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Energy Properties of 22 Timber Species from Oaxaca, Mexico

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ABSTRACT

The potential use of forest species as fuels depends on their energy quality. However, in rural communities in developing countries, fuelwood is still an energy source without any technical study evaluating its energetic characteristics. Therefore, this study aimed to analyze the energetic characteristics of 22 forest species from four communities in the state of Oaxaca, Mexico. The basic wood density, proximal analysis, and high heating value were evaluated. As a result of the analysis, the fuel number (FN) is proposed as a measure of the energy quality of biomass fuels in the form of firewood. FN considers the basic wood density, the fixed carbon, and the high heating value of each species. Wood basic density ranged from 0.472 g·cm^{-3} for *Pinus pseudostrobus* to 0.814 g·cm^{-3} for *Dodonaea viscosa*, fixed carbon ranged from 4.74% to 21.27% for *Liquidambar styraciflua* and *Quercus rugosa*, respectively, and high heating value from 18.33 MJ·kg^{-1} to 22.07 MJ·kg^{-1} for *Liquidambar styraciflua* and *Pinus leiophylla*, respectively. Classifying wood according to FN, in decreasing order, *Quercus rugosa* stands out as the best wood (66.97%), followed by *Liquidambar styraciflua* (39.52%). Regarding the fuel value index, the nine pine species showed the highest values (27.32 to 77.76). The FN provides a measure of the quality of biomass fuels in the form of firewood, and can be evaluated by easily measured variables.

Keywords: basic wood density; proximate analysis; high heating value; fuel number; fuel value index

INTRODUCTION

The use of wood as fuel started when humanity discovered how to make fire for cooking or heating (Ramos et al. 2016). Currently, wood is an essential raw material in the energy supply for many sectors in the world, such as industrial, commercial, transportation, and household. In rural communities in developing countries, biomass from forests is used as an energy source for cooking, both due to economic and cultural conditions (Sierra-Vargas et al. 2014). In addition, its use contributes significantly to climate change mitigation (de Oliveira et al. 2022).

Despite efforts to control biomass energy use, biomass remains the most attractive resource for local populations and, therefore, continues to be of great importance (Massuque et al. 2021). Globally, it is estimated that about half of the population uses plant or animal biomass as the primary source of energy for domestic use, where firewood is the primary fuel (Aguirre-Cortés et al. 2018, CONABIO 2020). The global consumption of firewood is estimated at over 1.5 billion m^3 per year. Europe uses more than 90 million m^3 of fuelwood per year (Parikka 2004), with an increase between 1992 and 2006 of 39 million m^3 (Buongiorno et al. 2012). In Mexico, in 2018, 1,069,380 m^3 of timber production was designated for energy use (SEMARNAT 2018). In addition, 11% of households use firewood or charcoal, which represents 40% of the total energy used (INEGI 2018).

The wood used as fuel must be evaluated to determine its suitability for bioenergy production (Lachowicz et al. 2018). The most important parameters to evaluate include volatile matter, ash content, fixed carbon, calorific value, moisture content, basic density, and chemical composition (Choi et al. 2014, de Paula Protásio et al. 2019). This study mainly evaluates the energetic wood characteristics from 22 species collected in the forests of Oaxaca, Mexico, and proposes a number to rank the quality of biomass fuels.

MATERIALS AND METHODS

Study Area

Woody biomass was collected in different areas of forest communities in the state of Oaxaca, Mexico: Ixtlán de Juárez, Oaxaca (17°20' N and 96°29' W), San Sebastián Coatlán, Miahutlán, Oaxaca (16°12'41.6" N and 96°49'15.9" W), Santa María Tlahuitoltepec, Mixe, Oaxaca (17°03' N and 95°58' W) and San Juan Metaltepec, Mixe, Oaxaca (17°10' N and 95°54' W).

Tree Selection and Sample Preparation

Two trees per species, healthy, without bifurcation, and representative of the study area, were selected and harvested. A directional felling was applied to the trees with an Oleo-Mac GS 370® chainsaw. A 1 m long log close to the root was taken from each tree, and a 2 cm slice was cut from each side (Ruiz-Aquino et al. 2019). To determine the energetic characteristics, the material was chipped, and ground in a Wiley-type mill; the material that was retained in the 40 mesh was used (Rutiaga-Quiñones et al. 2020).

Determining the Basic Wood Density

From each slice, cubes of 2 cm per side were cut with a KNOVA KN SCM-10A® band saw. The fresh volume of each cube was determined by the immersion method, determining the mass of water displaced by a wooden cube when immersed in water (Figure 1), the mass in grams being numerically equal to the volume in centimeters (Test method B- Volume by Water Immersion (ASTM 2007a)). Subsequently, once the cubes were in their anhydrous state, their basic wood density (BWD) was calculated as the ratio of the anhydrous weight and the fresh green volume (ASTM 2007a).

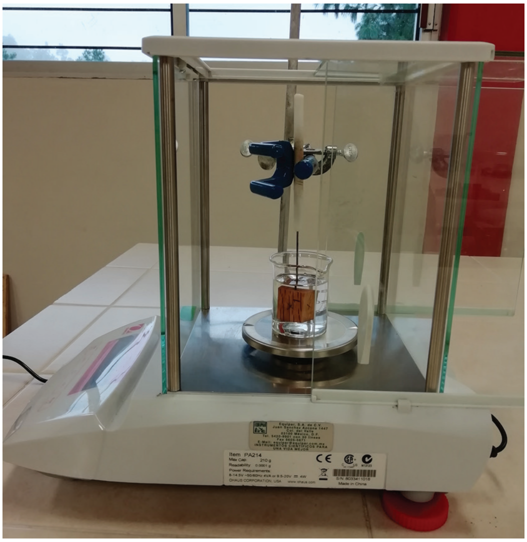
Figure 1. Determination of fresh volume by the immersion method.

Proximal Analysis

Ash content and volatile matter (VM) content were calculated using ASTM D1102-84 (2007b), and ASTM E872-82 (2013), respectively. Additionally, fixed carbon (FC) was calculated as the sum of ash and volatile matter subtracted from 100 (ASTM 2006). All percentages were calculated taking as reference the anhydrous weight of the samples.

High Heating Value

A 1341 flat jacket calorimeter (Parr, USA), equipped with a digital thermometer (Parr, 6775), ignition unit (Parr, 2901), and calorimetric pump (Parr, 1108) was used to calculate the high heating value (HHV), in accordance with ASTM E 711-87 (2004).

Fuel Number

The use of a number is proposed to rank the quality of biomass fuels. As independent variables, three parameters are considered as good indicators of energy quality: BWD, FC, and HHV (Demirbaş and Demirbaş 2009). For the development of the Fuel Number (FN), maximum values of each of the independent variables were taken. In the case of basic density, the cell wall density of 1.53 $g \cdot cm^{-3}$ is practically constant for all woods (Desch and Dinwoodie 1981, Usta 2003). For fixed carbon, it is considered that the higher it is, the better the fuel quality is. In addition, fixed carbon is an important generator of heat during combustion (Kongprasert et al. 2019); different studies agree that the value of fixed carbon in biomass fuels in the form of firewood or densified, does not exceed 30% (Uceda 1984, Vassilev et al. 2010, Ruiz-Aquino et al. 2019, Ramírez-Ramírez et al. 2021, 2022). In the HHV, lignin (25.58 $MJ \cdot kg^{-1}$) was taken as the maximum value because, in general, the HHV of biomass fuels increases with lignin content and is highly correlated (Demirbaş 2001, 2002, 2003). If we consider hypothetical data for fuel with the best characteristics outlined above, then FN takes a maximum value of 100%. Under this premise, it is relatively simple to rank the quality of biomass fuels, considering that the higher the FN, the better the fuel quality.

Fuel Value Index

In the present study, a comparison has also been made with the Fuel Value Index (FVI) proposed by Bhatt and Todaria (1992), where calorific value and density are considered positive characters and ash content is a negative parameter (Equation 1):

$$FVI = \frac{(HHV)(BD)}{A} \qquad (1)$$

where HHV is high heating value ($MJ \cdot kg^{-1}$), BD is basic wood density ($g \cdot cm^{-3}$), and A is ash content (%).

All analyses were performed with five replicates, and the mean value and standard deviation have been reported. No software was used to calculate these values.

RESULTS AND DISCUSSION

Basic Density

Table 1 summarizes the mean values and standard deviation in parentheses for the 22 studied tree species in the study; thirteen belong to the broadleaved hardwood and nine to the conifer group. In the broadleaved hardwoods group, the basic wood density varies from 0.475 g·cm^{-3} for *Liquidambar styraciflua* to 0.814 g·cm^{-3} for *Dodonaea viscosa*. Concerning oaks, the results are within the defined interval (0.543 to 0.889 g·cm^{-3}) reported by different authors (De la Paz Pérez-Olvera and Dávalos-Sotelo 2008, Herrera-Fernández 2013, Ruiz-Aquino et al. 2015, Herrera-Fernández et al. 2017). Based on the classification by Sotomayor (2005), *Dodonaea viscosa* is classified as very high-density wood, while the five oak species are classified in the category of high density. In the case of conifers, the obtained values ranged from 0.472 g·cm^{-3} (*Pinus pseudostrobus*) to 0.600 g·cm^{-3} (*P. patula*), the nine species were classified as medium density woods (0.401 to 0.600 g·cm^{-3}) proposed by Sotomayor (2005). In general, the BWD values for pine wood are in accordance with data previously reported by Peña and Rojas (2006) and Sotomayor (2005). The basic density of wood is a physical property that influences biomass combustion processes (Demirbaş and Demirbaş 2009). Kumar et al. (2010) found that higher basic density increases the calorific value of wood due to the energy contained per unit of volume. This coincides with findings by Ruiz-Aquino et al. (2015), who mention that high-density woods are preferred as fuels in a rural community in Oaxaca, Mexico. BWD and extractives content are characteristics responsible for providing high energy density, longer duration, and intensity of combustion, which are important characteristics for choosing the type of fuelwood (Massuque et al. 2020).

Proximal Analysis

Fuel's volatile matter is the portion of condensable and non-condensable gases and vapors which are released when the fuel is heated for a specific time and at specific temperature (Basu 2018). Volatile matter levels are inversely proportional to fixed carbon content (Pereira et al. 2012). According to Ragland et al. (1991), the volatile content for wood ranges from 70% to 90%, relative to the anhydrous weight of the sample, and can be subdivided into light

Table 1. Basic wood density, proximate analysis, and high heating value of 22 tree species.

Species	BWD (g·cm^{-3})	VM (%)	Ash (%)	FC (%)	HHV (MJ·kg^{-1})
Dodonaea viscosa Jacq.	0.814 (0.01)	82.04 (2.27)	0.81 (0.01)	17.15 (2.26)	21.06 (0.12)
Quercus rugosa Née.	0.797 (0.02)	76.60 (3.90)	2.12 (0.04)	21.27 (3.92)	19.91 (0.10)
Q. glaucoides M. Martens & Galeotti.	0.786 (0.01)	78.12 (1.82)	3.42 (0.04)	18.46 (1.82)	20.20 (0.15)
Q. resinosa Liebm.	0.777 (0.01)	80.13 (1.58)	1.12 (0.03)	18.74 (1.58)	20.28 (0.17)
Q. laurina Humb. & Bonpl.	0.720 (0.03)	79.45 (2.11)	3.03 (0.08)	17.51 (2.13)	19.93 (0.51)
Leucaena diversifolia (Schltdl.) Benth.	0.709 (0.02)	82.45 (0.75)	1.45 (0.03)	16.09 (0.77)	20.85 (0.13)
Q. candicans Née.	0.704 (0.02)	86.16 (1.78)	1.35 (0.04)	12.48 (1.79)	20.88 (0.19)
Acacia pennatula Schltdl. & Cham.	0.608 (0.02)	78.04 (4.27)	4.51 (0.01)	17.44 (4.27)	19.54 (0.30)
Arbutus xalapensis Kunth.	0.601 (0.03)	81.24 (1.32)	1.54 (0.03)	17.21 (1.32)	21.05 (0.36)
Montanoa leucantha subsp. arborescens (DC.) V. A. Funk.	0.548 (0.02)	82.95 (2.18)	1.19 (0.32)	15.86 (2.33)	20.11 (0.52)
Alnus jorullensis Kunth.	0.525 (0.03)	82.76 (2.76)	0.49 (0.00)	16.74 (2.76)	21.04 (0.24)
Lippia myriocephala Schltdl. & Cham.	0.504 (0.04)	83.69 (2.02)	1.11 (0.02)	15.20 (2.01)	20.53 (0.21)
Liquidambar styraciflua L.	0.475 (0.01)	94.70 (1.01)	0.54 (0.01)	4.74 (1.04)	18.33 (0.97)
Pinus patula Schiede ex Schltdl. et Cham.	0.600 (0.01)	92.81 (1.11)	0.39 (0.03)	9.28 (0.37)	19.86 (0.17)
P. rudis Endl.	0.580 (0.01)	94.82 (1.01)	0.30 (0.01)	4.88 (0.25)	19.08 (0.19)
P. douglasiana Martínez.	0.540 (0.01)	92.84 (2.05)	0.28 (0.02)	6.88 (0.46)	19.45 (0.27)
P. devoniana Lindley	0.572 (0.03)	84.96 (1.33)	0.16 (0.03)	21.75 (0.35)	14.87 (0.58)
P. lawsonii Roezl ex Gordon	0.556 (0.02)	84.56 (1.15)	0.17 (0.03)	18.83 (0.11)	15.27 (1.15)
P. hartwegii Lindley	0.526 (0.03)	86.12 (1.29)	0.21 (0.06)	21.40 (0.33)	13.67 (0.28)
P. leiophylla Schiede ex Schltdl. et Cham.	0.523 (0.02)	84.61 (1.20)	0.17 (0.01)	22.07 (0.22)	15.22 (1.21)
P. ayacahuite Enhrenb ex Schltdl.	0.480 (0.01)	93.04 (3.25)	0.37 (0.01)	21.06 (0.24)	6.59 (0.17)
P. pseudostrobus Lindl.	0.472 (0.03)	86.03 (0.56)	0.17 (0.05)	21.53 (0.18)	13.79 (0.57)

BWD = Basic Wood Density, VM = Volatile Matter, FC = Fixed Carbon, HHV = High Heating Value hydrocarbons, tar, carbon monoxide, carbon dioxide, hydrogen, and moisture.

The volatile material content in broadleaves varied from 76.60% for *Quercus rugosa* to 94.70% for *Liquidambar styraciflua* (Table 1), while in the conifer group, the variation was from 84.56% to 94.82% for *Pinus lawsonii* and *P. rudis*, respectively. In general, the values found for hardwoods coincide with those reported by different authors. For acacia species, a range of 75.30% to 86.50% has been reported (Agostinho-Da Silva et al. 2014, Eloy et al. 2015, Apolinar et al. 2016). *Alnus jorullensis* presented 82.767 %, like that reported by Ruiz-Aquino et al. (2019), and 82.61% was reported for *Alnus acuminata*. The results for conifers are close to values reported for pine wood (78.9% to 89.8%) (Rutiaga-Quiñones et al. 2020).

Ash content in hardwoods varied from 0.49% for *Alnus jorullensis* to 4.51% for *Acacia pennatula*, and in conifers from 0.16% for *Pinus devoniana* to 0.39% for *P. patula*. Out of the 13 hardwoods species in the present study, 12 were in the content range (1% to 3.4%) according to Gutiérrez-Acosta et al. (2021), except *Acacia pennatula*, which presented the highest ash content (4.51%). Regarding the four pine species (*P. patula*, *P. rudis*, *P. douglasiana* and *P. ayacahuite*), they were within the ash range (0.27% to 0.95%) referred by Rutiaga Quiñones et al. (2020). On the other hand, *Pinus pseudostrobus*, *P. leiophylla*, *P. hartwegii*, *P. lawsonii*, and *P. devoniana* were positioned within the range (0.13% to 0.23%) for bioenergy use reported by Pintor-Ibarra et al. (2017). All conifers in this study were within the range (0.1% to 1.1%) reported for pine sawdust (Ramírez-Ramírez et al. 2021). In general, ash content in conifers is lower than in broadleaved hardwoods, which coincides with the study by Gutiérrez-Acosta et al. (2021). The ash content in biomass influences fuel quality and higher content decreases the calorific value (Demirbaş and Demirbaş 2009, Klašnja et al. 2013, Martínez-Pérez et al. 2015, Ngangyo-Heya et al. 2016, Ruiz-Aquino et al. 2019). In combustion equipment (for example, stoves, ovens, furnaces, boilers, among others), it is preferable to use firewood with lower ash content because the containing minerals cause corrosion and potential problems to the equipment (Massuque et al. 2020).

Fixed carbon is the solid carbonaceous residue from the release of volatiles from biomass (McKendry 2002). It is related to the amount of ash and volatiles; thus, a higher amount of these components is reflected in a lower concentration of fixed carbon (Ruiz-Aquino et al. 2019). The fixed carbon content in the wood of the species studied (Table 1) ranged from 4.74% (*Liquidambar styraciflua*) to 21.27% (*Quercus rugosa*), and in conifer species from 4.88% (*Pinus rudis*) to 15.27% (*P. lawsonii*). All 22 tree species in the present study suit well within the range (6.5% to 26.3%), as reported for 28 wood and woody biomass samples by Vassilev et al. (2010). In our study, *Liquidambar styraciflua* has the highest volatile matter, and, therefore, it is considered the species that shows the lowest amount of fixed carbon.

High Heating Value

The HHV in hardwoods ranged from 18.33 MJ·kg^{-1} for *Liquidambar styraciflua* to 21.06 MJ·kg^{-1} for *Dodonaea viscosa*, and in conifers from 18.83 MJ·kg^{-1} for *Pinus lawsonii* to 22.07 MJ·kg^{-1} for *P. leiophylla*. The HHV of 12 studied hardwoods was within the range (19 to 21 MJ·kg^{-1}) as reported for hardwoods by Mark et al. (1985), while only four conifers were below the mentioned range (20-22 MJ·kg^{-1}). The slightly higher HHV values of conifers can be explained by the higher extractive contents and lignin in conifer wood (Ragland et al. 1991).

Fuel Number

Taking the values considered as the maximum for the parameters: basic density (BWD = 1.53 g·cm^3), fixed carbon (FC = 30%), and higher calorific value of lignin (HHV = 25.58 MJ·kg^{-1}), the FN was calculated as the average of the mentioned parameters (Equation 2):

$$FN = \frac{76.74\ BD + 3.91\ FC + 4.59\ HHV}{3.52} \qquad (2)$$

where BD is basic density (g·cm^{-3}) BWD, FC is Fixed carbon content (%), and HHV is high heating value (MJ·kg^{-1}).

Table 2 presents a comparison between the fuel number (FN) calculated and proposed in the study, and the fuel value index (FVI) proposed by Bhatt and Todaria (1992).

Classifying the tree species' wood based on FN in decreasing order, *Quercus rugosa* stands out as the best wood (66.97%), followed by *Liquidambar styraciflua* (39.52%). It can be observed that except for *Quercus candicans*, which may be due to its low fixed carbon content (Table 1), oak species are considered as most important. This hierarchy is congruent with the findings by Ramírez-López et al. (2012), who found that, in eight social communities in Chiapas, Mexico, oak firewood is preferred due to its heating quality. Similarly, Soares (2006) and Ruiz-Aquino et al. (2015) indicate that the most preferred fuel species belong to the *Quercus* genus. The preference for the use of oak wood as fuel lies in the high basic density of the wood, high fixed carbon content, high calorific value, and low ash content, characteristics that influence energy quality the most (Abbot et al. 1997). On the contrary, the low FN of *Liquidambar styraciflua* is explained by the high amount of volatiles (94.7%), its medium basic density (0.475 g·cm^{-3}), and low fixed carbon content (4.74%), being the species with the lowest calorific value (18.33 MJ·kg^{-1}), in comparison with the other studied species. The second most important species is *Dodonaea viscosa*, also preferred as a fuelwood in an indigenous community in Oaxaca due to its high BWD, high fixed carbon content, high calorific value, and low ash content coupled with easy ignition properties (Silva-Aparicio et al. 2018).

Fuel Value Index

Regarding the FVI, the highest value was found in *Pinus devoniana* (77.76) and the lowest in *Acacia pennatula* (2.63). The nine pine species showed the highest FVI values (27.32 to 77.76). However, in practice, this fuelwood is quickly consumed, and is not preferred as a good material for certain uses, such as cooking food (Ramírez-López et al. 2012, Morales-Máximo et al. 2019). The high FVI values in pine wood are more influenced by how it is calculated, i.e., the product of the calorific value and BWD is more significant, while fixed carbon is not considered. Conifers

Table 2. Fuel number (FN) and fuel value index (FVI)* for 22 timber species.

Species	FN (%)	FVI
Quercus rugose Née.	66.97	7.49
Dodonaea viscosa Jacq.	64.25	21.16
Quercus resinosa Liebm.	64.21	14.07
Q. glaucoides M. Martens & Galeotti.	63.98	4.64
Q. laurina Humb. & Bonpl.	61.14	4.74
Leucaena diversifolia (Schltdl.) Benth.	60.51	10.19
Arbutus xalapensis Kunth.	59.67	8.21
Acacia pennatula Schltdl. & Cham.	58.10	2.63
Alnus jorullensis Kunth.	57.47	22.54
Pinus devoniana Lindley	57.35	77.76
P. leiophylla Schiede ex Schltdl. et Cham.	57.09	67.90
P. rudis Endl.	56.61	36.89
Quercus candicans Née.	56.44	10.89
Montanoa leucantha subsp.arborescens (DC.) V. A. Funk.	55.78	9.26
Lippia myriocephala Schltdl. & Cham.	54.64	9.32
Pinus hartwegii Lindley	54.55	53.60
P. pseudostrobus Lindl.	53.68	59.78
P. lawsonii Roezl ex Gordon	53.63	61.59
P. ayacahuite Enhrenb ex Schltdl.	52.26	27.32
P. patula Schiede ex Schltdl. et Cham.	51.99	30.55
P. douglasiana Martínez.	50.36	37.51
Liquidambar styraciflua L.	39.52	16.12

* FVI calculated by the equation proposed by Bhatt and Todaria (1992).

have a higher calorific value than hardwoods due to the higher amount of lignin; however, the quality of fuelwood should not be ranked based on HHV alone. In the RFN, the three parameters (HHV, BWD and FC) have the same importance and the ranking results are congruent with the preference of users (Ramírez-López et al. 2012, Ruiz-Aquino et al. 2015).

The FN provides a measure of the quality of biomass fuels in the form of firewood. However, fuel quality is currently taking a back seat due to deforestation and land-use change, causing primary fuelwood users to use species that are closer in proximity to decrease transportation costs (Deka et al. 2002, Ramírez-López et al. 2012).

CONCLUSION

The basic wood density varied in a range from 0.475 g·cm^{-3} for *Liquidambar styraciflua* to 0.814 g·cm^{-3} for *Dodonaea viscosa*. Within this range, the five species of oaks are classified as having high wood density, ideal for their use as fuels. On average, coniferous firewood presented lower ash content, an indispensable attribute for its use as densified fuel. The high heating value of conifers was, on average, higher than that of hardwoods. Good fuel quality was verified with the FN, given the combination of wood density, high calorific value, and fixed carbon content. Based on the FN, four *Quercus* species indicate better fuel quality. The nine pine species showed the highest values for FVI (27.32 to 77.76), but in practice, they are not favorable for use by the local communities.

Author Contributions

FRA, MEJM, JGRQ conceived and designed the research; FRA, MEJM carried out the field and laboratory measurements; MEFC, WSG, MESM, CAV processed the data; FRA, MEJM, JGRQ, MEFC, WSG, MESM, CAV drafted the manuscript, and wrote the manuscript. All authors read and approved the final manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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