1220.46)**a**	4603.11 (1086.77)**a**	19.56 (0.143)**a**	29.29 (0.74)**a**
	Average	9923.49 (1435.77)**A**	4350.76 (985.52)**A**	19.63 (0.236)**A**	29.38 (0.65)**A**
P. serotina	Sapwood	28008.89 (6264.36)**a**	28040.93 (418.74)**a**	19.71 (0.299)**a**	29.48 (0.61)**a**
	Heartwood	32221.07 (2359.53)**a**	26218.87 (540.94)**a**	19.56 (0.143)**a**	29.29 (0.74)**a**
	Average	30114.98 (5020.64)**C**	27129.90 (1057.42)**D**	19.63 (0.236)**A**	29.38 (0.65)**A**

The values in parentheses represent the standard deviation. Equal upper case letters in each column represent statistical equality per species ($p \geq 0.05$). Equal lower case letters in each column represent statistical equality between sapwood and heartwood within each species ($p \geq 0.05$).

The charcoal FVI of *P. serotina* was significantly higher than FVI of four remaining species. This index assigns a value according to the energy capacity of wood fuels and classifies the species based on the physical properties of their wood (Alves et al. 2008). According to Márquez-Reynoso et al. (2017), the FVI is not related to the preference that people have over which wood to use, which is rather influenced by other characteristics such as the availability of firewood, proximity and viability to obtain it.

High heating value

It was determined little variation of the high heating value (HHV) between the wood of the studied species (Tab. 3). The values obtained in this study are within the reported range for twenty species of the Peruvian Amazon (19.3-20.5 MJ·kg^{-1}) (Uceda 1984) and it is higher than the average obtained for ten Mexican species 17.78 MJ·kg^{-1} and 18.62MJ·kg^{-1} for sapwood and heartwood, respectively (Martínez-Pérez et al. 2015). HHV must not be considered as the main indicator of the goodness of a fuel (Corradi-Pereira et al. 2012) because the volatiles and ash have a highly significant influence on their qualities to be used as fuels (Rivera and Uceda 1987).

No statistical differences were found between the HHV of charcoal by wood type (sapwood-heartwood) for each species ($p>0.05$). However, among species *A. acuminata* with a HHV of 32.11 MJ·kg^{-1} was significantly higher than the other species. The average for sapwood and heartwood of the five species was 30.99 MJ·kg^{-1}, an increase of 55.5% was observed with respect to the average HHV of wood of these species (19.93 MJ·kg^{-1}) (Fig. 2).

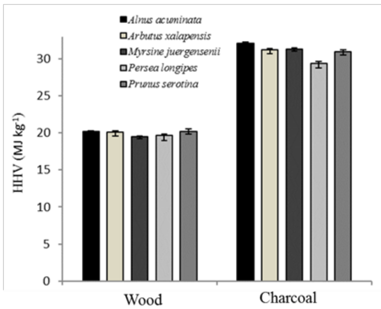

Fig. 2: High heating value (MJ·kg^{-1}) in wood and charcoal of five tree species.

Based on the classification proposed by Rivera and Uceda (1987), species with HHV lower than 33.49 MJ·kg^{-1} can be used as fuels with good qualities and according to Heya et al. (2014); HHV values between 29.0 and 35.0 MJ·kg^{-1} represent important sources of energy.

CONCLUSIONS

Five species are found below the 8% of moisture content required to reduce the consumption of material to evaporate the excess water. Based on their basic density, the woods of the five species studied are classified as light woods; however, they showed good yields when are transformed into charcoal.

The use of wood and charcoal as fuel are a good alternative, considering the calorific value as a basis. In relation to the fixed carbon of charcoal, it is possible to increase it if the carbonization temperature is controlled which would result in a lower quantity of volatiles and lower yields.

In elaboration of charcoal in the laboratory good yields were obtained so with a sequel of appropriate carbonization, it is feasible to achieve yields that are attractive for charcoal producers of the region.

The five species studied have good potential as a source of locally available energy, either in the form of firewood or in the form of charcoal with significantly better energetic properties. In addition, these species are an abundant forest resource in the Sierra Juarez region and their inclusion in management plans could be important in the development of the forestry sector.

REFERENCES

1. Agostinho-Da Silva, D., Otomar-Caron, B., Sanquetta, C.R., Behling, A., Scmidt, D., Bamberg, R., Eloy, E., Dalla-Corte, A.P., 2014: Ecuaciones para estimar el poder calorífico de la madera de cuatro especies de árboles. Revista Chapingo Serie Ciencias Forestales y del Ambiente 20(2): 177-186.
2. Aguirre-Cortés, E., López-Martínez, J. O., Vargas-Larreta, B., Pat-Fernández, J. M., Macario-Mendoza, P., 2018: Preferences for the use of firewood in a cultural landscape in southern Mexico. Revista Chapingo Serie Ciencias Forestales y del Ambiente 24(2): 147-160.
3. Alves, R.M., Muniz, P. de M., Santos de A., A.L., Patriota, A.L.F., de Albuquerque, U.P., 2008: Can wood quality justify local preferences for firewood in an area of caatinga (dryland) vegetation? Biomass and Bioenergy 32(6): 503-509.
4. ASTM D1102-84R07, 2007: Standard test method for ash in wood.
5. ASTM D143-94, 2007: Standard test methods for small clear specimens of timber.
6. ASTM D1762-84, 2007: Standard test method for chemical analysis of wood charcoal.
7. ASTM E872-82, 2006: Standard test method for volatile matter in the analysis of particulate wood fuels.
8. Bustamante-García, V., Carrillo-Parra, A., González-Rodríguez, H., Garza-Ocañas, F., Prieto-Ruíz, J.A., Corral-Rivas, J.J., Vega-Nieva, 2014: Tecnologías para la transformación de la biomasa en carbón vegetal. In: Tecnicas en el manejo sustentable de los recursos naturales (ed. Garza, O.F., Guevara, G.J.A., Villalón, M.H., Carrillo, P.A.). Pp 142-165, Universidad Autónoma de Nuevo León. México.
9. Bustamante-García, V., Carrillo-Parra, A., González-Rodríguez, H., Ramírez-Lozano, R.G., Corral-Rivas, J.J., Garza-Ocañas F., 2013: Evaluation of a charcoal production process from forest residues of *Quercus sideroxyla* Humb. & Bonpl. in a Brazilian beehive kiln. Industrial Crops and Products 42: 169-174.
10. Carmona-Cerda, R.J., 2015: Caracterización física, química y energética de biomasa leñosa como materia prima biocombustible. Tesis doctoral. Universidad de Cordoba. Cordoba, España, 102 pp.
11. Carrillo-Parra, A., Foroughbakhch-Pournavab, R., Bustamante-García, V., 2013: Calidad del carbón de *Prosopis laevigata* (Humb. & Bonpl. ex Willd.) M.C. Johnst. y *Ebenopsisebano* (Berland.) Barneby & J.W. Grimes elaborado en horno tipo fosa. Revista Mexicana de Ciencias Forestales 4(17): 62-71.
12. Castellanos-Bolaños, J.F., Treviño-Garza, E.J., Aguirre-Calderón, O.A., Jiménez-Pérez, J., Musalem-Santiago, M., López-Aguillón, R., 2008: Estructura de bosques de pino pátula bajo manejo en Ixtlán de Juárez, Oaxaca, México. Madera y Bosques 14(2): 51-63.
13. Corradi-Pereira, B.L., Costa-Oliveira, A., Macedo-Ladeira, A.M., Oliveira-Carneiro, A., Carvalho-Santos, L., Rocha-Vital, B., 2012: Quality of wood and charcoal from *Eucalyptus* clones for ironmaster use. International Journal of Forestry Research ID 523025: 1-8.
14. Dalla-Salda, G., Martínez-Meier, A., Cochard, H., Rozenberg, P., 2009: Variation of wood density and hydraulic properties of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) clones related to a heat and drought wave in France. Forest Ecology and Management 257(1): 182-189.
15. Daniel, P., Helms, U. Baker, F., 1982: Principios de silvicultura traducido de la segunda edición inglesa por Ramón Elizondo Mata. Mc Graw - Hill. México, 492 pp.

16. Demirbas, A., 2004: Potential applications of renewable energy sources, biomass combustion in boiler power systems and combustion related environmental issues. Progress in Energy and Combustion Science 31(2): 171-192.
17. DIN 1749, 1989: Grill charcoal and grill charcoal briquettes, requirements, tests.
18. EN 1860-2, 2005: Appliances, solid fuels and firelighters for barbecuing: Barbecue charcoal and barbecue charcoal briquettes. Requirements and test methods.
19. FAO 1983: Métodos simples para fabricar carbón vegetal. Departamento de Montes 41, 154 pp.
20. Fengel, D., Wegener, G., 2003: Wood: Chemistry, ultrastructure, reactions. Verlag Kessel. Germany, 613 pp.
21. Goche-Télles, J.R., Fuentes-Salinas, M., Borja-de la Rosa, A., Ramírez-Maldonado, H., 2000: Variación de las propiedades físicas de la madera en un árbol de *Abiesreligiosa* y de *Pinus ayacahuite* var. Veitchii. Revista Chapingo Serie Ciencias Forestales y del Ambiente 6(1): 83-92.
22. Goche-Télles, J.R., Velázquez-Martínez, A., Borja-de la Rosa, A., Capulín-Grande, J., Palacios-Mendoza, C., 2011: Variación radial de la densidad básica en *Pinus patula* Schltdl. et Cham. de tres localidades en Hidalgo. Revista Mexicana de Ciencias Forestales 2(7): 71-78.
23. Gowlett, J.A.J., 2016: The discovery of fire by humans: a long and convoluted process. Philosophical Transactions of the Royal Society B 371: 1-12.
24. Heya, M.N., Pournavab, F.R., Carrillo-Parra, A., Colin-Urieta, S., 2014: Bioenergy potential of shrub from native species of north-eastern Mexico. International Journal of Agricultural Policy and Research 2(12): 475-483.
25. Honorato-Salazar, J.A., Colotl-Hernández, G., Apolinar-Hidalgo F., Aburto, J., 2015: Principales componentes químicos de la madera de *Ceiba pentandra*, *Hevea brasiliensis* y *Ochroma pyramidale*. Madera y bosques 21(2): 131-146.
26. Marcos, M.F., 1989: El carbón vegetal propiedades y obtención. Agroguías Mundi Prensa. España, 116 pp.
27. Márquez-Montesino, F., Cordero-Alcántara, T., Rodríguez-Mirasol, J., Rodríguez-Jiménez, J.J., 2001: Estudio del potencial energético de biomasa *Pinus caribaea* Morelet var. *Caribaea* (Pc) y *Pinus tropicalis* Morelet (Pt); *Eucaliptus saligna* Smith (Es), *Eucalyptus citriodora* Hook (Ec) y *Eucalytus pellita* F. Muell (Ep); de la provincia de Pinar del Río. Revista Chapingo Serie Ciencias Forestales y del Ambiente 7(1): 83-89.
28. Marquez-Reynoso, M.I., Ramírez-Marcial, N., Cortina-Villar, S., Ochoa-Gaona, S., 2017: Purpose, preferences and fuel value index of trees used for firewood in El Ocote Biosphere Reserve, Chiapas, Mexico. Biomass and Bioenergy 100: 1-9.
29. Martínez-Pérez, R., Pedraza-Bucio, F.E. Orihuela-Equihua, R., López-Albarrán, P., Rutiaga-Quiñones, J.G., 2015: Calorific value and inorganic material of ten Mexican wood species. Wood Research 60(2): 281-292.
30. Melissari, B., 2012: Comportamiento de cenizas y su impacto en sistemas de combustión de biomasa. Memoria de trabajos de difusión científica y técnica 10: 69-82.
31. Mohan, D., Pittman, C.U., Steele, P.H., 2006: Pyrolysis of wood/biomass for bio-oil: A critical review. Energy & fuels 20(3): 848-889.
32. NBN M11-001, 1984: Charcoal and charcoal briquettes for domestic use: designation-specification-tests.

33. Ordóñez-Díaz, J.A.B., Galicia-Naranjo, A., Venegas-Mancera, N.J., Hernández-Tejeda, T., Ordóñez-Díaz, M.J., Dávalos-Sotelo, R., 2015: Densidad de las maderas mexicanas por tipo de vegetación con base en la clasificación de J. Rzedowski: compilación. Madera y Bosques 21: 77-126.
34. Purohit, A.N., Nautiyal, A.R., 1987: Fuel wood value index of Indian mountain tree species, Int. Tree Crops J. 4: 177-182.
35. Querol, X., 2008: Calidad del aire, partículas en suspensión y metales. Revista Española de Salud Pública 82(5): 447-454.
36. Rainforest Alliance, 2006: Resumen Público de Certificación de la Comunidad de Ixtlán de Juárez Oaxaca. Consejo de Manejo Forestal y de Smart Wood. United States of America, 34 pp.
37. Risbrudt, C.D., 2005: Wood and Society. In: Handbook of wood chemistry and wood Composites (Ed. Rowell R.M.). Pp. 1-9, CRC Press USA.
38. Rivera, I.P., Uceda, M.C., 1987: Características físico-químicas de la madera y carbón de once especies forestales de la Amazonia Peruana. Revista Forestal del Perú 14(2): 1-8.
39. Rowell, R.M., Pettersen, R., Han, J.S., Rowell, J.S., Tshabalala, M.A., 2005: Cell wall chemistry. In: Handbook of wood chemistry and wood composites (ed. Rowell, R.M.). Pp. 35-74, CRC Press. USA.
40. Ruiz-Aquino, F., González-Peña, M.M., Valdez-Hernández, J.I., Revilla, U.S., Romero-Manzanares, A., 2015: Chemical characterization and fuel properties of wood and bark of two oaks from Oaxaca, Mexico. Industrial Crops and Products 65: 90-95.
41. SAS Institute Inc., 2002: SAS/ETS* 9.0 User's guide. Carry, NC. SAS Institute Inc. 1023-1355.
42. SEMARNAT (Secretaría de Media Ambiente y Recursos Naturales), 2014: Anuario Estadístico de la Producción Forestal. México, 227 pp.
43. Siddique, R., 2008: Wood ash. Waste materials and by-products in concrete. Springer. Berlin Heidelberg, Germany, 414 pp.
44. Soto, G., Núñez, M., 2008: Fabricación de pellets de carbonilla, usando aserrín de *Pinus radiata* (D. Don), como material aglomerante. Maderas, Ciencia y Tecnología 10(2): 129-137.
45. STF (Servicios Técnicos Forestales de Ixtlán de Juárez), 2015: Programa de manejo forestal para el aprovechamiento y conservación de los recursos forestales maderables de Ixtlán de Juárez. Ciclo de corta 2015-2024, 423 pp.
46. Uceda, C.M.E., 1984: Determinación del poder calorífico de 20 especies forestales de la Amazonía Peruana. Revista Forestal del Perú 12(1-2): 1-15.
47. Vignote-Peña, S., Martínez-Rojas, I., 2006: Tecnología de la Madera. Ediciones Mundi-Prensa. Madrid, 678 pp.
48. Vogel, E., Wolf, F., 1986: Características del carbón vegetal en algunas especies madereras del noreste de México. Revista Ciencia Forestal 11(59): 181-189.
49. Werkelin, J., Lindberg, D., Boström, D., Skrifvars, B.J., Hupa, M., 2011: Ash-forming elements in four Scandinavian wood species part 3: Combustion of five spruce samples. Biomass and Bioenergy 35(1): 725-733.

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