

On the Basic Chemical Composition of Selected Biomass Types from Four Regions of Mexico, for Bioenergetic Purposes

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The chemical composition of hardwoods sawdust and citrus residues from four states of the Mexican Republic (Quintana Roo, Durango, Veracruz, and Sonora) were determined. The results ranged as follows: total extractives from 8.2% (*Quercus* spp.) to 35.0% (lime leaves), holocellulose from 45.4% (lime leaves) to 70.6% (*Lysiloma latisiliquum*), lignin from 3.9% (lemon peels) to 25.4% (*Caesalpinia platyloba*), ash from 0.4% (orange branches) to 6.3% (lemon peels), pH from 5.1 (*Swartzia cubensis*) to 7.3 (orange branches), and calorific value of 19.8 MJ/kg (*Lysiloma latisiliquum* and *Quercus* spp.) to 21.7 MJ/kg (*Olneya tesota*). With the exception of the oak samples, in all the biomass samples the extractives content is relatively high (10.1% for *Lysiloma latisiliquum* to 35% for Persian lime leaves), and could represent a potential for future study and applications in the field of antioxidants. Due to the chemical properties and calorific value, the biomass samples studied present potential for local use as densified biofuels (pellets or briquettes).

Keywords: Tropical woods; Hardwoods; Citrus residues; Extractives; Lignin; High heating value

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INTRODUCTION

The primary source of energy in the world is based on fossil fuels, with harmful effects both for the environment and for society itself, due to the high emissions of greenhouse gases and other polluting emissions derived from the coal combustion process, natural gas, and petroleum derivatives (García *et al.* 2016). The awareness of these environmental problems, the energy crisis, and the tightening of legislation in this regard have promoted research aimed at using biomass for power generation (Faba *et al.* 2014); biomass is non-fossilized organic matter, originated in a spontaneous or provoked biological process (Velázquez-Martí 2018).

A proposal for classifying the most important sources of biomass for energy purposes includes biomass from energy plantations, and biomass from waste or remains of human activities. Energy plantations include herbaceous materials and woody materials. The remains and residues include the following: remains of agricultural crops, forestry

operations, agri-food industries, forest industries, livestock operations, marine products or remains, and human activities (Velázquez-Martí 2018).

Biomass is a source of energy, as it can be transformed into fuel products that are classified as solid, liquid, and gaseous biofuels (Camps and Marcos 2008; Velázquez-Martí 2018). Solid biofuels (firewood, wood chips, pellets, briquettes, and charcoal) are important energy vectors derived from lignocellulosic biomass (Riegelhaupt 2016). Emissions and residues from the combustion process of biofuels from biomass pollute less than fuels derived from oil or coal, which is why they are considered a cleaner source of energy (Velázquez-Martí 2018). Around the world, it is estimated that the annual production of lignocellulosic biomass is approximately 1×10^{10} million tons, and it is the most abundant renewable raw material (Sánchez and Cardona 2008).

In the process of wood industrialization, large amounts of lignocellulosic biomass are generated (Zavala and Cortés 2000), and on few occasions with some local uses (Correa-Méndez *et al.* 2014). These lignocellulosic residues are important for energy generation (Karinkanta *et al.* 2018), but due to the variation in the chemical composition of different types of biomass (Werkelin *et al.* 2005; Spinelli *et al.* 2011), it is necessary to evaluate their properties with a view to using them as biofuels for domestic or industrial uses (Mitchual *et al.* 2014).

Recent studies have released data on particle size, proximate analysis, ultimate analysis, and ash microanalysis of sawdust from coniferous woods and hardwoods, as well as lemon peel residues from fruit processing, and citrus branches and leaves from orchard pruning, collected in different states of the Mexican Republic (Rutiaga-Quñones *et al.* 2020). This same work team has also reported data on the chemical composition of coniferous sawdust (Chávez-Rosales *et al.* 2021), and the characteristics and properties of briquettes made with this coniferous wood sawdust have been discussed (Ramírez-Ramírez *et al.* 2021). Data on the chemical composition of the lignocellulosic materials studied here is scarce, so it is important to know the results of the chemical analysis and based on this, these materials could be used to make densified biofuels, and help the energy transition in Mexico. It is important to know the inorganic material content of the biomass, because the ash content is one of the important factors for classifying densified solid biofuels (ÖNORM 2000; ISO 2014). This work determined the chemical composition of the biomass of hardwoods generated in the process of primary transformation of wood and of citrus residues from orchard pruning. This information will be useful in making pellets or briquettes and will provide baseline data for comparison with other types of biomass.

EXPERIMENTAL

Biomass Samples

This research examined hardwood sawdust—the product of the primary transformation of wood—and residues of citrus fruits obtained from pruning work in orchards, and from a fruit processing company. The biomass samples were collected in different companies and forest ejidos in four states of the Mexican Republic (Quintana Roo, Durango, Veracruz, and Sonora). Table 1 lists the samples in order of collection. Sawdust samples were collected at the following sites: ejido Noh-Bec (sample 1), ejido Petcacab (samples 2 to 5), ejido Tres Garantías (sample 6), Maderas and Tarimas Alba (sample 7), ejido Pueblo Nuevo (sample 8), citrus orchards in Martínez de la Torre (samples 9 to 11), Grupo Altex (sample 12), and Artesanías Don Lupe (sample 13). The

collected material was dried outdoors and was subsequently milled and sieved to use the 40 mesh fraction in the analyses (Mejía-Díaz and Rutiaga-Quiñones 2008).

Chemical Analysis

The extractives content was determined using solvents of increasing polarity by successive extraction in Soxhlet equipment (cyclohexane, acetone, methanol) and finally hot water under reflux, for 6 h in each case (Mejía-Díaz and Rutiaga-Quiñones 2008). Holocellulose (Wise *et al.* 1946) and lignin (Runkel and Wilke 1951) in the material after successive extraction were determined. In the original material, the ash content and pH were determined as per UNE-EN 14775 (2010) Sandermann and Rothkamm (1959), respectively.

High Heating Value Calculation

The calorific value of the biomass samples was calculated using the mathematical model based on the chemical composition (White 1987). For this purpose, the average value of the chemical composition of biomass samples was used.

Statistical Analysis

The analyses were performed in triplicate, and the mean value and standard deviation are reported. No software was used to calculate these values.

Table 1. Origin and Name of the Biomass Samples

Sample	Origin	Scientific Name	Common Name	Biomass Type
1	Quintana Roo	<i>Swartzia cubensis</i> (Britt. and Willson) Standl.	K'atalox	Sawdust
2		<i>Lysiloma latisiliquum</i> L. Benth.	Tzalam	Sawdust
3		<i>Caesalpinia platyloba</i> S. Watson	Chackté-Viga	Sawdust
4		<i>Manilkara zapota</i> (L.) v. Royen	Chicozapote	Sawdust
5		<i>Swartzia cubensis</i> (Britt. and Willson) Standl.	K'atalox	Sawdust
6		<i>Swietenia macrophylla</i> King	Caoba, Mahagoni	Sawdust
7	Durango	<i>Quercus</i> spp.	Oak	Sawdust
8		<i>Quercus</i> spp.	Oak	Sawdust
9	Veracruz	<i>Citrus x latifolia</i> Tanaka ex Q. Jiménez	Persian lime	Branches
10		<i>Citrus x latifolia</i> Tanaka ex Q. Jiménez	Persian lime	Leaves
11		<i>Citrus x sinensis</i> Osbeck	Orange	Branches
12		<i>Citrus x limon</i> L. Burm	Lemon	Lemon peels
13	Sonora	<i>Olneya tesota</i> A. Gray	Palo fierro	Sawdust

RESULTS AND DISCUSSION

Extractives Content

Table 2 summarizes the results of the successive extraction process with different solvents of increasing polarity. The total of extractives from the biomass samples studied ranged from 8.2% (*Quercus* spp.) to 35.0% (lime leaves). In the case of hardwoods, the total extractives content varied from 8.2% (*Quercus* spp.) to 30.7% (*Olneya tesota*). These

values are close to those reported for different hardwoods from the Mexican southeast (Rodríguez-Jiménez *et al.* 2019). In the case of *Manilkara zapota* and *Swietenia macrophylla*, the values found here are lower than those previously reported (Rutiaga-Quiñones 2001). The total extractives content for the oak samples was 8.2%, which generally matched other reports (Rutiaga-Quiñones *et al.* 2000; Rutiaga-Quiñones 2001; Herrera-Fernández *et al.* 2017; Ruíz-Aquino *et al.* 2020). The extractives content together with the ash content are two important parameters that affect the calorific value of wood, and therefore its use as fuel (Demirbaş and Demirbaş 2004). In the case of materials from pruning, the total extractives content ranged from 10.3% (orange branches) to 35% (lime leaves). Relatively high contents of extractives have been observed in branches and leaves of different tree species (Räisänen and Athanassiadis 2013; Guendehou *et al.* 2014; Cárdenas-Gutiérrez *et al.* 2018).

For all samples except lime leaves and lemon peels, the highest amount of extractives corresponded to the extraction with acetone, followed by methanol (Table 2). This result indicates the presence of components of medium polarity; polyphenolic substances have been detected in these types of extracts in conifers and hardwoods (Kim *et al.* 2008; Rocha-Guzmán *et al.* 2009; Rosales-Castro *et al.* 2009, 2012; Argueta-Solís *et al.* 2018). A high concentration of extractives in acetone and methanol has been observed in previous studies with tropical woods (Rutiaga-Quiñones 2001), oak woods (Rutiaga-Quiñones *et al.* 2000; Rutiaga-Quiñones 2001; Herrera-Fernández *et al.* 2017; Ruíz-Aquino *et al.* 2020), and branches of some tree species (Räisänen and Athanassiadis 2013; Cárdenas-Gutiérrez *et al.* 2018). Essential oils in lemon peel have appreciable antifungal and antibacterial activity (Qadir *et al.* 2018).

Holocellulose Content

The holocellulose content for all samples ranged from 45.4% (lime leaves) to 70.6% (*Lysiloma latisiliquum*) (Table 3). The results for hardwoods ranged from 50.0% (*Olneya tesota*) to 70.6% (*Lysiloma latisiliquum*); these values are higher than those reported for other hardwoods species (Rutiaga-Quiñones 2001; Rodríguez-Jiménez *et al.* 2019). The values found here for the oak samples are close to those reported for oak woods (Rutiaga-Quiñones *et al.* 2000, 2001; Ruiz-Aquino *et al.* 2015). In the case of branch samples, the values found here are similar to those reported in studies carried out with branches of different tree species (Räisänen and Athanassiadis 2013).

Lignin Content

The amount of Runkel lignin in the studied samples ranged from 3.9% (lemon peels) to 25.4% (*Caesalpinia platyloba*) (Table 3). For the hardwood samples, the results ranged from 16.0% (*Lysiloma latisiliquum*) to 25.4% (*Caesalpinia platyloba*), and in general are within the reported range (21.3 to 39.8%) for some tropical woods (Fengel and Wegener 1983). The value obtained for *Lysiloma latisiliquum* is lower than that reported for the same tropical species (19.9%) (Rodríguez-Jiménez *et al.* 2019). The results reported for *Manilkara zapota* (30.7%) and for *Swietenia macrophylla* (31.1%) (Rutiaga-Quiñones 2001) are higher than those found here in the samples of the same tropical species. For the oak samples, the results obtained are in the range reported for some oak species (21.4%) (Rutiaga-Quiñones *et al.* 2000), (22.4 to 23.8%) (Rutiaga-Quiñones 2001), (14.7 to 19.4%) (Herrera-Fernández *et al.* 2017), (14.9 to 16.8%) (Ruíz-Aquino *et al.* 2020). The lignin content in the branch samples is within the interval found in branches of different tree species from 20.8% (Downy birch) to 22.8% (Scots pine) (Räisänen and Athanassiadis

2013), and 17.6% (*Quercus rugosa*) to 28.9% (*Q. candicans*) (Cárdenas-Gutiérrez *et al.* 2018). The result of the Runkel lignin content in lemon peels and leaves should be taken with caution, because no protein was determined here and no adjustment was made, and it is known that the presence of protein has been detected in tree foliage (Fengel and Wegener 1983; Tzvetkova and Hadjiivanova 2006). The contribution of lignin improves the properties of biomass fuels; combustion calorimetry shows that the pyrolysis of lignin has a higher calorific value (Varfolomeev *et al.* 2015; Herrera-Fernández *et al.* 2017). Approximately 95% of the world's lignin production is used to produce energy through cogeneration systems, while the remaining 5% is marketed for the formulation of adhesives, dispersants, surfactants, and rubbers (Tribot *et al.* 2019).

Table 2. Extractives Content in Biomass Samples (%)

Sample	Origin	Cyclohexane	Acetone	Methanol	Hot Water	Total
1	Quintana Roo	0.4 ± 0.10	4.8 ± 0.74	4.3 ± 0.18	1.6 ± 0.14	11.1 ± 0.97
2		0.3 ± 0.12	4.3 ± 0.85	2.1 0.30	3.4 ± 0.04	10.1 ± 0.46
3		5.5 ± 1.08	6.5 ± 0.74	2.4 ± 0.18	2.2 ± 0.25	16.6 ± 0.78
4		1.9 ± 0.03	5.9 ± 0.28	3.2 ± 0.51	1.9 ± 0.01	12.9 ± 0.85
5		2.5 ± 0.04	6.0 ± 0.63	2.9 ± 0.08	1.7 ± 0.33	13.1 ± 0.83
6		1.1 ± 0.01	7.1 ± 0.37	2.9 ± 0.13	2.8 ± 0.07	13.9 ± 0.44
7	Durango	0.2 ± 0.05	3.6 ± 0.56	1.4 ± 0.19	3.0 ± 0.26	8.2 ± 0.68
8		0.3 ± 0.01	3.4 ± 0.21	1.6 ± 0.20	2.9 ± 0.01	8.2 ± 0.42
9	Veracruz	4.7 ± 0.21	14.8 ± 0.36	1.6 ± 0.15	3.3 ± 0.21	24.4 ± 0.51
10		8.0 ± 0.65	3.9 ± 1.2	1.8 ± 0.37	21.3 ± 0.96	35.0 ± 1.95
11		0.5 ± 0.08	4.5 ± 0.67	1.1 ± 0.23	4.2 ± 0.82	10.3 ± 0.30
12		1.6 ± 0.59	3.0 ± 0.58	1.0 ± 0.25	23.1 ± 0.83	28.7 ± 1.75
13	Sonora	0.6 ± 0.04	22.0 ± 0.39	4.8 ± 0.13	3.3 ± 0.07	30.7 ± 0.55

Ash Content

The mineral content of all samples ranged from 0.4% (orange branches) to 6.3% (lemon peels) (Table 3). The values for the hardwood samples ranged from 1.0% (*Quercus* spp.) to 3.4% (*Manilkara zapota*). The ash content in tropical woods is usually higher than in pine woods, and the results found here generally coincide with data for tropical woods (Fengel and Wegener 1983; Rodríguez-Jiménez *et al.* 2019). The amount of inorganic substances in the oak samples are lower than the results reported for different oak species (Rutiaga-Quiñones *et al.* 2000, 2001; Herrera-Fernández *et al.* 2017; Ruíz-Aquino *et al.* 2020). In the case of branches, the results obtained here are within the range found in branches of different tree species (0.08% in *Quercus rugosa*, 1.3% in *Q. candicans*) (Cárdenas-Gutiérrez *et al.* 2018). Inorganic substances are concentrated in the foliage of

trees, compared with wood or bark, and the results obtained here agree with data reported for leaves of different tree species (Guendehou *et al.* 2014).

The ash content of woody biomass varies from 0.5 to 3% of dry weight (Chandrasekaran *et al.* 2012); however, Vassilev *et al.* (2010), report ash content on a dry basis above 10%. The ash content present in the biomass is important for the calculation of the amount of waste that will be generated after the combustion process and for the design of the boilers (Velázquez-Martí 2018). The ash content in biomass is also important because high ash content corresponds to a lower calorific value (Martínez-Pérez *et al.* 2015; Velázquez-Martí 2018), in addition to influencing the quality of densified solid biofuels (Obernberger and Thek 2010). Depending on the ash content, there is a classification for pellets (ISO 2014) and for briquettes (ÖNORM 2000). Thus, biomass with ash content less than 0.7% (Table 3) could be used to make class A1 pellets. Biomass with ash content less than 1.5% (Table 3) to make class A2 pellets, while biomass with ash content less than 3.0% (Table 3) to make class pellets B, according to ISO 17225-2 (ISO 2014). Biomass with ash content less than 0.5% (Table 3) could be used to make briquettes, according to ÖNORM 7135 (ÖNORM 2000).

Table 3. Holocellulose, Lignin, Ash, pH, and Calorific Value (HHV) in Biomass Samples

Sample	Origin	Holo-cellulose	Runkel Lignin	Ash (%)	pH	HHV (MJ/kg)
1	Quintana Roo	62.3 ± 0.16	20.4 ± 0.17	1.3 ± 0.01	5.2 ± 0.10	21.0
2		70.6 ± 1.55	16.0 ± 0.58	3.3 ± 0.02	4.9 ± 0.14	19.8
3		63.9 ± 0.60	25.4 ± 0.79	2.2 ± 0.03	5.2 ± 0.08	20.9
4		63.8 ± 0.60	24.6 ± 0.31	3.4 ± 0.03	5.6 ± 0.07	20.6
5		64.0 ± 0.67	23.8 ± 0.53	2.5 ± 0.02	5.1 ± 0.04	20.5
6		64.4 ± 0.83	22.7 ± 0.37	2.1 ± 0.02	5.6 ± 0.04	20.5
7	Durango	69.7 ± 0.47	18.4 ± 0.54	3.1 ± 0.01	5.7 ± 0.02	19.8
8		69.8 ± 0.38	18.8 ± 0.02	1.0 ± 0.02	5.4 ± 0.05	19.8
9	Veracruz	63.4 ± 0.01	17.2 ± 0.01	0.5 ± 0.18	6.4 ± 0.31	20.8
10		45.4 ± 0.55	15.5 ± 0.46	6.1 ± 0.34	6.5 ± 0.17	21.4
11		69.5 ± 0.20	21.2 ± 0.61	0.4 ± 0.03	7.3 ± 0.01	20.2
12		64.2 ± 0.96	3.9 ± 0.34	6.3 ± 0.62	6.0 ± 0.19	20.1
13	Sonora	50.0 ± 0.37	23.3 ± 0.53	1.4 ± 0.22	5.7 ± 0.03	21.7

In addition to knowing the amount of ash in the biomass, it is important to know the chemical elements present in its ash. In the organic phase there are six elements (C, H, N, S, Cl, and O) and in the inorganic phase there are at least nine chemical elements (Si, Al, Ti, Fe, Ca, Mg, Na, K, and P), which serve to characterize a biomass (Velázquez-Martí 2018). Elemental analysis of these same biomass samples studied here was recently reported, and sulfur was not found in the samples. In this study it is concluded that the biomass samples have low nitrogen content, and low environmental impact is speculated when using this biomass to generate densified solid biofuels (Rutiaga-Quiñones *et al.* 2020). In this study, Cl was not detected, which is scarce in wood (Obernberger *et al.* 2006) and its concentration in biomass ranges from 0.01 to 2.3% (Khan *et al.* 2009). On the other hand, the chemical elements detected in these same biomass samples are also disclosed: Al (all samples), As (samples 1, 2, and 5), B, Ba, and Ca (all samples), Cr (samples 1 to 8, 10 to 13), Cu, Fe, K, Li, Mg, and Mn (all samples), Mo (samples 1 to 5, 12 and 13), Na, Ni (all samples), Pb (samples 4 to 9, 11 to 13), Si (all samples except sample 9), Sr (all

samples), V (simple 3, 7, 8, 11, 12), and Zn (all samples, except sample 9). A high concentration of K is found (Rutiaga-Quiñones *et al.* 2020), which would limit the use of this biomass to produce densified biofuels due to the problems of melting point, deposit formation, aerosols and emission of fine particles (Oberberger and Thek 2004); Van Lith *et al.* 2006), however, high K content in ash can be advantageous for use as a fertilizer (Camps and Marcos 2008).

pH Value

The pH value for all biomass samples studied ranged from 5.1 (*Swartzia cubensis*) to 7.3 (Orange branches) (Table 3). These values are in the 3.7 (*Pterocarpus soyauxii*) to 8.2 (*Terminalia superba*) range for some hardwoods (Fengel and Wegener 1983). The pH in hardwoods ranged from 5.1 (*Swartzia cubensis*) to 5.7 (*Olneya tesota*) and corresponds to a weakly acidic pH (Kollmann 1959). The pH reported for *Manilkara zapota* (5.5) and for *Swietenia macrophylla* (5.3) (Rutiaga-Quiñones 2001) is close to the values found here. There was no evidence of the effect of pH on the biofuels properties, but it is known that it is an important indicator of the use of wood due to its interaction in preservation process, pulping, adhesion, plastification, and fibre- and particleboard production (Fengel and Wegener 1983).

High Heating Value Calculation

The calorific value for all samples ranged from 19.8 MJ/kg (*Lysiloma latisiliquum* and *Quercus* spp.) to 21.7 MJ/kg (*Olneya tesota*) (Table 3). Values reported for different tropical woods range from 16.2 MJ/kg (*Neomillspaughia emarginata*) to 18.5 MJ/kg (*Lonchocarpus yucatanensis*), calculated with a mathematical model based on the elemental composition of biomass (Rodríguez-Jiménez *et al.* 2019), and are lower to those calculated here. The result obtained for the oak samples is higher than the average value reported for oak woods (17.7 MJ/kg) (Herrera-Fernández *et al.* 2017). On the other hand, the calorific value calculated for the branch samples is close to the data reported for branches of different biomass (19.6 MJ/kg for almond branches, 19.1 MJ/kg for citrus branches, and 22.1 MJ/kg for branches olive trees) (Velázquez-Martí 2018). Finally, the calorific values of the biomass samples studied agreed with the typical range for woody hardwood materials (19.4 to 20.4 MJ/kg) and with the typical range for woody residues from hardwood pruning (19.5 to 20.0 MJ/kg) (UNE-EN 14961-1 2011).

CONCLUSIONS

1. In all biomass samples except oak, the content of extractives is relatively high (10.1% for *Lysiloma latisiliquum* to 35% for Persian lime leaves), and it represents a potential for future study and applications in the field of antioxidants.
2. Due to the content of mineral substances, the biomass of the Persian lime (Sample 9) and orange branches (Sample 11) could be used to make class A1 pellets (ash content less than 0.7%) or briquettes (ash content less than 0.5%).
3. Biomass with ash content lower than 1.5% (*Swartzia cubensis*, sample 1), and *Olneya tesota*, simple 13) could be used to obtain class A2 pellets, while biomass with ash content lower than 3.0% (*Lysiloma latisiliquum* (sample 2), *Swartzia cubensis* (sample 5), and *Swietenia macrophylla* (sample 6)) could be used in the production of class B

pellets.

4. Due to the chemical properties and calorific values, the biomass samples studied show potential for local use as densified biofuels.

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REFERENCES CITED

- Argueta-Solís, M. G., Aguilar, C. N., Pintor-Ibarra, L. F., Chávez-González, M., Rojas-Molina, R., Wong-Paz, J. E., Pedraza-Bucio, F. E., and Rutiaga-Quiñones, J. G. (2018). “Inhibición de la oxidación de lípidos y constituyentes fenólicos relacionados en la madera y la corteza de tres especies de encino (*Quercus candicans*, *Q. laurina* y *Q. rugosa*) [Inhibition of lipid oxidation and related phenolic constituents in the wood and bark of three oak species (*Quercus candicans*, *Q. laurina*, and *Q. rugosa*)],” *Agrociencia* 52(5), 757-766.
- Camps, M. M., and Marcos, M. F. (2008). *Los Biocombustibles[Biofuels]* (2nd Ed.), Ediciones Mundi-Prensa, Madrid, Spain.
- Cárdenas-Gutiérrez, M. A., Herrera-Bucio, F. E. P.-B. R., López-Albarrán, P., Rutiaga-Quiñones, J. G., Correa-Méndez, F., and Herrera-Bucio, R. (2018). “Chemical components of the branches of six hardwood species,” *Wood Res.* 63(5), 795-808.
- Chandrasekaran, S. R., Hopke, P. K., Rector, L., Allen, G., and Lin, L. (2012). “Chemical composition of wood chips and wood pellets,” *Energ. Fuels* 26(8), 4932-4937. DOI: 10.1021/ef300884k
- Chávez-Rosales, J. S., Pintor-Ibarra, L. F., González-Ortega, N., Orihuela-Equihua, R., Lujan-Álvarez, C., and Rutiaga-Quiñones, J. G. (2021). “Chemical composition of *Pinus* spp. sawdust from five regions of Mexico, for bioenergetic purposes,” *BioResources* 16(1), 816-824. DOI: 10.15376/biores.16.1.816-824
- Correa-Méndez, F., Carrillo-Parra, A., Rutiaga-Quiñones, J. G., Márquez-Montesino, F., González-Rodríguez, H., Jurado-Ybarra, E., and Garza-Ocañas, F. (2014). “Contenido de humedad y sustancias inorgánicas en subproductos maderables de pino para su uso en pélets y briquetas [Moisture and inorganic substance content in pine timber products for use in pellets and briquettes],” *Rev. Chapingo Ser. Cie.* 20(1), 77-88. DOI: 10.5154/r.rchscfa.2013.04.012
- Demirbaş, A., and Demirbaş, A. H. (2004). “Estimating the calorific values of lignocellulosic fuels,” *Energ. Explor. Exploit.* 22(2), 135-143. DOI: 10.1260/2F0144598041475198
- Faba, L., Díaz, E., and Ordoñez, S. (2014). “Transformación de biomasa en biocombustibles de segunda generación [Transformation of biomass into second generation biofuels],” *Madera Bosques* 20(3), 11-24. DOI: 10.21829/myb.2014.203148

- Fengel, D., and Wegener, G. (1983). *Wood-Chemistry, Ultrastructure, Reactions*, Walter de Gruyter, Berlin, Germany.
- García, C. A., Riegelhaupt, E., and Masera, O. (2016). “Introducción [Introduction],” in: *Estado del Arte de la Bioenergía en México*, Red Temática de Bioenergía (RTB) del CONACYT., C.A. García Bustamante and O. Masera (eds.), Imagia Comunicación, Guadalajara, México, pp. 9-14.
- Guendehou, G. H. S., Liski, J., Tuom, M. I., Moudachirou, M., Sinsin, B., and Mäkipää, R. (2014). “Decomposition and changes in chemical composition of leaf litter of five dominant tree species in a West African tropical forest,” *Trop. Ecol.* 55(2), 207-220.
- Herrera-Fernández, A. C., Carrillo-Parra, A., Pedraza-Bucio, F. E., Correa-Méndez, F., Herrera-Bucio, R., López-Albarrán, P., and Rutiaga-Quiñones, J. G. (2017). “Densidad, composición química y poder calorífico de la madera de tres especies de encino (*Quercus candicans*, *Q. laurina* y *Q. rugosa*) [Density, chemical composition and calorific value of three oak wood species (*Quercus candicans*, *Q. laurina*, and *Q. rugosa*)],” *Ciencia Nicolaita* 72, 136-154.
- ISO 17225-2 (2014). “Solid biofuels – Fuel specifications and classes,” International Organization for Standardization, Geneva, Switzerland.
- Karinkanta, P., Ämmälä, A., Illikainen, M., and Niinimäki, J. (2018). “Fine grinding of wood – Overview from wood breakage to applications,” *Biomass. Bioenerg.* 113(6), 31-44. DOI: 10.1016/j.biombioe.2018.03.007
- Khan, A. A., Jonga, W. D., Jansens, P. J., and Spliethoff, H. (2009). “Biomass combustion in fluidized bed boilers: Potential problems and remedies,” *Fuel Process Technol.* 90(1), 21-50. DOI: 10.1016/j.fuproc.2008.07.012
- Kim, J. I., Kim, H. H., Kim, S., Lee, K. Y., Ham, I. H., and Whang, W. K. (2008). “Antioxidative compounds from *Quercus salicina* Blume Stem,” *Arch. Pharm. Res.* 31, 274-278. DOI: 10.1007/s12272-001-1152-2
- Kollmann, F. (1959). *Tecnología de la Madera y sus Aplicaciones [Wood Technology and its Applications]*, Ministerio de Agricultura – Instituto Forestal de Investigaciones y Experiencias, Madrid, Spain.
- Martínez-Pérez, R., Pedraza-Bucio, F. E., Orihuela-Equihua, R., López-Albarrán, P., and Rutiaga-Quiñones, J. G. (2015). “Calorific value and inorganic material of ten mexican wood species,” *Wood Research* 60(2), 281-292.
- Mejía-Díaz, L. A., and Rutiaga-Quiñones, J. G. (2008). “Chemical composition of *Schinus molle* L. wood and kraft pulping process,” *Rev. Mex. Ing. Quím.* 7(2), 145-149.
- Mitchual, S. J., Frimpong-Mensah, K., and Darkwa, N. A. (2014). “Evaluation of fuel properties of six tropical hardwood timber species for briquettes,” *J. Sustain. Bioenergy Syst.* 4(1), 1-9. DOI: 10.4236/jsbs.2014.41001
- Obernberger, I., and Thek, G. (2004). “Physical characterisation and chemical composition of densified biomass fuels with regard to their combustion behaviour,” *Biomass. Bioenerg.* 27(6), 653-669. DOI: 10.1016/j.biombioe.2003.07.006
- Obernberger, I., Brunner, T., and Bärnthaler, G. (2006). “Chemical properties of solid biofuels—significance and impact,” *Biomass. Bioenerg.* 30(11), 973-982. DOI: 10.1016/j.biombioe.2006.06.011
- Obernberger, I., and Thek, G. (2010). *The Pellet Handbook*, Earthscan, London, England.
- ÖNORM M 7135 (2000). “Compressed wood or compressed bark in natural state-pellets and briquettes, requirements and test specifications,” Österreichisches Normungsinstitut [Austrian Standards Institute], Vienna, Austria.

- Qadir, R., Anwar, F., Mehmood, T., Shahid, M., and Zahoor, S. (2018). "Variations in chemical composition antimicrobial and haemolytic activities of peel essential oils from three local *Citrus* cultivars," *Pure Appl. Biol.* 7(1), 282-291. DOI: 10.19045/bspab.2018.70034
- Ramírez-Ramírez, M. A., Carrillo-Parra, A., Ruíz-Aquino, F., Pintor-Ibarra, L. F., González-Ortega, N., Orihuela-Equihua, R., Carrillo-Ávila, N., Luján-Álvarez, and Rutiaga-Quiñones, J. G. (2021). "Valorization of briquettes fuel using *Pinus* spp. sawdust from five regions of Mexico," *BioResources* 16(2), 2249-2263. DOI: 10.15376/biores.16.2.2249-2263.
- Räisänen, T., and Athanassiadis, D. (2013). "Basic chemical composition of the biomass components of pine, spruce and birch," *Forest Refine.* 1-4.
- Riegelhaupt, E. (2016). "Biocombustibles sólidos [Solid biofuels]," in: *Estado del Arte de la Bioenergía en México. Red Temática de Bioenergía (RTB) del CONACYT.*, C. A. García Bustamante, and O. Masera (eds.), Imagia Comunicación, Guadalajara, México, pp. 23-33.
- Rocha-Guzmán, N. E., Gallegos-Infante, J. A., González-Laredo, R. F., Reynoso-Camacho, R., Ramos-Gómez, M., García-Gasca, T., Rodríguez-Muñoz, M. E., Guzmán-Maldonado, S. H., Medina-Torres, L., and Lujan-García, B. A. (2009). "Antioxidant activity and genotoxic effect on HeLa cells of phenolic compounds from infusions of *Quercus resinosa* leaves," *Food Chem.* 115, 1320-1325. DOI: 10.1016/j.foodchem.2009.01.050
- Rodríguez-Jiménez, S., Duarte-Aranda, S., and Canché-Escamilla, G. (2019). "Chemical composition and thermal properties of tropical wood from the Yucatán dry forests," *BioResources* 14(2), 2651-2666. DOI: 10.15376/biores.14.2.2651-2666
- Rosales-Castro, M., González-Laredo, R. F., Rocha-Guzmán, N. E., Gallegos-Infante, J. A., Peralta-Cruz, J., and Karchesy, J. J. (2009). "Evaluación química y capacidad antioxidante de extractos polifenólicos de cortezas de *Pinus cooperi*, *P. engelmannii*, *P. leiophylla* y *P. teocote* [Chemical evaluation and antioxidant capacity of polyphenolic extracts from barks of *Pinus cooperi*, *P. engelmannii*, *P. leiophylla*, and *P. teocote*]," *Madera Bosques* 15(3), 87-105.
- Rosales-Castro, M., González-Laredo, R. F., Rocha-Guzmán, N. E., Gallegos-Infante, J. A., Rivas-Arreola, M. J., and Karchesy, J. J. (2012). "Antioxidant activity of fractions from *Quercus sideroxyla* bark and identification of proanthocyanidins by HPLC-DAD and HPLC-MS," *Holzforschung* 66, 577-584. DOI: 10.1515/hf-2011-0157
- Ruiz-Aquino, F., González-Peña, M. M., Valdez-Hernández, J. I., Revilla, U. S., and Romero-Manzanares, A. (2015). "Chemical characterization and fuel properties of wood and bark of two oaks from Oaxaca, Mexico," *Ind. Crop. Prod.* 65, 90-95. DOI: 10.1016/j.indcrop.2014.11.024
- Ruiz-Aquino, F., Luna-Bautista, L., Luna-Bautista, A. E., Santiago-García, W., Pintor-Ibarra, L. F., and Rutiaga-Quiñones, J. G. (2020). "Anatomical characterization, physical, and chemical properties of wood of *Quercus macdougalii* Martínez, endemic species of the Sierra Juárez of Oaxaca, Mexico," *BioResources* 15(3), 5975-5998. DOI: 10.15376/biores.15.3.5975-5998
- Runkel, R., and Wilke, Y. K. D. (1951). "Zur Kenntnis des thermoplastischen Verhaltens von Holz [To know the thermoplastic behavior of wood]," *Holz als Roh- und Werkstoff* 9(7), 260-270. DOI: 10.1007/BF02617370
- Rutiaga-Quiñones, J. G., Pintor-Ibarra, L. F., Orihuela-Equihua, R., González-Ortega, N., Ramírez-Ramírez, M. A., Carrillo-Parra, A., Carrillo-Ávila, N., Navarrete-García, M.

- A., Ruíz-Aquino, F., Rangel-Méndez, J. R., *et al.* (2020). “Characterization of Mexican waste biomass relative to energy generation,” *BioResources* 15(4), 8529-8553. DOI: 10.15376/biores.15.4.8529-8553
- Rutiaga-Quiñones, J. G., Windeisen, E., and Strobel, C. (2000). “Composición química del duramen de la madera de *Quercus candicans* Neé [Chemical composition of the heartwood of *Quercus candicans* Neé wood.],” *Madera Bosques* 6(2), 73-80.
- Rutiaga-Quiñones, J. G. (2001). *Chemische und biologische Untersuchungen zum Verhalten dauerhafter Holzarten und ihrer Extrakte gegenüber holzabbauenden Pilzen* [Chemical and biological investigations on the behavior of durable wood species and their extracts towards wood degrading fungi], Buchverlag Gräfelfing, Germany.
- Sánchez, Ó., and Cardona, C. (2008). “Trends in biotechnological production of fuel ethanol from different feedstocks,” *Bioresource Technol.* 99(13), 5270-5295. DOI: 10.1016/j.biortech.2007.11.013
- Sandermann, W., and Rothkamm, M. (1959). “Über die Bedeutung der pH-Werte von Handelsholzern und deren Bedeutung für die Praxis [About the importance of the pH values of commercial timber and their importance in practice],” *Holz als Roh- und Werkstoff* 17(11), 433-440. DOI: 10.1007/BF02605386
- Spinelli, R., Nati, C., Sozzi, L., Magagnotti, N., and Picchi, G. (2011). “Physical characterization of commercial woodchips on the Italian energy market,” *Fuel* 90(6), 2198-2202. DOI: 10.1016/j.fuel.2011.02.011
- Tribot, A., Amer, G., Alio, M. A., de Baynast, H., Delattre, C., Pons, A., Mathias, J. D., Callois, J. M., Vial, Ch., Michaud, P., and Dussap, C. G. (2019). “Wood-lignin: Supply, extraction processes and use as bio-based material,” *Eur. Polym. J.* 112, 228-240. DOI: 10.1016/j.eurpolymj.2019.01.007
- Tzvetkova, N., and Hadjiivanova, Ch. (2006). “Chemical composition and biochemical changes in needles of Scots pine (*Pinus sylvestris* L.) stands at different stages of decline in Bulgaria,” *Trees* 20, 405-409. DOI: 10.1007/s00468-006-0052-8
- UNE-EN 14775 (2010). “Método para la determinación del contenido en cenizas [Method for the ash content determination],” Asociación Española de Normalización y Certificación (AENOR), Madrid, Spain.
- UNE-EN 14961-1 (2011). “Especificaciones y clases de combustibles. Parte 1: Requisitos generales [Fuel specifications and classes. Part 1: General requirements],” Asociación Española de Normalización y Certificación (AENOR), Madrid, Spain.
- Van Lith, S. C., Alonso, V., Jensen, P. A., Frandsen, F. J., and Glarborg, P. (2006). “Release to the gas phase of inorganic elements during wood combustion. Part 1: Development and evaluation of quantification methods,” *Energ. Fuel.* 20(3), 964-978. DOI: 10.1021/ef050131r
- Varfolomeev, M. A., Grachev, A. N., Makarov, A. A., Zabelkin, S. A., Emel’yanenko, V. N., Musin, T. R., Gerasimov, A. V., and Nurgaliev, D. K. (2015). “Thermal analysis and calorimetric study of the combustion of hydrolytic wood lignin and products of its pyrolysis,” *Chem. Tech. Fuels and Oil* 51(1), 140-145. DOI: 10.1007/s10553-015-0586-9
- Vassilev, S. V., Baxter, D., Andersen, L. K., and Vassileva, C. G. (2010). “An overview of the chemical composition of biomass,” *Fuel* 89(5), 913-933. DOI: 10.1016/j.fuel.2009.10.022
- Velázquez Martí, B. (2018). *Aprovechamiento de la Biomasa para uso Energético [Exploitation of Biomass for Energy Use]* (2nd Ed.), Editorial Reverté, Barcelona,

Spain.

- Werkelin, J., Skrifvars, B.-J., and Hupa, M. (2005). "Ash-forming elements in four Scandinavian wood species. Part 1: Summer harvest," *Biomass Bioenerg.* 29(6), 451-456. DOI: 10.1016/j.biombioe.2005.06.005
- White, R. H. (1987). "Effect of lignin content and extractives on the higher heating value of Wood," *Wood Fiber Sci.* 19(4), 446-452.
- Wise, L. E., Murphy, M., and D'Addieco, A. A. (1946). "Chlorite holocellulose, its fraction and bearing on summative wood analysis and on studies on hemicelluloses," *Paper Trade J.* 122(2), 35-43.
- Zavala, D. Z., and Cortés, R. H. (2000). "Análisis del rendimiento y utilidad del proceso de aserrío de trocería de pino [Analysis of the performance and utility of the pine log sawing process]," *Madera Bosques* 6(2), 41-55. DOI: 10.21829/myb.2000.621374

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