Characterization of Mexican Waste Biomass Relative to Energy Generation

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In this work, physical and chemical analyses of 28 sawdust samples (tropical woods, pine woods, and oak woods) derived from the primary process of wood transformation and 4 samples of citrus residues were performed, as an option to make densified biofuels. The study included the determination of initial moisture, particle size distribution, proximate analysis, ultimate analysis, calculation of the calorific value, and ash microanalysis. The initial moisture content of the biomass samples ranged from 6.04 to 75.21%. The biomass granulometry results indicate that the highest proportion corresponds to the 1.0-mm (33.10%) (Fraction retained in mesh 0.5 mm). Other results obtained indicate the following ranges: ash content (0.27 to 6.27%), volatile matter (78.90 to 90.50%), fixed carbon (9.10 to 20.44%), carbon (49.13 to 50.78%), oxygen (42.62 to 44.49%), and hydrogen (5.24 to 6.55%). The calculated calorific value ranged from 17.65 MJ/kg to 20.72 MJ/kg. The chemical elements with the highest concentration in the biomass samples were K and Ca, followed in some cases by Al and P. The biomass with the greatest possibilities for making densified biofuels of better quality is the group of pine woods because they have low mineral content, low nitrogen content, and high calorific value.

Keywords: Lignocellulosic residues; Bioenergy; Calorific value; Chemical analysis

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INTRODUCTION

It is known that currently the primary source of energy in the world is based on fossil fuels. This strong dependence has had harmful effects both on the environment and society itself, reducing energy security and producing high emissions of greenhouse gases and other pollutants from the combustion process of coal, natural gas, and petroleum derivatives (García *et al.* 2016). The effect on climate change from the use of these fossil fuels and perhaps the decrease in oil reserves has encouraged the demand for energy from renewable sources worldwide (Escorsim *et al.* 2018). Mexico depends on fossil fuels to satisfy its energy needs, where oil represents 62.4%, followed by natural gas with 19.7%, and coal with 4.3% of total demand (SENER 2019). This indicates that Mexico has a long way to go in its transition to renewable sources (García *et al.* 2016), even having the advantage of its great potential of biomass resources to produce solid biofuels, liquid biofuels, and biogas (REMBIO 2011).

The share of renewable energies in Mexico is 10.4% and is distributed as follows: 1.5% for hydroenergy, 5.7% biomass (firewood and sugarcane bagasse), 2.8% geoenergy (including solar and wind), and 0.1% biogas (SENER 2019). The primary sources of biomass supply include native forests and jungles and plantations or crops for energy. The secondary sources of biomass are those derived from the processes of wood use and industrialization, agricultural crops, and agro-industrial waste (Tauro *et al.* 2016). Mexico's forest vegetation comprises of 138 million hectares, which is equivalent to 70% of the national territory, while its forests and rain forests comprise 64.9 million hectares, of which 15 million hectares can be used for forestry (CONAFOR 2017). It has been estimated that the technical potential of bioenergy in Mexico is equivalent to 3,569 PJ/yr or 42% of primary energy consumption in 2008; wood represents 54% of the total potential with 1,923 PJ annually, of which 1,515 PJ/yr come from the management of native forests, while 345 PJ/yr could be obtained by establishing 2.9 million hectares of forest plantations with eucalyptus (REMBIO 2011). The use of wood for bioenergetic purposes could stimulate forest production for industrial uses through the commercialization of residues and less or less valued species (Tauro *et al.* 2016).

Due to its abundance, wood as a lignocellulosic material has been used throughout history not only as a construction material, but also in the manufacturing of furniture, plywood, particleboard, in coal production, in the pulp and paper industry, and with other chemicals derived from their heat or chemical treatment (Fengel and Wegener 1983). Recently a study examined bio-based rigid polyurethane foam compounds made from apricot kernel shells, which are precisely lignocellulosic residues (Fidan and Ertaş 2020). Wood-processing industries generate a large amount of waste (sawdust, bark, shavings, chips, and slabs) that usually have no further use (Zavala and Cortés 2000), which makes biomass an economically competitive source of energy with fossil fuels (García *et al.* 2012). Furthermore, the use of wood as energy is of little value, so the focus should be on the use of wood waste and forest residues (Karinkanta *et al.* 2018). Thus, in a favorable medium-term scenario (2025 to 2030), with the obligation of the industry to use clean energy, an increase in the demand for sawdust, chips, bark, and other bio-waste is expected (Arias-Chalico 2018).

Solid biofuels, including firewood, wood chips, pellets, briquettes, and charcoal, are considered important energy vectors derived from biomass (Riegelhaupt 2016). Previous studies of different biomasses indicate wide variation in their composition (Werkelin *et al.* 2005; Spinelli *et al.* 2011), so it is necessary to evaluate the characteristics and properties of these biofuels and other derivatives of wood industrialization, for domestic or industrial uses (Mitchual *et al.* 2014). In this sense, the objective of the present study was the physical and chemical evaluation of sawdust from coniferous woods and hardwoods, derived from the primary processing of wood, as well as from lemon peel residues from a fruit processing plant and citrus residues (branches and leaves) coming from pruning activities in orchards. The goal was to determine the feasibility of using them for the production of densified biofuels and also to generate reference data for comparison with other samples of biomass biofuels.

EXPERIMENTAL

Materials

The biomass samples for this study include sawdust from hardwoods and softwoods, as well as citrus residues; these materials were collected in eight states (Quintana Roo, Chihuahua, Michoacán, Durango, Oaxaca, Veracruz, Nuevo León, and Sonora) of the Mexican Republic. Sawdust samples come from the primary transformation process of the wood from different logging industries (in Quintana Roo: Ejido Noh-Bec, Ejido Petcacab, and Ejido Tres Garantías; in Chihuahua: Ejido El largo, Ejido Agua azul, Grupo Gazo, and Multimaderas; in Michoacán: Madererría Zamora, Maderas Preciosas Don Jesús, and Ejido Lázaro Cárdenas; in Durango: Grupo Sezarik, Maderas y Tarimas Alba, Ejido Vencedores, Ejido La Cañita, and Ejido Pueblo Nuevo; in Oaxaca: Unidad Comunal Forestal, Agropecuaria y de Servicios, Productora Comunal de Muebles Ixtlán, and Aserradero Mapsi; and in Sonora: Artesanías Don Lupe), the lemon peel from a fruit processing plant (Grupo Altex, in Veracruz), and the citrus residues (branches and leaves) come from pruning activities in the orchards (Martínez de la Torre, Veracruz).

Moisture Content

The initial moisture content of each material was determined immediately after its collection as per UNE-EN 14774-1 (2010). For citrus residues (branches), it was necessary to reduce their size to make this determination. Later, all the materials were left to dry in the open air in the shade, because later a chemical analysis of this biomass will also be carried out.

Granulometry

Subsequently, the particle size of each material was determined as per UNE-EN 15149-2 (2011), except for citrus residues. Only a fraction of the collected biomass was ground and sieved, and the 40-mesh fraction was used to determine proximate analysis and ultimate analysis.

Proximate Analysis

The ash content as per UNE-EN 14775 (2010) and the volatile matter as per ASTM E872–82 (2013) were determined. For this case, absolutely dry 40 mesh biomass was used. Fixed carbon was calculated by difference, subtracting the ash content and the volatile content from 100 (García *et al.* 2012).

Ultimate Analysis

The content of carbon, hydrogen, nitrogen, and sulfur was measured in a Costech brand elemental analyzer (Model 4010; Costech International S.p.A., Milan, Italy) as per UNE-CEN/TS 15104 EX (2008). For this case, absolutely dry 40 mesh biomass was used. Oxygen content was calculated by difference (Ghetti *et al.* 1996).

High Heating Value Calculation

For the calculation of the calorific value for various lignocellulosic materials, numerous investigations on mathematical models have been published. For this case and based on the chemical analyses developed here, prediction models based on elemental analysis (HHV = 0.335C + 1.423H - 0.154O - 0.145N; C = carbon, H = hydrogen, O = oxygen, N = nitrogen) (Demirbaş 1997), to the proximate analysis (HHV = 0.3543FC + 0.1708VM; FC = fixed carbon, VM = volatile material) (Cordero *et al.* 2001), and to the ash content (HHV = 19.914 - 0.2324A; A = ashes) (Sheng and Azevedo 2005) were used.

Ash Microanalysis

Microanalysis of the ashes was determined by inductively coupled plasma atomic emission spectrophotometer (ICP-AES) in a Varian spectrometer (Model 730-ES; Varian Inc. (Agilent), Mulgrave, Australia) (Arcibar-Orozco *et al.* 2014).

Statistic Analysis

Initial moisture, granulometry, and proximate analysis were performed three times and the results illustrated the average and standard deviation. Results obtained by means of instrumental analysis (ultimate analysis and ash microanalysis) only report the value obtained. The authors did not use any software to calculate the averages and standard deviations.

RESULTS AND DISCUSSION

Moisture Content

Table 1 summarizes the total of the samples, and they appear in the order of collection, the place of origin, if any, name of the species, and initial moisture content. The humidity of the biomass to make densified biofuels is an important factor (Obernberger and Thek 2010) and influences the properties of these materials (Núñez-Retana *et al.* 2019). The initial moisture content of the biomass samples ranged from 6.0% to 75.2%. This difference is due to the fact that sometimes at the time of collection it was just processing green wood and on other occasions it was material already stored outdoors. In the case of the pine sawdust samples, the moisture content ranged from 6.6% to 75.2%, while the moisture of the hardwoods ranged from 6.0% to 52.4%. The citrus residues had an initial moisture of 19.2% to 70.9%. A recent study reports 3.1% moisture content for apricot stone shell (Fidan and Ertaş 2020).

According to the results obtained here, it can be said that in general the initial moisture content of lignocellulosic materials is within the initial values found for pine woods (Correa-Méndez *et al.* 2014; Pintor-Ibarra *et al.* 2017) or for biomass in general (Vassilev *et al.* 2010; Velázquez 2018).

To use this biomass for the production of densified biofuels, it would be necessary to adjust the moisture content by means of some drying process and achieve the adequate humidity, because to make pellets the material must be no more than 10% (Obernberger and Thek 2010) and to make briquettes the maximum humidity must be 18% (ÖNORM 7135 2000).

Table 1. Origin, Name, and Humidity of the Biomass Samples

Sample	Origin	Name	Moisture Initial (%)
1	Quintana Roo	*Swartzia cubensis*	35.58 ± 0.23
2		*Lysiloma latisiliquum*	52.38 ± 0.46
3		*Caesalpinia platyloba*	47.68 ± 0.06
4		*Manilkara zapota*	44.13 ± 0.21
5		*Swartzia cubensis*	25.11 ± 0.26
6		*Swietenia macrophylla*	25.83 ± 0.31
7	Chihuahua	*Pinus* spp.	49.15 ± 0.63
8		*Pinus* spp.	37.40 ± 0.14
9		*Pinus* spp.	54.40 ± 0.35
10		*Pinus* spp.	54.44 ± 0.25
11	Michoacán	*Pinus* spp.	31.23 ± 0.58
12		*Pinus* spp.	12.27 ± 0.55
13		*Pinus* spp.	8.57 ± 0.58
14		*Pinus* spp.	6.60 ± 0.57
15		*Pinus* spp.	46.58 ± 1.35
16	Durango	*Pinus* spp.	39.74 ± 0.45
17		*Pinus* spp.	6.70 ± 0.15
18		*Pinus* spp.	43.12 ± 0.75
19		*Quercus* spp.	46.30 ± 0.18
20		*Pinus* spp.	63.46 ± 0.40
21		*Pinus* spp.	56.40 ± 0.79
22		*Quercus* spp.	33.59 ± 0.66
23		*Pinus* spp.	32.67 ± 0.36
24	Oaxaca	*Pinus* spp.	41.93 ± 0.20
25		*Pinus* spp.	8.50 ± 0.18
26		*Pinus* spp.	75.21 ± 0.38
27	Veracruz	Persian lime branches	41.76 ± 0.24
28		Persian lime leaves	70.89 ± 0.52
29		Orange branches	29.05 ± 0.65
30		Lemon peels	19.23 ± 0.78
31	Nuevo León	*Pinus* spp.	12.16 ± 0.37
32	Sonora	*Olneya tesota*	6.04 ± 0.22

Granulometry

The particle size of the collected biomass samples appears in Table 2, except for citrus residues (samples 27 through 30). The particle size that is generated in the primary processing of wood depends on the wood, the type of saws (band or circular saws) that are used, the cutting speed and feeding speed, and the number and characteristics of the teeth of the mountains and their edge. In this work, the characteristics of the cutting tools used to process the wood were not followed up; however, the particle size obtained corresponds to the typical size of sawdust (1 to 5 mm) (Obernberger and Thek 2010; UNE-EN 14961-1 2011) and is considered optimal for making pellets (Ortíz *et al.* 2003; Obernberger and Thek 2010). The biomass granulometry results indicated that the highest proportion corresponds to the 1.0-mm (33.10%) (retained fraction in mesh 0.5 mm), followed by the 0.5-mm (19.65%) (retained fraction in mesh 0.25 mm), and the 1.4-mm (13.16%) (retained fraction in mesh 1.0 mm), and in a smaller proportion corresponded to the mesh at 3.15 mm (3.20%) (retained fraction in mesh 2.8 mm) and greater than 3.15 mm (3.64%) (retained fraction in mesh 3.15 mm). In contrast, it is known that particles from 0.60 to 0.80 mm produce good quality pellets (Turner 1995) and a recent study used a particle size less than 4 mm obtaining pellets with acceptable physical and mechanical characteristics (Carrillo-Parra *et al.* 2018). Other studies suggest mixtures of different particle sizes with good results on pellet properties (MacBain 1966; Payne 1978; Grover and Mishra 1996). Based to the results obtained, the biomass studied can be used to make densified biofuels.

Table 2. Particle Size Distribution of Sawdust Samples (%)

Mesh (mm)	3.15	2.8	2.0	1.4	1.0	0.5	0.25	Tray
Retained fraction (mm)	> 3.15	3.15	2.8	2.0	1.4	1.0	0.5	≤ 0.25
Sample	Quintana Roo							
1	1.15 ± 0.30	0.48 ± 0.5	2.69 ± 0.28	7.92 ± 0.37	13.43 ± 0.49	43.82 ± 0.83	22.50 ± 0.78	8.01 ± 0.87
2	1.31 ± 0.71	0.46 ±0.15	1.42 ± 0.33	5.07 ± 0.88	11.21 ± 0.97	42.81 ± 1.51	26.91 ± 1.84	10.80 ± 2.42
3	7.11 ± 1.55	1.84 ± 0.07	2.29 ± 0.18	3.29 ± 0.13	8.64 ± 0.42	45.29 ± 0.85	28.35 ± 0.65	3.19 ± 0.11
4	2.07 ± 1.43	0.42 ± 0.16	1.03 ± 0.19	2.78 ± 0.41	7.64 ± 0.80	38.81 ± 1.15	31.63 ± 0.85	15.62 ± 1.22
5	2.77 ± 0.37	2.98 ± 0.08	4.39 ± 0.33	6.88 ± 0.41	13.04 ± 0.40	40.61 ± 0.19	19.67 ± 0.47	9.66 ± 0.29
6	0.72 ± 0.23	0.35 ± 0.11	0.82 ± 0.06	3.09 ± 0.39	7.44 ± 0.49	33.77 ± 1.25	31.01 ± 0.47	22.80 ± 1.48
Chihuahua								
7	0.11 ± 0.05	0.03 ± 0.02	0.19 ± 0.04	1.25 ± 0.17	5.47 ± 0.45	39.08 ± 0.90	35.97 ± 0.75	17.90 ± 0.79
8	2.23 ± 0.49	0.55 ± 0.06	0.97 ± 0.18	1.52 ± 0.19	3.93 ± 0.43	31.19 ± 0.93	37.31 ± 0.42	22.30 ± 1.43
9	1.04 ± 0.22	0.37 ± 0.02	0.72 ± 0.12	2.68 ± 0.10	10.11 ± 0.42	47.12 ± 0.97	29.77 ± 0.78	8.20 ± 0.63
10	1.21 ± 0.54	1.35 ± 0.15	9.18 ± 1.14	33.18 ± 1.07	24.50 ± 1.08	22.56 ± 0.83	5.89 ± 0.76	2.13 ± 0.21
Michoacán								
11	2.28 ± 0.64	1.26 ± 0.20	2.98 ±0.14	10.56 ±0.35	18.93 ±0.25	40.81 ±0.77	17.22 ±0.28	5.94 ±0.14
12	2.72 ± 1.01	4.48 ± 0.34	11.31 ±0.71	18.59 ±0.85	19.90 ±0.44	25.80 ±0.89	12.29 ±1.20	6.91 ±0.59
13	4.42 ± 0.68	1.66 ± 0.22	1.59 ±0.89	4.91 ±0.24	8.51 ±0.22	34.85 ±0.70	28.35 ±0.35	15.71 ±0.63
14	10.42 ± 1.05	6.25 ± 0.42	16.74 ±0.43	25.30 ±0.33	15.88 ±0.48	17.31 ±0.83	5.65 ±0.42	2.46 ±0.15
15	1.22 ± 0.82	1.05 ± 0.31	3.77 ±0.41	11.35 ±0.83	18.96 ±0.63	42.47 ±1.43	17.06 ±0.24	4.11 ± 1.36
Durango								
16	2.07 ± 0.35	3.33 ± 0.22	14.61 ± 0.12	31.97 ± 0.65	19.87 ± 0.04	21.17 ± 0.63	5.13 ± 0.39	1.84 ± 0.06
17	2.68 ± 0.73	2.28 ± 0.14	5.52 ± 0.21	10.65 ± 0.20	12.02 ± 0.05	24.74 ± 0.15	19.94 ± 0.53	22.17 ± 0.59
18	19.30 ± 2.06	20.94 ± 0.68	27.54 ± 0.78	18.61 ± 0.60	6.36 ± 0.46	4.42 ± 1.09	1.67 ± 0.55	1.16 ± 0.19
19	1.48 ± 0.71	1.31 ± 0.47	3.67 ± 0.64	10.74 ± 1.35	16.42 ± 1.30	36.89 ± 0.27	19.97 ± 2.16	9.53 ± 2.41
20	0.42	0.35	2.07	11.46	20.68	48.88	13.77	2.37

	± 0.16	± 0.07	± 0.09	± 0.70	± 0.86	± 0.65	± 0.83	± 0.33
21	4.42 ± 1.04	3.54 ± 1.04	8.10 ± 0.33	11.67 ± 0.14	10.27 ± 0.15	25.17 ± 0.45	23.51 ± 1.14	13.34 ± 0.97
22	1.55 ± 0.34	1.34 ± 0.61	3.65 ± 0.96	10.22 ± 1.53	15.83 ± 1.01	36.65 ± 0.81	20.67 ± 2.01	10.09 ± 1.19
23	10.11 ±1.80	4.48 ± 0.39	14.60 ± 1.14	24.13 ± 0.67	18.08 ± 0.47	21.01 ± 1.34	5.73 ± 0.90	1.86 ± 0.29
Oaxaca								
24	0.47 ± 0.28	1.15 ± 0.25	3.97 ± 0.38	12.15 ± 0.38	19.12 ± 0.34	43.74 ± 0.43	17.57 ± 0.37	1.83 ± 0.35
25	15.31 ± 1.06	20.49 ± 0.60	26.63 ± 0.82	19.45 ± 0.67	8.25 ± 0.57	5.96 ± 0.19	2.17 ± 0.60	1.74 ± 0.17
26	1.22 ± 0.27	1.62 ± 0.33	3.08 ± 0.47	11.63 ± 0.35	18.99 ± 0.45	41.57 ± 0.22	18.92 ± 0.38	2.97 ± 0.41
Nuevo León								
31	1.26 ± 0.11	3.62 ± 0.30	9.33 ± 0.65	20.58 ± 0.58	20.54 ± 0.42	26.83 ± 0.97	13.58 ± 0.28	4.26 ± 0.96
Sonora								
32	0.87 ± 0.09	1.54 ± 0.29	1.08 ± 0.43	2.07 ± 0.35	8.36 ± 0.28	43.58 ± 0.63	38.24 ± 0.41	4.26 ± 0.28

Proximate Analysis

Table 3 summarizes the results of the proximate analysis. The moisture content of the dry biomass samples ranged from 5.0% (*Olneya tesota*) to 13.2% (*Caesalpinia platyloba*). In relation to the results of the ash content of the biomass studied, the values obtained range from 0.27% (*Pinus* spp.) to 6.27% (lemon peel). It is observed that the amount of inorganic substances from the *Pinus* spp. biomass (0.27% to 0.95%) is less compared to the amount found in tropical woods (1.32% to 3.38%) and in oak woods (1.02% to 3.12%), which agrees with the literature (Fengel and Wegener 1983). For citrus residues, the values found ranged from 0.38% (orange branches) to 6.27% (lemon peel). Some values are close to the ash content found in apricot stone shell (1.29%) shell (Fidan and Ertaş 2020).

Tropical woods usually contain a high concentration of mineral substances (Fengel and Wegener 1983), which coincided with the results obtained in this study. However, the values of the amount of ash found here were lower than the reported range (4.77% to 7.22%) in other tropical woods (Rodríguez-Jiménez *et al.* 2019). The ash content in the biomass of *Pinus* spp. was within the typical range (0.1% to 1.0%) (UNE-EN 14961-1 2011) and coincided with previous reports for various pine species (Bernabé-Santiago *et al.* 2013; Correa-Méndez *et al.* 2014; Pintor-Ibarra *et al.* 2017). The value for the biomass of oak woods (sample 22), in general coincided with data reported for oak woods (Herrera-Fernández *et al.* 2017; Cárdenas-Gutiérrez *et al.* 2018) and sample 19 presented a high value, perhaps due to a contamination of the sample at the collection site. The amount of ash in citrus branches was within the range reported for branches of various wood species (Ngangyo-Heya *et al.* 2016; Cárdenas-Gutiérrez *et al.* 2018). The content of mineral substances is an important characteristic of a solid biofuel (Obernberger and Thek 2010); it allows determining the amount of waste generated in the combustion process and is useful for the design of biomass combustion equipment (Velázquez 2018). The biomass samples studied, whose values are less than 0.70%, 1.5%, and 3.0%, could be used to make class A1, class A2, and class B pellets, respectively, as per ISO 17225-2 (2014). Biomass samples with values less than 0.50% ash could be used to make briquettes as per ÖNORM 7135 (2000), complying with international standards.

In relation to volatile matter, which is the fraction that is transformed into gas in the combustion process (Velázquez 2018), the values found in biomass ranged from 78.9% (*Pinus* spp.) to 90.5% (orange branches), and in general they were within the range reported for biomass (47.8% to 86.3%) (Vassilev *et al.* 2010). The ranges found for the wood biomass groups were as follows: tropical woods (81.7% to 87.3%), pine woods (78.9% to 89.8%), and oak woods (82.6% to 84.9%); these are values that in summary coincide with previous reports for various timber species (Telmo *et al.* 2010; Vassilev *et al.* 2010; García *et al.* 2012).

Table 3. Proximate Analysis Data for Biomass Wastes

Sample	Origin	Name	Moisture (%)	Ash (%)	VM (%)	CF (%)
1	Quintana Roo	*Swartzia cubensis*	8.66 ± 0.07	1.32 ± 0.01	85.53 ± 0.70	13.14 ± 0.70
2		*Lysiloma latisiliquum*	9.50 ± 0.10	3.34 ± 0.02	87.33 ± 0.28	9.32 ± 0.28
3		*Caesalpinia platyloba*	13.24 ± 0.13	2.20 ± 0.03	81.71 ± 0.14	16.08 ± 0.14
4		*Manilkara zapota*	10.56 ± 0.14	3.38 ± 0.03	82.11 ± 0.33	14.50 ± 0.33
5		*Swartzia cubensis*	9.95 ± 0.61	2.52 ± 0.02	83.55 ± 0.58	13.92 ± 0.58
6		*Swietenia macrophylla*	8.51 ± 0.13	2.14 ± 0.02	86.43 ± 0.06	11.42 ± 0.06
7	Chihuahua	*Pinus* spp.	11.18 ± 0.13	0.47 ± 0.01	87.79 ± 0.54	11.73 ± 0.54
8		*Pinus* spp.	8.87 ± 0.26	0.45 ± 0.01	88.41 ± 0.36	11.13 ± 0.36
9		*Pinus* spp.	9.88 ± 0.09	0.73 ± 0.03	86.41 ± 0.37	13.05 ± 0.37
10		*Pinus* spp.	8.38 ± 0.11	0.53 ± 0.01	88.41 ± 0.29	11.05 ± 0.29
11	Michoacán	*Pinus* spp.	9.71 ± 0.06	0.91 ± 0.06	85.46 ± 0.78	13.62 ± 0.78
12		*Pinus* spp.	10.82 ± 0.07	0.51 ± 0.05	85.40 ± 0.16	14.09 ± 0.16
13		*Pinus* spp.	11.32 ± 0.08	0.44 ± 0.06	83.08 ± 0.26	16.48 ± 0.26
14		*Pinus* spp.	11.49 ± 0.06	0.64 ± 0.02	78.90 ± 0.12	20.44 ± 0.12
15		*Pinus* spp.	12.07 ± 0.11	0.33 ± 0.01	83.83 ± 0.17	15.83 ± 0.17
16	Durango	*Pinus* spp.	10.44 ± 0.13	0.59 ± 0.06	88.83 ± 0.24	10.58 ± 0.24
17		*Pinus* spp.	9.22 ± 0.09	0.73 ± 0.02	86.53 ± 0.58	12.73 ± 0.58
18		*Pinus* spp.	7.51 ± 0.17	0.55 ± 0.07	86.88 ± 0.08	12.56 ± 0.08
19		*Quercus* spp.	12.28 ± 0.19	3.12 ± 0.01	82.55 ± 0.15	14.32 ± 0.15
20		*Pinus* spp.	12.36 ± 0.62	0.27 ± 0.05	84.54 ± 0.22	15.18 ± 0.22
21		*Pinus* spp.	11.17 ± 0.14	0.75 ± 0.01	85.46 ± 0.54	13.78 ± 0.54
22		*Quercus* spp.	12.38 ± 0.13	1.02 ± 0.02	84.91 ± 0.59	14.07 ± 0.59
23		*Pinus* spp.	12.27 ± 0.22	0.95 ± 0.01	82.40 ± 0.61	16.64 ± 0.61
24	Oaxaca	*Pinus* spp.	11.83 ± 0.18	0.66 ± 0.10	83.34 ± 0.33	15.99 ± 0.33
25		*Pinus* spp.	8.44 ± 0.20	0.35 ± 0.03	88.83 ± 0.44	10.82 ± 0.63
26		*Pinus* spp.	11.47 ± 0.29	0.48 ± 0.04	80.38 ± 0.16	19.13 ± 0.16
27	Veracruz	Persian lime branches	6.71 ± 0.29	0.48 ± 0.18	87.42 ± 0.97	12.09 ± 0.97
28		Persian lime leaves	9.69 ± 0.33	6.11 ± 0.34	82.17 ± 0.35	11.71 ± 0.35
29		Orange branches	4.91 ± 0.17	0.38 ± 0.03	90.50 ± 0.24	9.10 ± 0.24
30		Lemon peels	12.29 ± 0.25	6.27 ± 0.62	80.39 ± 0.31	13.33 ± 0.31
31	Nuevo León	*Pinus* spp.	8.78 ± 0.10	0.51 ± 0.11	89.84 ± 0.15	9.64 ± 0.15
32	Sonora	*Olneya tesota*	5.01 ± 0.22	1.44 ± 0.22	81.86 ± 0.62	16.69 ± 0.15

Fixed carbon, which is the fraction that is oxidized in the solid phase during the combustion of biomass (Velázquez 2018), ranged from 9.1% (orange branches) to 20.4% (*Pinus* spp.) and was in the reported range (0.5% to 37.9%) for biomass (Vassilev *et al.* 2010). In relation to the wood biomass, the variations are the following: tropical woods (9.3% to 16.7%), pine woods (9.6% to 20.4%), and oak woods (14.1% to 14.3%); these fixed carbon values generally coincided with data reported for various woods (Telmo *et al.* 2010; Vassilev *et al.* 2010; García *et al.* 2012).

Ultimate Analysis

The results of the ultimate analysis are presented in Table 4 and in general are in agreement with values reported for different types of biomass (Vassilev *et al.* 2010). The percentage of nitrogen and sulfur in the wood is usually low, but in other parts of the tree the concentration may be higher (Camps and Marcos 2008), as shown by the results on the amount of nitrogen in the citrus biomass. Sulfur was not detected in the samples. Carbon and oxygen are the main components in solid biofuels and are the ones that participate in the exothermic reaction during combustion, generating CO_2 and H_2O (Obernberger *et al.* 2006). For all biomass samples, the carbon content ranged from 49.1% (*Lysiloma latisiliquum*) to 50.8% (*Pinus* spp.), oxygen from 42.6% (lime leaves) to 44.5% (*Lysiloma latisiliquum*), and hydrogen from 5.2% (lemon peel) to 6.6% (*Pinus* spp.). These values are lower than the results obtained for apricot stone shell (Fidan and Ertaş 2020).

For wood biomass, the amount of carbon varied as follows: tropical woods (49.1% to 49.6%), pine woods (49.6% to 50.8%), and oak woods (50.0% to 50.6%). The oxygen concentration had the following variation: tropical woods (43.6% to 44.5%), pine woods (42.9% to 43.9%), and oak woods (43.3% to 43.9%). The hydrogen content varied as follows: tropical woods (6.0% to 6.2%), pine woods (6.2% to 6.6%), and oak woods (6.0% to 6.0%). The values obtained here are within the range reported for softwoods (C: 47 to 54%, O: 40 to 44%, and H: 5.6 to 7.0) and for hardwoods (C: 48 to 52%, O: 41 to 45%, and H: 5.9 to 6.5%) as per ISO 17225-2 (2014). The average values of C, O, and H for the sawdust were 50.16, 43.46, and 6.23%, respectively. For citrus residues, the average amount of carbon was 50.1%, oxygen 43.3%, and hydrogen 5.7%.

Most of the nitrogen is converted to gaseous nitrogen and nitric oxides (NOx) during the combustion process (Obernberger *et al.* 2006). The nitrogen content ranged in tropical woods from 0.14% to 0.42%, in pine woods from 0.10% to 0.74%, and in oak woods from 0.12% to 0.14%. With the exception of the value of 0.74% (*Pinus* spp.), these values coincided with the typical range for coniferous and hardwood woods (0.10% to 0.50%) as per ISO 17225-2 (2014). In contrast, the biomass of citrus residues contained more nitrogen compared to the biomass of woods, ranging from 0.36% (branches) to 2.10% (leaves) and these results were in the range reported for branches (0.33% to 2.87%) and sheets (1.03% to 3.04%) (García *et al.* 2012).

The lowest values of nitrogen were for the sawdust of pine woods, which coincided with the literature (Velázquez 2018), while the highest values corresponded to biomass of tropical woods and citrus residues. In contrast, the C/N ratio presents high variability with values from 24 (lime leaves) to 5025 (*Pinus* spp.). For the evaluation of the nutritional balance of the biomass substrate, where microorganisms participate in the fermentation process, this C/N ratio is important and high values indicate little nitrogen availability (Velázquez 2018).

Table 4. Ultimate Analysis Data for Biomass Wastes

Sample	Origin	Name	C (%)	H (%)	O (%)	N (%)	C/N
1	Quintana Roo	*Swartzia cubensis*	49.62	6.19	43.77	0.42	118
2		*Lysiloma latisiliquum*	49.13	6.02	44.49	0.36	136
3		*Caesalpinia platyloba*	49.78	6.21	43.69	0.32	156
4		*Manilkara zapota*	49.99	6.12	43.62	0.27	185
5		*Swartzia cubensis*	49.50	6.18	44.05	0.27	183
6		*Swietenia macrophylla*	49.67	6.08	44.11	0.14	355
7	Chihuahua	*Pinus* spp.	50.35	6.28	43.29	0.08	629
8		*Pinus* spp.	50.78	6.26	42.90	0.06	846
9		*Pinus* spp.	50.18	6.26	43.51	0.05	1004
10		*Pinus* spp.	50.57	6.43	42.93	0.07	722
11	Michoacán	*Pinus* spp.	50.25	6.15	43.59	0.01	5025
12		*Pinus* spp.	50.51	6.30	43.14	0.05	1010
13		*Pinus* spp.	50.71	6.20	43.03	0.06	845
14		*Pinus* spp.	50.74	6.21	42.93	0.12	423
15		*Pinus* spp.	50.56	6.19	43.19	0.06	843
16	Durango	*Pinus* spp.	50.20	6.50	43.21	0.09	556
17		*Pinus* spp.	49.84	6.34	43.08	0.74	67
18		*Pinus* spp.	49.63	6.55	43.74	0.08	620
19		*Quercus* spp.	50.63	5.96	43.27	0.14	362
20		*Pinus* spp.	50.59	6.31	43.01	0.09	562
21		*Pinus* spp.	50.09	6.25	43.64	0.02	2505
22		*Quercus* spp.	50.04	5.99	43.85	0.12	417
23		*Pinus* spp.	50.66	6.2	43.04	0.10	507
24	Oaxaca	*Pinus* spp.	49.91	6.23	43.75	0.11	454
25		*Pinus* spp.	50.26	6.15	43.52	0.07	718
26		*Pinus* spp.	50.73	6.21	42.96	0.10	507
27	Veracruz	Persian lime branches	50.10	6.01	43.35	0.54	93
28		Persian lime leaves	49.57	5.71	42.62	2.10	24
29		Orange branches	49.89	5.87	43.88	0.36	139
30		Lemon peels	50.67	5.24	43.36	0.73	69
31	Nuevo León	*Pinus* spp.	49.59	6.50	43.85	0.06	827
32	Sonora	*Olneya tesota*	49.85	6.20	43.66	0.29	172

Knowledge of the elemental composition of biomass is important because it allows predicting the reactions that will occur in the biomass combustion processes and helps to determine the number of reagents, products generated, and the heat given off in them (Velázquez 2018). In contrast, NOx emissions have an environmental impact on the combustion of solid fuels (Nussbaumer 2002), and this increases proportionally with the nitrogen content of the biomass (Lyngfelt *et al.* 1996). Due to the relatively low nitrogen results in the biomass studied, low environmental impact would be expected when used as densified biofuels.

High Heating Value Calculation

The results of the calorific value calculated using the prediction models based on the ultimate analysis (Demirbaş 1997), proximate analysis (Cordero *et al.* 2001), and the ash content (Sheng and Azevedo 2005) are presented in Table 5. It is observed that the results obtained by the mathematical model based on elemental analysis were slightly lower than the other two models used.

Table 5. High Heating Value (HHV) Calculated for Biomass Wastes (MJ/kg)

Sample	Origin	Name	HHV by Ultimate Analysis	HHV by Proximate Analysis	HHV by Ash Content
1	Quintana Roo	*Swartzia cubensis*	18.63	19.26	19.61
2		*Lysiloma latisiliquum*	18.12	18.22	19.14
3		*Caesalpinia platyloba*	18.74	19.65	19.40
4		*Manilkara zapota*	18.70	19.16	19.13
5		*Swartzia cubensis*	18.55	19.20	19.33
6		*Swietenia macrophylla*	18.48	18.81	19.42
7	Chihuahua	*Pinus* spp.	19.13	19.15	19.80
8		*Pinus* spp.	19.30	19.04	19.81
9		*Pinus* spp.	19.01	19.38	19.74
10		*Pinus* spp.	19.47	19.02	19.79
11	Michoacán	*Pinus* spp.	18.87	19.42	19.70
12		*Pinus* spp.	19.23	19.58	19.80
13		*Pinus* spp.	19.18	20.03	19.81
14		*Pinus* spp.	19.21	20.72	19.77
15		*Pinus* spp.	19.09	19.93	19.84
16	Durango	*Pinus* spp.	19.40	18.92	19.78
17		*Pinus* spp.	18.98	19.29	19.74
18		*Pinus* spp.	19.20	19.29	19.79
19		*Quercus* spp.	18.76	19.17	19.19
20		*Pinus* spp.	19.29	19.82	19.85
21		*Pinus* spp.	18.95	19.48	19.74
22		*Quercus* spp.	18.52	19.49	19.68
23		*Pinus* spp.	19.15	19.97	19.69
24	Oaxaca	*Pinus* spp.	18.83	19.90	19.76
25		*Pinus* spp.	18.88	19.01	19.83
26		*Pinus* spp.	19.20	20.51	19.80
27	Veracruz	Persian lime branches	18.58	19.21	19.80
28		Persian lime leaves	17.86	18.18	18.49
29		Orange branches	18.26	18.68	19.83
30		Lemon peels	17.65	18.45	18.46
31	Nuevo León	*Pinus* spp.	19.10	18.76	19.80
32	Sonora	*Olneya tesota*	18.76	19.89	19.58
Average			18.85 ± 0.43	19.33 ± 0.58	19.59 ± 0.36

For the model based on the last analysis, the calculated calorific value ranged from 17.7 MJ/kg (lemon peel) to 19.4 MJ/kg (*Pinus* spp.). For the biomass groups the variation was as follows: tropical woods from 18.1 MJ/kg (*Lysiloma latisiliquum*) to 18.8 MJ/kg (*Olneya tesota*), pine woods (18.8 to 19.5 MJ/kg), oak woods (18.5 to 18.8 MJ/kg), and citrus residues from 17.7 MJ/kg (lemon peels) to 18.6 MJ/kg (lime branches).

For the model based on proximate analysis, the calorific value results ranged from 18.2 (lime leaves) to 20.7 MJ/kg (*Pinus* spp.), and the variation in the biomass groups was as follows: tropical ones of 18.2 MJ/kg (*Lysiloma latisiliquum*) at 19.9 MJ/kg (*Olneya tesota*), pine woods (18.8 to 20.7 MJ/kg), oak woods (19.2 to 19.5 MJ/kg), and citrus residues of 18.2 MJ/kg (lime leaves) at 19.2 MJ/kg (lime branches).

For the results obtained with the model based on the amount of ash, the values ranged from 18.5 (lemon peel) to 19.9 MJ/kg (*Pinus* spp.). For the biomass groups, the variation of the calorific value was as follows: tropical from 19.1 MJ/kg (*Lysiloma latisiliquum*) to 19.6 MJ/kg (*Swartzia cubensis*), pine woods (19.7 to 19.9 MJ/kg), oak woods (19.2 to 19.7 MJ/kg), and citrus residues from 18.5 MJ/kg (lemon peels) to 19.8 MJ/kg (orange branches).

According to the results obtained by the three mathematical equations used, the values of the calorific value for the group of tropical woods (18.1 to 19.6 MJ/kg), in general were greater than the range (16.2 to 18.5 MJ/kg) obtained by calculation with a mathematical model based on elemental analysis for woods of other tropical species (Rodríguez-Jiménez *et al.* 2019), but they were slightly less than the experimental data reported for some tropical woods (19.0 to 20.7 MJ/kg) (Telmo *et al.* 2010). Likewise, this study’s average values for the biomass group of pine (18.8 to 20.7 MJ/kg) and oak (18.5 to 19.7 MJ/kg) were within the range of typical variation reported for softwoods (18.5 to 19.8 MJ/kg) and for hardwoods (18.4 to 19.2 MJ/kg) as per UNE-EN 14961-1 (2011).

Ash Microanalysis

The following tables (Table 6 to 6d) show the microanalysis data of the ashes of all the biomasses studied. In this study 23 chemical elements were detected, and there was variability in the concentration and in the number of chemical elements present in each biomass. For the tropical wood group, the concentration varied from 0.89 ppm (Cr in *Lysiloma latisiliquum*) to 228,498 ppm (K in *Caesalpinia platyloba*), in the pine wood group from 0.01 ppm (As, Mo) to 29,166 ppm (Ca), in the oak wood group from 0.53 ppm (V) to 378,271 ppm (K), in citrus branches from 1.64 ppm (Cr in orange branches) to 29,480 ppm (P in lime branches), in lime leaves from 0.22 ppm (Cr) to 259,108 ppm (K), and in lemon peels from 1.03 ppm (Co) to 282,617 ppm (K).

Major elements that constitute the ash are considered Al, Ca, Fe, K, Mg, Mn, Na, P, Si, and Ti (UNE-EN 14961-1 2011) and are important in the characterization of the ashes of a biofuel (Velázquez 2018); the only one not detected here was Ti. The minor elements present in solid biofuels are considered As, Cd, Cr, Co, Cu, Hg, Ni, Pb, V, and Zn (UNE-EN 14961-1 2011), of which Hg was not detected in the samples of biomass studied here. Other chemical elements detected here were B, Ba, Li, Mo, and Sr. The typical chemical elements present in wood are Ca, K, Mg, Mn, Na, P, and Cl (Fengel and Wegener 1983), with the exception of Cl, all were detected here. In general, the results of the microanalysis of the ashes coincide with previous studies carried out on different species of wood (Rutiaga-Quiñones and García-Díaz 1999; Villaseñor-Araiza and Rutiaga-Quiñones 2000; Bernabé-Santiago *et al.* 2013; Correa-Méndez *et al*. 2013; Correa-Méndez *et al*. 2014; Ávila-Calderón and Rutiaga-Quiñones 2015; Martínez-Pérez *et al.* 2015;

Ngangyo-Heya *et al*. 2016; Pintor-Ibarra *et al*. 2017; Cárdenas-Gutiérrez *et al*. 2018; Ruíz-Aquino *et al*. 2019).

Table 6. Ash Microanalysis Data for Biomass Wastes (ppm)

Sample	Origin	Name	Al	As	B	Ba	Ca
1	Quintana Roo	*Swartzia cubensis*	1652	10.21	161.90	50.29	26474
2		*Lysiloma latisiliquum*	1017	6.32	116.25	42.48	18600
3		*Caesalpinia platyloba*	4352	0.00	88.98	56.36	23057
4		*Manilkara zapota*	1277	0.00	76.00	33.49	20475
5		*Swartzia cubensis*	2033	8.71	119.49	50.00	21216
6		*Swietenia macrophylla*	1536	0.00	78.80	402.97	24200
7	Chihuahua	*Pinus* spp.	8811	4.19	173.84	549.02	27252
8		*Pinus* spp.	3301	2.96	158.97	905.76	26830
9		*Pinus* spp.	9474	5.08	205.46	994.15	28069
10		*Pinus* spp.	9863	8.58	193.64	571.12	23260
11	Michoacán	*Pinus* spp.	14926	0.00	192.14	247.87	22213
12		*Pinus* spp.	11882	0.00	453.23	676.10	27518
13		*Pinus* spp.	17618	0.00	225.12	273.60	22318
14		*Pinus* spp.	14153	0.00	228.46	272.23	24196
15		*Pinus* spp.	17544	0.00	285.99	274.44	24830
16	Durango	*Pinus* spp.	6691	0.01	224.93	980.67	23476
17		*Pinus* spp.	2367	0.01	209.17	589.02	19257
18		*Pinus* spp.	8854	0.44	224.86	969.51	25859
19		*Quercus* spp.	1886	0.00	205.92	906.79	29036
20		*Pinus* spp.	9368	0.25	226.67	872.71	25852
21		*Pinus* spp.	4175	0.01	190.51	962.63	29166
22		*Quercus* spp.	3035	0.00	184.41	919.61	27608
23		*Pinus* spp.	4101	0.01	183.89	846.27	27573
24	Oaxaca	*Pinus* spp.	21793	20.18	178.05	283.00	19032
25		*Pinus* spp.	18713	14.36	710.23	241.00	23850
26		*Pinus* spp.	12669	23.60	182.59	191.62	18373
27	Veracruz	Persian lime branches	239.12	0.00	225.37	940.93	24031
28		Persian lime leaves	372.40	0.00	359.69	1938	22220
29		Orange branches	639.86	0.00	168.83	658.83	23796
30		Lemon peels	4407	0.00	220.25	1423	20983
31	Nuevo León	*Pinus* spp.	11536	9.02	153.27	592.54	23234
32	Sonora	*Olneya tesota*	1257	0.00	56.25	83.63	20463

Table 6a. Ash Microanalysis Data for Biomass Wastes (ppm)

Sample	Origin	Name	Cd	Co	Cr	Cu	Fe
1	Quintana Roo	*Swartzia cubensis*	0.00	0.00	10.78	34.00	2580
2		*Lysiloma latisiliquum*	0.00	0.00	0.89	20.21	682.44
3		*Caesalpinia platyloba*	0.00	0.00	2.23	28.92	2127
4		*Manilkara zapota*	0.00	0.00	4.32	26.26	814.00
5		*Swartzia cubensis*	0.00	0.00	10.90	44.36	2794
6		*Swietenia macrophylla*	0.00	0.00	9.51	56.64	1351
7	Chihuahua	*Pinus* spp.	0.00	0.00	15.51	100.51	9249
8		*Pinus* spp.	0.00	0.00	12.87	103.59	2874
9		*Pinus* spp.	0.00	0.00	58.78	130.93	7253
10		*Pinus* spp.	0.00	0.00	19.15	104.75	7769
11	Michoacán	*Pinus* spp.	0.00	0.00	39.31	118.98	9699
12		*Pinus* spp.	0.00	0.00	26.53	131.34	9356
13		*Pinus* spp.	0.00	0.00	15.06	103.09	7769
14		*Pinus* spp.	0.00	0.00	23.33	108.26	9854
15		*Pinus* spp.	0.00	0.00	14.90	117.21	4705
16	Durango	*Pinus* spp.	0.00	0.00	7.26	102.06	4780
17		*Pinus* spp.	0.00	0.00	7.54	162.17	1928
18		*Pinus* spp.	0.00	0.00	6.51	112.64	4972
19		*Quercus* spp.	0.00	0.00	2.49	35.23	1598
20		*Pinus* spp.	0.00	0.00	8.83	244.01	8491
21		*Pinus* spp.	0.00	0.00	1.62	137.90	2812
22		*Quercus* spp.	0.00	0.00	1.98	31.74	2311
23		*Pinus* spp.	0.00	0.00	2.09	134.76	2758
24	Oaxaca	*Pinus* spp.	0.00	0.00	18.87	124.33	4439
25		*Pinus* spp.	0.00	0.00	62.73	188.18	7750
26		*Pinus* spp.	0.00	0.00	11.10	190.36	8970
27	Veracruz	Persian lime branches	0.00	0.00	0.00	72.77	509.10
28		Persian lime leaves	0.00	0.00	0.22	31.89	707.13
29		Orange branches	0.00	0.00	1.64	23.83	720.84
30		Lemon peels	0.00	1.03	9.47	124.11	5297
31	Nuevo León	*Pinus* spp.	0.00	0.00	8.72	100.76	7729
32	Sonora	*Olneya tesota*	0.00	0.00	4.22	36.55	819.02

Table 6b. Ash Microanalysis Data for Biomass Wastes (ppm)

Sample	Origin	Name	K	Li	Mg	Mn	Mo
1	Quintana Roo	*Swartzia cubensis*	222886	13.35	2404	70.66	1.67
2		*Lysiloma latisiliquum*	187808	11.73	2452	18.91	2.44
3		*Caesalpinia platyloba*	228498	63.21	2739	65.18	1.79
4		*Manilkara zapota*	201690	14.17	3286	34.78	1.93
5		*Swartzia cubensis*	216887	39.45	1830	70.66	1.43
6		*Swietenia macrophylla*	158314	12.32	2042	50.13	0.00
7	Chihuahua	*Pinus* spp.	345656	16.48	8332	3076	0.01
8		*Pinus* spp.	353328	14.67	7067	5652	0.01
9		*Pinus* spp.	357993	13.13	7494	6746	0.86
10		*Pinus* spp.	201688	11.32	6440	3434	0.01
11	Michoacán	*Pinus* spp.	43566	7.09	7730	3854	2.32
12		*Pinus* spp.	40331	6.65	8191	6422	0.36
13		*Pinus* spp.	43839	7.19	7451	4069	0.82
14		*Pinus* spp.	46601	8.25	7287	3486	0.84
15		*Pinus* spp.	37535	9.72	7595	2672	1.61
16	Durango	*Pinus* spp.	362167	5.53	7761	6129	0.00
17		*Pinus* spp.	263570	2.81	6243	4120	0.00
18		*Pinus* spp.	366982	7.04	7708	5963	0.00
19		*Quercus* spp.	378271	7.01	6597	4671	0.00
20		*Pinus* spp.	385963	6.88	7203	5898	0.00
21		*Pinus* spp.	241219	9.67	5886	3919	0.00
22		*Quercus* spp.	315395	9.65	5475	3679	0.00
23		*Pinus* spp.	219526	8.26	5190	3488	0.00
24	Oaxaca	*Pinus* spp.	299074	10.28	5927	5169	2.16
25		*Pinus* spp.	326979	19.69	6782	6549	1.09
26		*Pinus* spp.	232913	14.35	5974	3092	2.49
27	Veracruz	Persian lime branches	281157	17.66	5629	322.09	0.00
28		Persian lime leaves	259108	17.12	5144	915.58	0.00
29		Orange branches	235380	11.43	3631	67.26	0.00
30		Lemon peels	282617	9.27	5662	4276	1.10
31	Nuevo León	*Pinus* spp.	201598	10.63	6428	3479	0.00
32	Sonora	*Olneya tesota*	201578	16.17	3265	36.62	2.04

Table 6c. Ash Microanalysis Data for Biomass Wastes (ppm)

Sample	Origin	Name	Na	Ni	P	Pb	Si
1	Quintana Roo	*Swartzia cubensis*	1019	77.31	1294	0.00	2175
2		*Lysiloma latisiliquum*	1091	17.19	427.17	0.00	848.28
3		*Caesalpinia platyloba*	1100	35.10	730.24	0.00	799.58
4		*Manilkara zapota*	876.10	1267.03	374.54	180.54	562.85
5		*Swartzia cubensis*	906.73	123.49	1912	29.60	1584
6		*Swietenia macrophylla*	892.25	271.73	975.58	68.92	397.25
7	Chihuahua	*Pinus* spp.	1152	511.87	5504	148.82	1588
8		*Pinus* spp.	1682	949.19	5425	110.27	1643
9		*Pinus* spp.	1906	571.90	6025	161.53	1638
10		*Pinus* spp.	1619	249.30	5610	340.59	2568
11	Michoacán	*Pinus* spp.	548.02	650.75	6512	289.19	1341
12		*Pinus* spp.	975.77	798.80	5574	948.77	3827
13		*Pinus* spp.	474.94	183.40	6342	226.81	3565
14		*Pinus* spp.	575.75	326.27	7611	828.82	2204
15		*Pinus* spp.	637.86	391.12	9229	880.76	3119
16	Durango	*Pinus* spp.	1661	781.26	8744	87.40	3687
17		*Pinus* spp.	1440	392.11	5228	31.00	1553
18		*Pinus* spp.	1377	412.94	7112	98.99	4182
19		*Quercus* spp.	1199	133.96	7538	72.01	1479
20		*Pinus* spp.	1213	155.61	6823	26.27	1181
21		*Pinus* spp.	1109	115.22	5426	40.83	2774
22		*Quercus* spp.	1024	357.36	5192	18.20	2165
23		*Pinus* spp.	1969	482.37	4850	19.52	1583
24	Oaxaca	*Pinus* spp.	400.13	859.92	6225	23.58	726.68
25		*Pinus* spp.	615.46	927.15	8793	89.08	106.45
26		*Pinus* spp.	325.19	154.97	8832	92.52	110.81
27	Veracruz	Persian lime branches	1081	50.43	29480	27.03	0.00
28		Persian lime leaves	1883	12.77	14055	0.00	1055
29		Orange branches	797.07	11.41	5811	9.71	37.55
30		Lemon peels	1731	328.67	11433	197.19	248.29
31	Nuevo León	*Pinus* spp.	1639	253.35	5608	361.27	2598
32	Sonora	*Olneya tesota*	689.16	1299	405.45	196.12	624.11

Table 6d. Ash Microanalysis Data for Biomass Wastes (ppm)

Sample	Origin	Name	Sr	V	Zn
1	Quintana Roo	*Swartzia cubensis*	280.77	0.00	45.15
2		*Lysiloma latisiliquum*	309.08	0.00	20.05
3		*Caesalpinia platyloba*	312.82	0.92	56.13
4		*Manilkara zapota*	361.05	0.00	99.11
5		*Swartzia cubensis*	323.75	0.00	70.11
6		*Swietenia macrophylla*	158.56	0.00	126.10
7	Chihuahua	*Pinus* spp.	437.02	18.01	649.38
8		*Pinus* spp.	427.55	10.08	926.46
9		*Pinus* spp.	469.51	19.97	969.33
10		*Pinus* spp.	490.93	13.29	584.49
11	Michoacán	*Pinus* spp.	218.74	36.80	643.09
12		*Pinus* spp.	617.29	19.80	995.25
13		*Pinus* spp.	333.33	13.23	910.75
14		*Pinus* spp.	293.14	16.85	737.93
15		*Pinus* spp.	372.57	16.80	987.39
16	Durango	*Pinus* spp.	437.37	3.86	865.56
17		*Pinus* spp.	249.01	0.40	709.81
18		*Pinus* spp.	396.69	4.08	908.40
19		*Quercus* spp.	449.76	0.53	123.73
20		*Pinus* spp.	305.40	7.25	953.80
21		*Pinus* spp.	528.88	1.48	294.77
22		*Quercus* spp.	484.07	0.62	222.43
23		*Pinus* spp.	422.20	2.46	250.57
24	Oaxaca	*Pinus* spp.	196.48	25.91	419.73
25		*Pinus* spp.	257.95	15.47	529.29
26		*Pinus* spp.	168.20	32.43	407.40
27	Veracruz	Persian lime branches	1235	0.00	166.30
28		Persian lime leaves	1158	0.00	86.88
29		Orange branches	691.66	9.98	50.92
30		Lemon peels	676.78	9.87	625.08
31	Nuevo León	*Pinus* spp.	495.93	9.33	574.89
32	Sonora	*Olneya tesota*	386.87	0.00	100.07

With the results of the microanalysis of the biomass samples, concentration limits were established and the chemical elements were grouped from highest to lowest concentration for the biomass of tropical woods (Table 7), for the biomass from pine sawdust (Table 8), and for the biomass of oak sawdust and citrus residues (Table 9). It is clearly apparent that the most abundant chemical elements present in lignocellulosic materials are K and Ca, and in some cases Al and P (Tables 7, 8, and 9). In general, for tropical woods the highest number of chemical elements was in the range of 99 to 10 ppm (Table 7), the group of pine woods was in the range of 990 to 100 ppm (Table 8), the oak woods was in the range of 9,900 to 1,000 ppm (Table 9), and the citrus residues were in the range of 990 to 100 ppm (Table 9).

In relation to the major elements detected in tropical woods, most of them were in the concentration range of 990 to 100 ppm and higher (Table 7), as well as citrus residues (Table 9) and for the pine woods was in the 9,900 to 1,000 ppm range (Table 8) as well as oak woods (Table 9). The major elements are of particular importance in the ash melting point, in the formation of slag, and in corrosion problems, while the minor elements are important in terms of the emission of fine particles and problems of environmental contamination (Telmo *et al.* 2010). The relative high concentration of the main major chemical elements, mainly K, could be a limitation for the use of these biomasses in the production of densified biofuels, because this element can decrease the melting point of ash and cause problems of formation of slag and deposit formation, in addition to aerosol formation and fine particle emission (Obernberger and Thek 2004; Van Lith *et al*. 2006).

The distribution of the minor elements present in the biomass samples studied was as follows. In tropical woods they were located from 99 to 10 ppm and lower (Table 7), in pine, oak, and citrus residues from 990 to 100 ppm and lower (Tables 9), even some of them were not detected. The typical values of the major chemical elements in European woods in mg/kg are as follows: conifers Ca (900), K (400), Mg (150), Si (150), Al (100), Mn (100), P (60), Fe (25), Na (20), and Ti (< 20); in broadleaf Ca (1200), K (800), Mg (200), Si (150), P (100), Mn (83), Na (50), Fe (25), Al (20), and Ti (< 20).

Table 7. Upper-limit Values of Elements in Tropical Wood Samples

Range of Upper-limit Values (ppm)	*Swartzia cubensis*	*Lysiloma latisiliquum*	*Caesalpina platyloba*	*Manilkara zapota*	*Swartzia cubensis*	*Swietenia macrophylla*	*Olneya resota*
400,000 to 200,000	Ca > K		K	K	K		K
199,000 to 100,000		K				K	
99,000 to 10,000		Ca	Ca	Ca	Ca	Ca	Ca
9,900 to 1,000	Fe > Mg > Si > Al > P > Na	Mg > Al > Na	Al > Mg > Fe > Na	Mg > Al > Ni	Al > Fe > P > Mg > Si	Mg > Al > Fe	Mg > Ni > Al
990 to 100	Sr > B	Si > Fe > P > Sr > B	Si > P > Sr	Na > Fe > Si > P > Sr > Pb	Na > Sr > > B > Ni	P > Na > Ba > Si > Ni > Sr > Zn	Fe > Na > Si > P > Sr > Pb > Zn
99 to 10	Ni > Mn > Ba > Zn > Cu > Li > Cr > As	Ba > Cu > Zn > Mn > Ni > Li	B > Mn > Li > Ba > Zn > Cu > Ni	Zn > B > Mn > > Ba > Cu > Li	Mn > Zn > Ba > Cu > Li > Pb > Cr	B > Pb > Cu > > Mn > Li > Cr	Ba > B > Mn > Cu > Li
9.9 to 0.1	Mo	As > Mo > Cr	Cr > Mo > V	Cr > Mo	As > Mo		Cr > Mo
Not Detected	Cd, Co, Pb, V	Cd, Co, Pb, V	As, Cd, Co, Pb	As, Cd, Co, V	Cd, Co, V	As, Cd, Co, Mo, V	As, Cd, Co, V

Table 8. Upper-limit Values of Elements in *Pinus* spp. Samples by Origin

Range of Upper-limit Values (ppm)	Chihuahua	Michoacán	Durango	Oaxaca	Nuevo León
400,000 to 200,000	K		K	K	K
199,000 to 100,000					
99,000 to 10,000	Ca	K > Ca > Al	Ca	Ca > Al	Ca > Al
9,900 to 1,000	Al > Mg > Fe > Mn > Si > P > Na	Fe > Mg > P > Mn > Si	Mg > P > Al > Mn > Fe > Si > > Na	P > Fe > Mg > Mn	Fe > Mg > P > Mn > Si > Na
990 to 100	Zn > Ba > Ni > Sr > Pb > B > Cu	Zn > Ba > Na > Pb > Ni > Sr > B > Cu	Ba > Zn > Sr > Ni > B > Cu	Ni > Zn > Na > B > Si > Ba > Cu > Pb > Sr	Ba > Zn > Sr > Pb > Ni > B > Cu
99 to 10	Cr > V > Li	Cr > V	Pb	Cr > V > As > Li	Li
9.9 to 0.1	As > Mo	Li > Mo	Li > Cr > V > As	Mo	V > As > Cr
Not Detected	Cd, Co	As, Cd, Co	Cd, Co, Mo	Cd, Co	Cd, Co, Mo

Table 9. Upper-limit Values of Elements in *Quercus* spp. Samples and Citric Biomass

Range of Upper-limit Values (ppm)	*Quercus* spp	Citric Samples			
		Lime Branches	Lime Leaves	Orangee Branches	Lemon Peels
400,000 to 200,000	K	K	K	K	K
199,000 to 100,000					
99,000 to 10,000	Ca	P > Ca	Ca > P	Ca	Ca > P
9,900 to 1,000	P > Mg > Mn > Al > Fe > Si > Na	Mg > Sr > Na	Mg > Ba > Na > Sr > Si	P > Mg	Mg > Fe > Al > Mn Na > Ba
990 to 100	Ba > Sr > Ni > B > Zn	Ba > Fe > Mn > Al > B > Zn	Mn > Fe > Al > B	Na > Fe > Sr > Ba Al > B	Sr > Zn > Ni > Si > B > Pb > Cu
99-10	Pb > Cu	Cu > Ni > Pb > Li	Zn > Cu > Li > Ni	Mn > Zn > Si > Cu Li > Ni	
9.9-0.1	Li > Cr > V		Cr	V > Pb > Cr	V > Cr > Li > Mo > Co
Not Detected	As, Cd, Co, Mo	As, Cd, Co, Cr, Mo, Si, V	As, Cd, Co, Mo, Pb, V	As, Cd, Co, Mo,	As, Cd

The typical values of the minor chemical elements in European woods in mg/kg, both for conifers and broadleaved trees, are as follows: Zn (10), Cu (2), Pb (2), V (< 2), Cr (1), Ni (0.5), Cd (0.1), As (< 0.1), and Hg (0.02) (UNE-EN 14961-1 2011). This scheme was not observed in the Mexican biomass samples studied here.

CONCLUSIONS

1. The particle size distribution of the biomass of the sawdust residues is adequate for the production of densified biofuels. The dimensions and proportions found here largely avoid grinding and energy consumption for drying.
2. The biomass with the greatest possibilities for making densified biofuels of better quality is the group of pine woods because they have low mineral content, low nitrogen content, and high calorific value.
3. The densification of pine biomass will be able to generate class A1, A2, and B pellets. Given that forests are dominated by coniferous woods, it is a good opportunity to generate densified biofuels of the best quality in terms of ash content as it is common that the percentage of these does not exceed 1.0% in the *Pinus* genus.
4. The biomass of the tropical wood group has a high content of inorganic material, which is a limitation for making densified biofuels or to meet demanding quality standards. However, in certain localities with abundant raw materials of this type, solid biofuels may be generated that do not demand high quality but may generate heat in some devices.
5. Citrus residues had a high content of ash and nitrogen, so they would be suitable for the production of densified biofuels with certain criteria of lower quality, according to the classification within internationally established standards.
6. The major chemical elements were in the range of 990 to 100 ppm and higher in tropical woods and citrus residues, while from 9,900 to 990 ppm in pine and oak woods.
7. Minor chemical elements were in the range of 99 to 10 ppm in tropical woods, while in pine woods, oak woods, and citrus residues were in the range of 990 to 100 ppm and less.

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