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Chemical and Energetic Properties of Seven Species of the Fabaceae Family

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ABSTRACT

In this work, the chemical compositions and energetic properties of the wood and bark of seven Fabaceae species were determined to evaluate their dendroenergetic potential. Chemical composition, elemental, proximate and heating value analyses were conducted. In addition, an ash microanalysis was performed. The obtained results varied as follows: cellulose (from 20.21% in *Parkinsonia aculeate* bark to 58.83% in *Albizia plurijuga* sapwood), hemicelluloses (from 8.81% in *Eysenhardia polystacya* heartwood to 23.71% in *Pakinsonia aculeate* wood), lignin (from 12.88% in wood to 26.53% in bark of *Parkinsonia aculeate*), extractives (from 11.68% in sapwood to 36.17% in bark of *Eysenhardia polystacya*), carbon (from 42.4% in *Albizia plurijuga* bark to 49.5% in *Eysenhardtia polystacya* heartwood), hydrogen (from 6.4% in *Eysenhardtia polystacya* bark to 7.3% in *Albizia plurijuga* sapwood), oxygen (from 42.3% in *Prosopis laevigata* bark to 50.5% in *Acacia pennatula* bark), nitrogen (from 0.11% in *Albizia plurijuga* heartwood to 1.64% in *Prosopis laevigata* bark), sulfur (from 0.04% in *Prosopis laevigata* heartwood to 0.14% in *Acacia farnesiana* wood, *Erythina caralloides* bark, and *Prosopis* laevigata bark), ash (from 0.76% in *Eysenhardtia polystacya* heartwood to 11.49% in *Acacia plurijuga* bark), volatile material (from 70.08% in *Eysenhardtia polystacya* bark to 91.75% in *Albizia plurijuga* sapwood), fixed carbon (from 6.97% in *Albizia plurijuga* sapwood to 23.44% in *Prosopis laevigata* bark), and calorific value (from 17.36 MJ·kg^{-1} in *Acacia pennatula* bark to 21.23 MJ·kg^{-1} in *Prosopis laevigata* bark). The most abundant chemical elements in wood ash and bark ash are listed here: Ca>K>P>Mg>Na. According to the obtained results, the wood and bark of the seven Fabaceae species could be used to produce solid biofuels for local use. Additionally, highlighting the high concentrations of extractives was important, especially in the bark samples, which could be a potential source of phytochemicals.

Keywords: wood; bark; ash microanalysis; ultimate analysis; proximal analysis; chemical composition; calorific value

INTRODUCTION

The family Fabaceae (Leguminosae) is in the order Fabales, which comprises trees, shrubs, and annual or perennial herbs. There are approximately 730 to 750 genera and 19,400 to 20,000 species, making it the third largest angiosperm plant family (Llamas and Acedo 2016, Stevens 2017). Many plants of this family are known because they serve as food for humans and domestic animals; others are used for ornamental and forage purposes. The genera *Acacia*, *Bahuinia*, *Erytrina*, or *Peltogyne* include species that have interesting wood due to their high flavonoid content (Llamas and Acedo 2016). Wood of other genera (e.g., *Prosopis*, *Ebenopsis*, *Acacia*, *Pakinsonia*, and *Eysenhardtia*) is used to make handicrafts, tool handles, saddles, construction materials, fence posts, charcoal, and firewood (Estrada-Castillón et al. 2005).

In Mexico, Fabaceae are the second most diverse group of plants, and their species are spread throughout the country (Sousa and Delgado 1993, Estrada-Castillón et al. 2005). In Lake Cuitzeo basin located in the state of Michoacán, Mexico, these species are abundant and develop in the vegetation of temperate forests, scrublands, and low deciduous forests; additionally, aquatic and underwater vegetation exists in this region (Bravo-Espinosa et al. 2008, Maza-Villalobos et al. 2014).

Seven species of the Fabaceae family (*Acacia farnesiana* (L.) Willd, *A. pennatula* (Schl. et Cham) Benth, *Albizia* *plurijuga* (Standl.) Britton & Rose, *Erythina caralloides* DC., *Eysenhardtia polystacya* (Ortega) Sarg., *Pakinsonia aculeate* L., and *Prosopis laevigata* (Humb. & Bonpl.) Jonhst.) stand out in Lake Cuitzeo basin; some research on them is available. For *Acacia farnesiana,* in a chemical study of its fruit, 23% protein and a high concentration of amino acids, such as histidine, valine, threonine, leucine and isoleucine, were found, and it was concluded that it is a resource potentially usable as a low-cost food option for sheep (Barrientos-Ramírez et al. 2012). A phytochemical study of its bark reports the presence of steroidal, terpene-type compounds, sulfur compounds and tannins (Daza-Bareño 2014) and a study of its wood for pulp and paper applications have been proposed (Ramírez-Casillas et al. 2019). These researchers report excellent bleachability in the cellulose pulp obtained through the ASAM process, in addition to the fact that this wood could be considered as raw material for obtaining dissolving grade cellulose. In relation to *Acacia pennatula* wood, data on energetic properties have been collected, such as calorific value (18.54 $KJ \cdot g^{-1}$), volatile matter (86.56%), ash (1.07%) and fixed carbon (12.37%), and it has been concluded that this wood could be used for energy production (Apolinar-Hidalgo et al. 2017). For *Erythina caralloides* wood, the antimicrobial activities of its extracts have been studied, and the results obtained show the antimicrobial potential and justify its traditional use for the treatment of some diseases of bacterial or fungal origin (Mata-González 2015). For *Eysenhardtia polystacya* bark, a study reported six new flavoniods, and it was concluded that their antioxidant properties are a promising strategy to improve therapeutic effects and could alleviate diabetes complications (Pérez-Gutiérrez et al. 2016). Regarding *Pakinsonia aculeata*, the essential oils of the air-dried aerial parts were studied and their antimicrobial and antioxidant activities were tested. It has been concluded that the essential oils showed moderate antimicrobial effect against bacteria and fungi (Al-Youssef and Hassan 2015). Finally, for *Prosopis laevigata*, the following data on the chemical composition have been reported: holocellulose (61.5% to 64.7%), lignin (29.8% to 31.4%) and total extractives content (14% to 16%) (Carrillo et al. 2008). Likewise, the following data have been reported in wood and bark: calorific value 16.7 $MJ \cdot kg^{-1}$ and 15.0 $MJ \cdot kg^{-1}$, and ash content 2.4% and 3.6%, respectively (Martínez-Pérez et al. 2015).

The wood of some of the Fabaceae species that grow in the region of Lake Cuitzeo—*Acacia farnesiana* and *Prosopis laevigata*—is used locally as fuel; the wood of the latter is used to make rustic furniture, doors, windows and floors. *Erythina caralloides* wood is used locally to make handicrafts. When wood is processed, the residue lignocellulosic biomass (e.g. bark, sawdust, chips and trimmings) is generated, which generally has no use and is usually deposited in the open air, which can cause environmental problems (Saval 2012).

The use of this type of biomass for energy purposes can help decrease carbon emissions and ensure environmental sustainability (Ferrandez-Villena et al. 2019, Reid et al. 2020). In addition, the growing demand for energy has led to the sustained use and depletion of fossil fuels; to maintain a sustainable and environmentally friendly energy level, renewable energy sources have been sought after (EIA 2022), including biomass. Therefore, it is relevant to determine the chemical and energetic properties of different biomasses, which can be used as energy sources. Recently, scholars on this topic have focused on studying lignocellulosic residues from some woods of the *Quercus* genus (Herrera-Fernández et al. 2017, Cárdenas-Gutiérrez et al. 2018) used for energy and of the *Pinus* genus (Pintor-Ibarra et al. 2017, Morales-Máximo et al. 2020, Rutiaga-Quiñones et al. 2020) used for wood. However, little information is available related to the wood species selected herein. Thus, for this work, seven Fabaceae species were chosen, which grow in the basin of Lake Cuitzeo, Michoacán. The objective is to determine the basic chemical compositional and energetic properties of their wood and bark to contribute to scientific knowledge and to determine the species' viability as biofuels.

MATERIALS AND METHODS

Collection Area and Preparation of Study Materials

The lignocellulosic materials were collected in the region of Lake Cuitzeo in the State of Michoacán, Mexico. In the Lake Cuitzeo basin, the average annual temperature and pluvial precipitation are 20°C to 22°C and 890 mm, respectively (Carlón-Allende and Mendoza 2007). The names of the tree species and some general data are shown in Table 1, and three individuals were collected from each species. From each tree, at a height of 1.30 m from the ground, a slice 10 cm in length was procured. Subsequently, wood and bark were separated, and when possible, the wood was separated into sapwood and heartwood. The chips obtained manually using a knife were air dried in the shade to a moisture content of approximately 12%. Finally, the material was ground in a mill (Model K20F, series 236, Micron S.A. de C.V., Mexico City, Mexico) and sieved in a Ro-Tap machine (Model RX-29, W.S. Tyler, Mentor, OH, USA); 40-mesh (425 μm) wood meal was used for chemical and energetic characterization. The 40 mesh fraction was the one that passed the same sieve and remained at the 60 mesh.

Basic Chemical Compositions

Cellulose, hemicelluloses and lignin contents were determined once using α-amylase in fibre analysis equipment (ANKOM Fibre Analyser, model AMKON200, ANKOM Technology, Macedon, New York, USA) according to the methodology described by Van Soest et al. (1991). The extractives content was determined according to the differences and by ash correction.

Ultimate Analysis

Carbon, hydrogen and nitrogen contents were determined once by the modified Dumas method using Perkin-Elmer, Model 2400 CHNS-O analyzer (Rotz and Giazzi 2012), and sulfur quantification was performed by the turbidimetric method with gum arabic. Oxygen content was calculated by the differences.

Proximate Analysis

For each dry lignocellulosic sample, the ash percentage was determined in triplicate based on UNE-EN ISO 18122 (2016), and the volatile material content was determined according to ASTM E872-82 (2013). Fixed carbon was calculated by the differences. The mean value and standard deviation were reported.

Table 1. Geographical location and general information on the seven Fabaceae species.

Scientific name	Common name	Coordinates	Diameter at 1.3 m (cm)	Total height (m)	Altitude (m)
Acacia farnesiana	Huizache	Tree 1: 19°57´49´´N 101°6´21´´W	10	3.40	1,870
		Tree 2: 19°57´50´´N 101°6´23´´W	14	2.80	1,880
		Tree 3: 19°58´29´´N 101°9´20´´W	16	4.20	1,840
A. pennatula	Tepame	Tree 1: 19°58´53´´N 101°7´16´´W	20	5.10	1,840
		Tree 2: 19°57´53´´N 101°6´19´´W	21	3.80	1,880
		Tree 3: 19°58´32´´N 101°5´47´´W	13	4.30	1,860
Albizia plurijuga	Palo blanco	Tree 1: 19°58´34´´N 101°5´40´´W	22	8.30	1,860
		Tree 2: 19°58´28´´N 101°15´51´´W	34	9.10	1,860
		Tree 3: 19°59´3´´N 101°8´45´´W	36	10.50	1,920
Erythina caralloides	Colorin	Tree 1:19°58´8´´N 101°6´28´´W	14	3.50	1,910
		Tree 2: 19°58´7´´N 101°6´24´´W	12	5.40	1,910
		Tree 3: 19°58´19´´N 101°6´3´´W	13	3.70	1,920
Eysenhardtia polystacya	Palo dulce	Tree 1: 19°58´32´´N 101°5´45´´W	16	5.30	1,860
		Tree 2: 19°58´38´´N 101°5´42´´W	15	4.80	1,850
		Tree 3: 19°58´13´´N 101°6´11´´W	24	4.60	1,930
Pakinsonia aculeate	Palo verde	Tree 1: 19°58´31´´N 101°8´55´´W	14	5.30	1,840
		Tree 2: 19° 58´27´´N 101°8´45´´W	21	6.10	1,840
		Tree 3: 19°58´13´´N 101°8´50´´W	10	3.60	1,840
Prosopis laevigata	Mezquite	Tree 1: 19°58´51´´N 101°7´15´´W	76	9.10	1,850
		Tree 2: 19°58´17´´N 101°7´30´´W	82	9.80	1,880
		Tree 3: 19°58´21´´N 101°7´28´´W	71	7.40	1,880

Calorific Value

The high heating value was determined in triplicate in a LECO calorimetric pump (LECO AC 600, LECCO Corporation, St. Joseph, USA) based on the UNE-EN ISO 18125 (2018) standard. The mean value and standard deviation were reported.

Ash Microanalysis

Ash microanalysis was determined once by using inductively coupled plasma optical emission spectrophotometer (ICP–AES) (VARIAN 730-ES, Varian Inc., (Agilent), Mulgrave, Australia) according to the procedure described by Arcibar-Orozco et al. (2014).

RESULTS AND DISCUSSION

Basic Chemical Composition

Table 2 features a summary of the results of the basic chemical analysis. The cellulose results ranged from 20.21% (*Parkinsonia aculeate* bark) to 58.83% (*Albizia plurijuga* sapwood); the values were in general agreement with data reported in the literature, e.g. 23.8% for *Fagus sylvatica* L. bark and 56.2% for *Cayra tomentosa* Sarg. wood (Fengel and Wegener 1984). Higher cellulose concentrations were observed in wood than in bark; these results were in general agreement with previous reports for hardwoods (Fengel and Wegener 1984, Honorato-Salazar and Hernández-

Pérez 1998, Bautista-Hernández and Honorato-Salazar 2005, Herrera-Hernández et al. 2017). Specifically, for *Acacia farnesiana* wood, 51.48% cellulose was reported (Ramírez-Casillas et al. 2019); this value is close to the one found herein. Conversely, 45.7% cellulose was found in the heartwood of *Prosopis leavigata* (Carrillo et al. (2008); this value is close to the one found herein.

For hemicelluloses, the results ranged from 8.81% (*Eysenhardia polystacya* heartwood) to 23.71% (*Pakinsonia aculeate* wood) (Table 2). The obtained results were generally close to values reported for some hardwood species: wood (from 21.2% to 36.0%), bark (from 9.3% to 23.1%) (Fengel and Wegener 1984), heartwood (from 12.88% to 24.38%) and sapwood (from 11.75% to 19.82%) (Ruiz-Aquino et al. 2019). Specifically, for *Acacia farnesiana* wood, Ramírez-Casillas et al. (2019) found 11.4% hemicelluloses, and Carrillo et al. (2008) reported 15.1% hemicelluloses in the heartwood of *Prosopis laevigata*; in both cases, the reported values were near the values obtained herein.

Regarding lignin content, the results ranged from 12.88% (wood) to 26.53% (bark) for *Parkinsonia aculeate* (Table 2). Lignin concentration is higher in bark than in wood (Sjöström 1981, Fengel and Wegener 1984), and this trend was generally observed in the results obtained in this research. Previous studies on *Acacia farnesiana* wood reported 17.40% lignin (Ramírez-Casillas et al. 2019), and for the heartwood of *Prosopis laevigata,* 29.8% lignin was reported (Carrillo et al. 2008); in both cases, the reported values were higher than those found herein, which could be due to the extraction method applied.

The extractives content ranged from 11.68% (sapwood) to 36.17% (bark) in *Eysenhardia polystacya* (Table 2). Clearly, a higher concentration of extractives was observed in bark than in wood; this finding agreed with literature data (Hillis 1971, Sjöström 1981, Fengel and Wegener 1984). Additionally, the extractives content was higher in heartwood than in sapwood, which agreed with previous reports (Fengel and Wegener 1984, Bautista-Hernández and Honorato-Salazar 2005, Herrera-Hernández et al. 2017). The bark extractives values obtained in this work were within the range reported for different wood species: from 20% to 40% (Sjöström 1981). Specifically, for the heartwood of *Prosopis laevigata*, extractives contents of 14.1% to 16.0% were found (Carrillo et al. 2008); these values were close to those obtained herein.

Due to the relatively high values of polysaccharides and the relatively low values of lignin (Table 2), the woods studied could be advantageous for the pulp and paper industry or for obtaining high-yield pulps (Casey 1990), in order to seek different applications in the field of nanocellulose. Regarding the bark, due to its high extractive content (Table 2), it could have potential in the search for chemical applications with different purposes (Fengel and Wegener 1984).

Table 2. Basic chemical compositions of lignocellulosic materials by species and samples.

Id	Species	Sample	Cellulose	Hemicelluloses	Lignin	Extractives
			(%)			
1	*Acacia farnesiana*	Wood	52.86	16.26	14.30	14.21
2		Bark	36.09	11.01	19.23	24.73
3	*A. pennatula*	Wood	45.58	20.85	13.39	17.29
4		Bark	37.03	11.98	16.95	23.00
5	*Albizia plurijuga*	Heartwood	49.07	19.83	10.60	19.43
6		Sapwood	58.83	12.83	13.67	13.44
7		Bark	29.26	17.69	13.12	28.44
8	*Erythina caralloides*	Wood	47.09	9.41	22.66	17.02
9		Bark	23.51	11.54	21.73	34.19
10	*Eysenhardtia polystacya*	Heartwood	48.97	8.81	20.55	20.91
11		Sapwood	53.05	12.34	21.63	11.68
12		Bark	22.34	10.20	21.25	36.17
13	*Pakinsonia aculeate*	Wood	37.41	23.71	12.88	24.27
14		Bark	20.21	15.47	26.53	27.13
15	*Prosopis leavigata*	Heartwood	45.35	14.09	22.14	16.72
16		Sapwood	41.32	18.50	23.39	14.93
17		Bark	23.92	9.70	25.57	34.96

Ultimate Analysis

Table 3 shows the results of the elemental analysis. The values found varied as follows: carbon (C) from 42.4% (*Albizia plurijuga* bark) to 49.5% (*Eysenhardtia polystacya* heartwood), hydrogen (H) from 6.4% (*Eysenhardtia polystacya* bark) to 7.3% (*Albizia plurijuga* sapwood), oxygen (O) from 42.3% (*Prosopis laevigata* bark) to 50. 5% (*Acacia pennatula* bark), nitrogen (N) from 0.11% (*Albizia plurijuga* heartwood) to 1.64% (*Prosopis laevigata* bark), and sulfur (S) from 0.04% (*Prosopis laevigata* heartwood) to 0.14% (*Acacia farnesiana* wood, *Erythina caralloides* bark, *Prosopis laevigata* bark). The average values for wood/xylem (bark) were as follows: carbon 47.2% (45.9%), hydrogen 7.1% (6.7%), oxygen 45.4% (46.2%), nitrogen 0.26% (1.13%), and sulfur 0.07% (0.09%). In general, the obtained results were close to the values reported for some hardwood species and other lignocellulosic biomasses (Vassilev et al. 2010, García et al. 2012, UNE-EN ISO 17225-2 2014, Rutiaga-Quiñones et al. 2020).

Bark samples contained higher concentrations of nitrogen, which could limit their use as solid biofuels due to the environmental problems of biomass combustion (Demirbaş 2005, Obernberger et al. 2006). Analysed samples with nitrogen concentrations of ≤0.5% could be used to make class A2 pellets, and those with concentrations of ≤1.0% could be used to make class B pellets (ENplus 2015). Conversely, the analysed samples had low sulfur contents (<1.0%), which was favorable because this chemical element could damage human health and foul combustion equipment (Obernberger et al. 2006, García et al. 2012). Low concentrations of these two chemical elements would be desirable in biomasses for combustion (Hartmann 2012, UNE-EN ISO 17225-2 2014).

For the C/N ratio, the results ranged from 30 to 435 (Table 3); this range was within the reported span (24 for lime leaves to 5,025 for pine sawdust) for various biomasses (Rutiaga-Quiñones et al. 2020). For fermentation processes, low biomass values (between 20 and 30) were adequate, since high values indicated low nitrogen availability (Velázquez-Martí 2018); thus, only the bark studied herein could be used for this purpose.

Proximate Analysis

The results of the proximal analysis are shown in Table 4. The lowest amount of ash (0.76%) was found in the *Eysenhardtia polystacya* heartwood sample, while the highest concentration (11.49%) was in the *Acacia plurijuga* bark sample. Clearly, the bark samples contained more inorganic substances than the wood samples, which was in agreement with previous reports (Fengel and Wegener 1984, Martínez-Pérez et al. 2015). The concentration of ash was higher in sapwood than in heartwood, and this trend coincided with other investigations in different woods (Rutiaga-Quiñones 2001, Ávila-Calderón and Rutiaga-Quiñones et al. 2014).

Ash evaluation is an important parameter for determining the qualities of solid biofuels (Demirbaş and

Table 3. Ultimate analysis and C/N ratio by species and samples.

Id	Species	Sample	C	H	O	N	S	C/N
			(%)					
1	*Acacia farnesiana*	Wood	46.5	6.8	46.2	0.32	0.14	145
2		Bark	46.8	6.5	45.5	1.16	0.08	40
3	*A. pennatula*	Wood	45.9	7.1	46.7	0.21	0.08	219
4		Bark	42.5	6.4	50.5	0.58	0.07	73
5	*Albizia plurijuga*	Heartwood	47.9	7.2	44.7	0.11	0.06	435
6		Sapwood	46.5	7.3	46.0	0.15	0.06	310
7		Bark	42.4	6.6	50.0	0.96	0.06	44
8	*Erythina caralloides*	Wood	46.3	6.9	46.3	0.41	0.08	113
9		Bark	48.7	7.2	43.1	0.91	0.14	54
10	*Eysenhardtia polystacya*	Heartwood	49.5	7.1	43.2	0.14	0.05	354
11		Sapwood	47.4	7.2	45.0	0.29	0.07	163
12		Bark	45.6	6.4	46.4	1.52	0.08	30
13	*Pakinsonia aculeate*	Wood	46.2	7.2	46.1	0.41	0.05	113
14		Bark	46.5	6.8	45.5	1.12	0.12	42
15	*Prosopis leavigata*	Heartwood	48.7	6.9	44.2	0.21	0.04	232
16		Sapwood	46.9	7.1	45.6	0.34	0.06	138
17		Bark	49.1	6.8	42.3	1.64	0.14	30

Demirbaş 2004). High concentrations negatively affected calorific value (Martínez-Pérez et al. 2012, Martínez-Pérez et al. 2015, Ngangyo-Heya et al. 2016, Carrillo-Parra et al. 2018) and caused problems in combustion and emission of polluting particles into the environment (Obernberger and Thek 2006, Tumuluru et al. 2010, Werkelin et al. 2011). The lignocellulosic samples analysed, with ash contents ≤2.0% (Table 4), could be used to produce class B pellets for marketing or local application purposes, according to international standards (ENplus 2015).

Regarding volatile material, the obtained results varied from 70.08% for *Eysenhardtia polystacya* bark to 91.75% for *Albizia plurijuga* sapwood (Table 4). Except for *Erythina caralloides*, less volatile matter was found in the bark samples, and more was found in sapwood than in heartwood (Table 4). The obtained results were generally in agreement with previous reports for different lignocellulosic biomasses (Vassilev et al. 2010, García et al. 2012, Rutiaga-Quiñones et al. 2020). Specifically, the result obtained for *Acacia pennatula* wood was close to the reported value (86.56%) for the same species (Apolinar-Hidalgo et al. 2017). Considering that biomass with a high concentration of volatile matter was suitable for thermochemical conversion, such as biogas or pyrolysis (Holt et al. 2006), the samples studied could be a source of biofuels derived from these processes.

Table 4 shows the results of the fixed carbon content, which varied from 6.97% for sapwood (*Albizia plurijuga*) to 23.44% for bark (*Prosopis laevigata*), and they were in the range reported for different biomasses (Vassilev et al. 2010, García et al. 2012, Rutiaga-Quiñones et al. 2020). Except for *Albizia plurijuga* and *Erythina caralloides*, the bark contained more fixed carbon than the wood (xylem). In particular, Apolinar-Hidalgo et al. (2017) reported 12.37% fixed carbon for *Acacia pennatula* wood; this value was similar to that found herein for the same species.

Calorific Value

The results of the high heating value (HHV) are shown in Table 4. The calorific values were obtained for each material analysed by averaging, and they were ordered from lowest to highest: 18.7 MJ·kg^{-1} (bark), 19.2 MJ·kg^{-1} (wood), 19.9 MJ·kg^{-1} (sapwood), and 20.3 MJ·kg^{-1} (heartwood). The calorific value obtained for the wood samples was at the lower limit of the reported range (19.5 MJ·kg^{-1} to 20.0 MJ·kg^{-1}) for hardwoods (UNE-EN-14961-1 2011). Except for the bark of *Prosopis laevigata*, the obtained results were within the reported range (15.0 MJ·kg^{-1} to 18.9 MJ·kg^{-1}) for bark of different hardwoods (Martínez-Pérez et al. 2015). The results of the sapwood and heartwood samples were similar to the values reported for some hardwoods (Ruiz-Aquino et al. 2019). The calorific values of the heartwood samples were slightly higher than those of the sapwood samples, which coincided with previous research (Martínez-Pérez et al. 2015, Ruiz-Aquino et al. 2019). Finally, the calorific value results obtained herein were within the reported range (17.1 MJ·kg^{-1} to 23.0 MJ·kg^{-1}) for wood in general (FAO 1991).

Table 4. Results of the proximate analysis and high heating value (HHV) by species and samples.

Id	Species	Sample	Ash (%)	Volatile matter (%)	Fixed carbon (%)	HHV (MJ·kg^{-1})
1	*Acacia farnesiana*	Wood	2.37	83.29	14.34	19.17
2		Bark	8.94	72.15	18.94	18.72
3	*A. pennatula*	Wood	2.89	85.08	12.01	18.32
4		Bark	11.04	71.95	17.00	17.36
5	*Albizia plurijuga*	Heartwood	1.07	86.59	12.32	20.33
6		Sapwood	1.23	91.75	6.97	20.01
7		Bark	11.49	78.76	9.77	18.03
8	*Erythina caralloides*	Wood	3.82	78.35	17.84	19.39
9		Bark	9.03	78.47	12.47	18.02
10	*Eysenhardtia polystacya*	Heartwood	0.76	81.76	17.47	20.53
11		Sapwood	1.30	85.71	12.98	19.95
12		Bark	10.04	70.08	19.87	17.86
13	*Pakinsonia aculeate*	Wood	1.73	85.62	12.63	19.83
14		Bark	10.66	74.24	15.07	19.63
15	*Prosopis leavigata*	Heartwood	1.70	78.46	19.83	20.16
16		Sapwood	1.86	81.49	16.62	19.81
17		Bark	5.85	70.72	23.44	21.23

Table 5. Ash microanalysis results.

Id	Al	B	Ba	Ca	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	Si	Sn	Sr	V	Zn
	(ppm)																			
1	29.69	86.07	352.01	5,857.73	ND	28.14	165.58	17,816.19	20.15	1,741.02	27.95	1,112.67	3.26	4,931.83	ND	13.46	ND	455.12	ND	15.88
2	106.51	55.94	145.80	1,148.42	ND	10.52	35.35	4,819.37	12.67	355.89	10.54	288.11	1.48	1,408.56	ND	142.96	0.26	120.63	0.13	10.77
3	10.45	45.34	245.41	3,608.25	ND	18.83	21.95	12,151.00	24.98	1,233.74	25.59	975.55	35.92	3,131.79	ND	ND	ND	329.02	ND	15.62
4	32.15	53.28	136.38	995.38	ND	6.92	ND	4,618.75	19.39	347.39	9.75	173.17	12.09	1,415.00	ND	48.48	0.12	115.94	ND	9.23
5	34.14	345.07	116.19	5,808.86	ND	39.72	86.76	19,958.07	137.36	2,075.61	11.92	2,773.95	13.55	340.06	ND	93.20	ND	517.85	ND	7.51
6	59.97	114.08	123.87	8,341.36	ND	30.83	11.51	23,627.18	59.55	2,442.03	47.34	2,076.00	4,094.75	5,393.37	ND	51.94	ND	600.06	ND	45.76
7	18.81	44.87	122.69	786.60	ND	3.53	ND	3,911.98	6.52	316.04	24.38	260.89	0.47	1,076.34	ND	7.43	0.16	104.66	ND	6.61
8	15.25	54.69	191.80	3,538.31	ND	23.70	ND	9,697.37	24.06	915.15	81.39	736.64	52.10	5,540.06	ND	456.42	ND	259.82	ND	29.33
9	27.18	72.23	143.92	1,179.51	0.18	10.91	1.11	4,802.26	25.69	334.18	70.02	265.17	127.39	1,546.80	ND	205.24	0.20	129.15	ND	21.44
10	52.07	262.23	886.69	11,972.38	ND	292.09	ND	26,465.17	13.19	3,414.15	134.04	601.81	177.20	637.67	ND	77.73	ND	861.95	ND	123.31
11	42.64	162.86	406.16	6,107.08	ND	85.84	0.41	17,414.83	153.77	1,720.43	124.44	1,856.34	8.52	11,380.60	ND	30.34	ND	447.32	ND	102.78
12	87.38	102.96	172.74	1,473.15	ND	26.72	7.04	5,679.15	22.92	486.36	35.26	302.65	1.13	1,807.69	ND	95.17	0.25	151.75	0.10	45.95
13	7.31	84.78	129.07	6,884.34	ND	34.02	ND	20,791.99	127.23	2,038.47	72.06	4,160.62	156.10	7,164.49	ND	251.43	1.00	503.97	ND	199.13
14	284.94	95.80	170.34	5,934.58	ND	15.10	1.30	19,482.88	5.38	2,042.74	48.40	1,822.37	118.08	1,453.56	0.32	616.68	5.04	512.88	0.09	34.38
15	154.87	60.27	100.90	6,933.19	ND	28.13	ND	20,249.06	59.68	648.53	16.33	2,818.17	0.02	349.69	ND	ND	0.18	523.49	ND	12.19
16	12.88	52.62	83.89	5,938.52	ND	31.66	ND	16,946.85	6.28	1,468.00	59.77	1,985.28	0.96	3,555.77	ND	ND	11.42	444.57	ND	25.03
17	83.02	109.07	116.78	2,204.21	ND	13.57	ND	7,611.24	12.01	526.32	56.53	498.99	24.14	636.42	ND	91.57	ND	192.89	0.11	10.97

ND = not detected.

Ash Microanalysis

Twenty inorganic elements were identified in the biomass ash of the seven Fabaceae species (Tables 5). The UNE-EN 14961-1 (2011) standard mentions that the most prevalent minerals in ash are aluminium, calcium, iron, potassium, magnesium, manganese, sodium, phosphorous, and silicon; these previous minerals were detected in the wood and in the bark of the seven species studied herein. The results obtained herein indicated that the most abundant elements in wood ash and bark ash of the seven Fabaceae species, from highest to lowest concentration, were calcium > potassium > phosphorous > magnesium > sodium. These minerals were found in a higher proportion in wood ash than in bark ash (Table 5). Some scholars have indicated that calcium, potassium, phosphorous, and magnesium were the main chemical elements in wood (Fengel and Wegener 1984, Ngangyo-Heya et al. 2016, Ruiz-Aquino et al. 2020, Rutiaga-Quiñones et al. 2020), agreeing with what was found herein. Conversely, the results obtained herein showed that calcium and potassium were the most abundant elements in the bark, coinciding with Sjöström (1981). Higher concentrations of potassium, phosphorus and magnesium were observed in the sapwood than in the bark, which was consistent with previous reports for some woods (Rowell 2005, Ávila-Calderón and Rutiaga-Quiñones 2014). Boron, copper, manganese, silicon, and zinc could be found (Sjöström 1981, Fengel and Wegener 1984, Rutiaga-Quiñones et al. 2020); in this work, these elements were detected in the wood and in the bark. In another ash microanalysis, calcium, potassium, magnesium, phosphorus, silicon, and aluminium were detected in the wood and bark of *Prosopis laevigata* (Martínez-Pérez et al. 2015).

The UNE-EN 14961-1 (2011) standard indicates that the chemical elements present in a lower proportion in the ash are: astatine, cadmium, chromium, cobalt, copper, mercury, nickel, lead, vanadium, and zinc. In this work, astatine, cadmium, cobalt, and mercury were not detected, and only chromium and lead (Table 5) were identified in low concentrations in the barks of *Erythina caralloides* and *Pakinsonia aculeate*, respectively. The microanalysis results detected strontium and barium and, to lesser extents, lithium and tin in some samples; another study with Mexican woods reported the presence of barium and lithium (Rutiaga-Quiñones et al. 2020).

Calcium, potassium, phosphorus and magnesium, which were found in greater proportion in this research, were important, since they could limit the applications of these biomasses as solid biofuels; according to various scholars, these minerals could challenge the melting point of ash and cause slag, corrosion, fine particle emission and scale formation in furnaces and boilers (Obernberger and Thek 2004, Van Lith et al. 2006, Obernberger and Thek 2010, Telmo et al. 2010). Calcium and magnesium could be favorable in combustion because they increase the melting point of the ash, reduce its amount in the combustion equipment and favor the safety of residues when dispersed in the environment (Van Lith et al. 2006). Finally, sodium, iron, and silicon could cause ash melting, scale, and corrosion problems (Obernberger and Thek 2004, Obernberger and Thek 2010).

CONCLUSIONS

The chemical compositions and energetic properties of wood and bark of seven Fabaceae species were determined to evaluate their applicability as biofuels. This study provides valuable insights into the wood and bark chemical composition shedding light on its potential applications in different wood industries and its suitability for various purposes. It is important to highlight that the bark samples have high concentration of extractives; thus, they could be an important source of phytochemicals. Due to the nitrogen content, the wood of the studied species could be used to produce class A2 pellets. By considering the ash concentration, the wood of the studied species with a value ≤2.0% could be used to make class B pellets. The sulfur content was relatively low, which would not limit the use of these materials to produce solid biofuels. The studied bark samples could be useful in fermentation processes due to their low C/N ratios. A high content of volatile material was found in the studied samples; thus, they could be suitable for thermochemical conversion. The microanalysis of the ash revealed the typical presence of inorganic substances. In general, no heavy chemical elements were detected. Based on the obtained results regarding the wood and bark of the seven Fabaceae species, solid biofuels could be made and used locally.

Author Contributions

FSH, LFPI, JGRQ conceived and designed the research, FSH, LFPI and NGO carried out the field measurements, FSH, RM, CANB performed laboratory analysis, FSH and JJAF processed the data, JGRQ secured the research funding, supervised the research and helped to draft the manuscript, JGRQ, JJAF and FSH wrote the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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