Article

The Bioenergetic Potential of Four Oak Species from Northeastern Mexico

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Received: 1 August 2019; Accepted: 27 September 2019; Published: 3 October 2019

Abstract: Lack of knowledge regarding the fuel quality of diverse tree species prevents their use. Furthermore, the potential use of wood with the bark of different tree species for pellet production is still relatively unexplored in the scientific literature. In Mexico, the sawdust of *Quercus* genus (oak) is underutilized, despite it being an important forest resource, due to some anatomical and technological characteristics. The sawdust of *Quercus* with bark is also considered to have a low economic value. The objective of this study was to analyze the energy characteristics of barked and debarked *Quercus sideroxyla*, *Q. rugosa*, *Q. laeta*, and *Q. conzattii* in order to evaluate their potential for pellet production. Granulometric distribution, bulk density, proximal analysis, and calorific value tests were carried out. The sawdust of the four tree species studied was in accordance with the limits established by the standard EN 14961-2. Sawdust with a particle size of 0.425 mm had the highest percentage of retained mass (30.33%) ($p < 0.05$) in the granulometry test. There were no statistical differences in granulometry ($p > 0.05$) between barked and debarked sawdust for all *Quercus* species. Barked sawdust presented higher bulk density ($p < 0.05$) than debarked sawdust (246 and 224 kg/m³, respectively). The moisture content did not show statistical differences ($p > 0.05$) between barked and debarked sawdust. The volatile material was higher ($p < 0.05$) in debarked sawdust (88.7%) than in barked sawdust (85.0%). The ash content was below 0.5%. The fixed carbon was higher ($p < 0.05$) in barked sawdust (14.6%). The calorific value was higher ($p < 0.05$) in barked sawdust and for the *Q. rugosa* species (19.5 MJ/kg). The results suggest that the oak species analyzed, both barked and debarked, showed good potential for pellet production. Future studies should quantify fuel quality for a variety of diameter distributions, and analyze pellet mechanical properties and ash slagging risk.

Keywords: bioenergy; solid biofuels; oaks

1. Introduction

Biomass is considered to be the renewable energy source with the highest potential to contribute to the energy needs of modern society for both industrialized and developing countries worldwide [1]. However, biofuels have low bulk densities, which limit their use to areas around their origin. Moreover, their heterogeneity is considerable in terms of moisture and granulometry, among others. These drawbacks are restrictive factors for their energy use [2]. To improve its energetic characteristics,

the densification of biomass is performed in cylinders called pellets, which are made of pulverized wood or agriculture biomass residues with or without additives, resulting in increased energy density [2–4]. The regular geometry and standard size of pellets (generally with diameters between 6–10 mm and lengths of 5–40 mm) [5] allow compact storage, reducing handling and transport costs and allowing automatic feeding in large-scale unit operations [3,4,6].

In the period between 2006–2015, the global production of wood pellets increased from 6–7 to 25.6 million tons [7]. This growth in pellet consumption has resulted in more variety in the use of raw materials for pellet manufacture [2]. There is an increasing interest in finding new raw materials suitable for pelletizing to further expand new potential pellet markets [8,9]. Nevertheless, the production and use of fuel pellets from diverse feedstocks has not been fully explored worldwide. Thus, further research and analysis is needed [4].

The evaluation of the suitability of feedstocks for the production of pellets requires an evaluation of the chemical and physical parameters affecting biofuel quality, which can largely vary between different tree species [2,3,10–14] and are also influenced by location, age, genetics, and the section of the tree [15–17].

Pellet quality is determined by the characteristics of the raw material and the production conditions [15,18,19], which are evaluated by international standards such as UNE-EN 14961 [20] and CAN/CSA-ISO 17225-2 [21], which mention the requirements and specifications that the raw material must accomplish to be used as quality solid biofuel. The chemical composition, ash content, and calorific value of firewood are the characteristics with the greatest influence on the behavior of a biofuel [22]. Higher ash content lowers the heating value and creates problems such as clinker formation, sintering, and dust emissions [4,23,24]. In addition, moisture content, density, and particle size also influence the energy efficiency [24]. Moreover, feedstock moisture content has an impact on pellet density and durability [6,15,25–27] and influences net calorific value and combustion efficiency [4,28]. The particle size distribution of the raw material can impact the pellet compression strength [25,29–31], durability [32–36], and pellet consumption rates [31].

In order to widen the raw material base and reduce the pellet production cost, it should be advantageous to utilize the whole log, including bark [37], which represents a considerable proportion of tree species [38]. However, the manufacture of wood pellets with bark can generate uncertainty, since the properties of the bark can modify the quality of the pellets produced. For example, increasing the bark content of pellets may increase the ash content, but may have a positive effect on the calorific value due to the increased content of lignin and extractives [37], and prolong the heat and mass transfer process compared to the wood particles [39]. Furthermore, the mechanical durability of pellets may also be affected by adding bark in raw material, as presented by Lehtikangas [29] and Filbakk et al. [37]. For this reason, the characterization of the biomass with bark and without bark it is extremely important for the pellet producer.

On the other hand, the percentage of bark on the tree is dependent on the species, stem diameter, and bark thickness [38]; it also varies from the base to top and even between branches, as demonstrated by Miranda et al. [40], who presented lower amounts of ashes and fixed carbon and higher percentage of volatiles for larger branches. Thus, the bark consists of different ratios of physicochemical composition than those of steam wood [41].

Traditional wood raw materials for pellets contain mostly sawdust without bark [37,42]. In recent years, some studies have analyzed pellet production based on tree bark [14,29,37,43]. For example, Filbakk et al. [37] studied the effect of bark content at different percentages on the wood pellets quality of *Pinus sylvestris*. They found that increments of ash content related to increasing bark content. Fernández et al. [44] investigated the energetic potential of new biomass sources using *Quercus ilex*. Relova et al. [45] studied the influence of the particle size of *Pinus caribea* bark in biomass compaction process. Likewise, Correa-Méndez et al. [46] studied the granulometric distribution on forest by-products including barked sawdust of *Quercus* spp. reporting statistical differences between sieve sizes. Nevertheless, such studies analyzing the quality of barked and debarked wood as potential

feedstocks for pelletization are still comparatively scarce, and have not covered the variety of tree species potentially available for pellet production.

The use of wood for energy purposes in Mexico is still very limited compared to the potential of residues from forest logging and forest industries [47–50]. In particular, the *Quercus* genus is considered the second most important timber forest resource after *Pinus* genus [51]. Oak wood could have a high commercial value when properly processed. However, this genus shows problems related to wood drying, brushing, chipping, and milling [52,53]. Therefore, its most common use in Mexico is currently as firewood and charcoal. For this reason, there is a need to evaluate the energetic potential and fuel quality of the main oak species in Mexico for the production of pellets. Likewise, it would also allow the more efficient utilization of these species for bioenergy production and expand the potential feedstocks for biofuel production in the country.

The aim of this work was to analyze the energetic characteristics of barked and debarked *Quercus sideroxyla*, *Q. rugosa*, *Q. laeta*, and *Q. konzattii* which are common in the Sierra Madre Occidental, México, to characterize their suitability to produce densified solid biofuels. In particular, the study analyzed the granulometric distribution, bulk density, moisture content, volatile matter, ash content, fixed carbon, and calorific value of barked and debarked sawdust of four oak species.

2. Materials and Methods

2.1. Study Area

Four logs of one meter in length of diameter at breast height (DBH) >25 cm belonging to the species *Quercus sideroxyla*, *Q. rugosa*, *Q. laeta*, and *Q. konzattii*, were randomly collected by motor-manual harvesting system from the logging areas of El Pinito, El Tule, El Nopal, and Llano Blanco ejidos belonging to the municipality of Guadalupe y Calvo, Chihuahua and from the locality of Nicolas Romero, Durango, Mexico.

2.2. Preparation and Characterization of Biomass

For each log, the diameter and percentage of bark was measured (Table 1). The diameter was measured at the base, in the middle, and at the top of all the logs per species, and the average was calculated. The percentage of stem wood was calculated from the area obtained from two measurements of the diameter with bark at the base of the log. The percentage of bark was calculated from the difference in the total stem-wood area minus the stem-wood area without bark. Logs were cut into two equal parts and seasoned on laboratory conditions; one half was debarked and the other half remained unbarked. All logs were manually cracked and chipped with an Industrial Duty SD4P25T61Y machine. Sawdust was produced with a TFS 420 hammer mill with a 3.15-mm screen.

Table 1. Average diameter, stem-wood, and bark proportion of the transversal section of four *Quercus* species.

Variable	Species			
	<i>Q. sideroxyla</i>	<i>Q. rugosa</i>	<i>Q. laeta</i>	<i>Q. konzattii</i>
Diameter	32.4	29.8	35.4	30.3
% Stem wood	88.3	90.1	97.1	95.3
% Bark	11.7	9.9	2.9	4.7

2.3. Granulometric Distribution and Bulk Density

The determination of the physical properties was carried out with one kilogram of sawdust of each treatment. The granulometric analysis was carried out with the following sieves: mesh 8 (2.36 mm), mesh 20 (0.850 mm), mesh 40 (0.425 mm), mesh 60 (0.250 mm), mesh 80 (0.180 mm), mesh

100 (0.150 mm), and mesh 200 (0.075 mm). Three repetitions of 150 g per treatment were used according to the norm EN-17827-2 [54].

The bulk density tests were carried out in triplicate in a 600-mL metallic cylinder following the procedure established by the standard EN-17828 [55], in which the container filled with sawdust is subjected to three hits over a flat surface in order to tamp contents.

2.4. Immediate Analysis

The moisture content was measured according to EN 18134-3 [56]. Samples were weighed on a 0.1-mg precision scale before and after being dried in an oven for four hours at 105 ± 2 °C.

The volatile matter was measured following the standard EN-18123 [57], in which the samples were subjected to a temperature of 900 ± 10 °C for seven minutes. The ash content was measured according to the standard EN-18122 [58]. In this procedure, the samples were initially weighed and were left in a muffle at 250 °C for one hour to release the volatiles; then, the temperature was increased to 550 °C for two hours, and the final weight is taken. Although there is no standard for measuring the fixed carbon content in wood, it is obtained by subtracting from the sum of the volatile material, moisture, and the ash content from 100% [59].

2.5. Calorific Value

The calorific power of the samples was calculated in an isoperbolic calorimeter LECO model AC600 according to the standard EN-14918 [60].

2.6. Statistical Analysis

Kolmogorov–Smirnov and Shapiro–Wilk normality tests and analysis of variance were performed to all the variables. The granulometric distribution was analyzed following a factorial design ($7 \times 4 \times 2$), where the factors were particle size (7), species (4), and bark content (2). The treatments were compared with the non-parametric Kruskal–Wallis test. The variables of bulk density, moisture content, volatile material, ash content, fixed carbon, and calorific value were analyzed carried out following factorial designs (4×2). Here, the factors were species (4) and bark content (2). A one-way analysis of variance (ANOVA) was applied, and Tukey tests were used to perform multiple means comparisons, except on ash content, for which the Kruskal–Wallis test was applied. All the tests were carried out with a significance level (α) of 5% with the statistical program RStudio® version 2.13.1 [61].

3. Results

3.1. Granulometry

The sawdust granulometric distribution of the four *Quercus* species showed statistical differences ($p < 0.05$) between particle sizes (Table 2). Sawdust with a particle size of 0.425 mm had the highest percentage (30.3%) (Figure 1). On the other hand, there were no statistical differences ($p > 0.05$) on the percentage of each particle size, neither between species nor between barked and debarked sawdust.

Table 2. Normality test and statistical analysis of the granulometric distribution of sawdust of four oak species.

Granulometric Distribution	Kolmogorov–Smirnov Test		Kruskal–Wallis Test					
			Particle Size		Species		Bark Content	
	Statistic	p-Value	chi-squared	p-Value	chi-squared	p-Value	chi-squared	p-Value
Retained mass	0.24682	1.384×10^{-10}	175.1	2.20×10^{-16}	0.25415	0.9684	0.28771	0.5917

Figure 1. Sawdust granulometric distribution of four oak species: (a) barked; (b) debarked. (Bars with different letters correspond to statistically different relative mass; $p < 0.05$).

3.2. Bulk Density

Bulk density showed statistical differences ($p < 0.05$) (Table 3) between species and between barked and debarked sawdust (Figure 2). *Quercus laeta* species barked had the higher density (259 kg/m^3) followed by *Q. rugosa* (254 kg/m^3). On the other hand, barked sawdust presented higher bulk density than debarked sawdust (246 and 224 kg/m^3 , respectively).

Table 3. Normality tests and statistical analysis of bulk density, proximal analysis, and calorific value of four oak species and bark content.

Property	Shapiro-Wilk Test		Kruskal-Wallis Test				ANOVA Test					
			Species		Bark Content		Species		Bark Content		Interaction Species: Bark Content	
	Statistic	p	χ^2	p	χ^2	p	F	p	F	p	F	p
BD	0.95193	0.2982	-	-	-	-	9.77	0.0004	13.1	0.0015	2.91	6.68×10^{-2}
MC	0.95247	0.3062	-	-	-	-	10.38	0.0002	1.263	0.273	2.19	6.50×10^{-6}
VM	0.96771	0.6109	-	-	-	-	0.884	0.446	24.98	5×10^{-5}	4.37	0.01986
A	0.85644	0.002885	7.98	0.0464	0.03	0.8625	-	-	-	-	-	-
FC	0.97071	0.6846	-	-	-	-	0.844	0.486	24.68	6×10^{-5}	4.3618	0.01999
CV	0.92223	0.06544	-	-	-	-	6.141	0.0039	10.96	0.0032	2.94	6.48×10^{-2}

BD = Bulk Density, MC = Moisture Content, VM = Volatile Matter, A = Ash, FC = Fixed Carbon, CV = Calorific Value, p = p -value, χ^2 = chi-squared, F = F value.

Figure 2. Sawdust bulk density of four barked and debarked oak species. (bars with different letters correspond to statistically different densities; $p < 0.05$).

3.3. Moisture Content

The moisture content showed statistical differences ($p < 0.05$) between species, while there were no statistical differences between barked and debarked sawdust ($p > 0.05$) (Figure 3a and Table 3). The average values ranged between 4.8%–5.7%, in which *Q. rugosa* debarked was the smallest, and *Q. conzattii* debarked had the highest content.

3.4. Volatile Matter

The volatile matter content of sawdust of the four oak species did not show significant statistical differences ($p > 0.05$). However, there were significant statistical differences ($p < 0.05$) between barked and debarked sawdust (Figure 3b and Table 3). Debarked sawdust showed an average volatile matter content of 88.6%, while barked sawdust had an average volatile matter content of 85.0%.

3.5. Ash Content

The ash content showed statistically significant differences between species ($p < 0.05$), while no significant statistical differences were found between barked and debarked sawdust ($p > 0.05$) (Table 3). All barked and debarked species presented values lower than 0.5% (Figure 3c). *Quercus laeta* showed the higher ash content (0.4%), followed by *Q. conzattii*, *Q. rugosa* and *Q. sideroxylla* with 0.3%.

3.6. Fixed Carbon

There were no significant differences ($p > 0.05$) in fixed carbon content between species (Figure 3d). However, there were statistical significant differences ($p < 0.05$) between barked and debarked sawdust (Table 3). Barked sawdust showed a higher content (14.6%), while the fixed carbon content for debarked sawdust was lower (11.0%).

Figure 3. (a) Moisture content; (b) Volatile matter; (c) Ash content; (d) Fixed carbon of four barked and debarked oak species (bars with different letters correspond to statistical significant differences; $p < 0.05$).

3.7. Calorific Value

There were significant differences ($p < 0.05$) for the calorific value between species and between bark content (Figure 4 and Table 3). Barked *Quercus rugosa* presented the highest average calorific value (19.5 MJ/kg), followed by *Q. sideroxylla* (19.2 MJ/kg), *Q. conzattii* (18.8 MJ/kg), and *Q. laeta* (18.6 MJ/kg); barked oak species had a higher calorific value.

Figure 4. Calorific value of four barked and debarked oak species (bars with different letters correspond to statistically different calorific values; $p < 0.05$).

4. Discussion

4.1. Physical Properties

The granulometric distribution of the sawdust of the four *Quercus* species (Figure 1) presented the same pattern reported by Correa-Méndez et al. [46] in a mixture of bark and wood of *Quercus* spp., by Santiago-Hansted et al. [62] for the species *L. leucocephala* and *G. piptadenia*, and by Miranda et al. [63] for *Quercus pyrenaica*, in which the higher percentage of retained mass was in the particle size of 0.425 mm. Holm et al. [64] found the highest retention (about 25%) of particles greater than 1.0 mm for hardwoods. Higher retention could be a problem by blocking the pellet matrix, because the particle size is related with the process of wood machining [46]. Obernberger and Thek [65] mentioned that particle sizes less than 5 mm are suitable for producing pellets. On the contrary, particles larger than 5 mm may have cracking points that cause breakage and fractures in pellets [66]. Therefore, pellets produced with small particle sizes have better hardness than those made of large particles [35,67]. However, an increase of the percentage in the use of small particles is not always beneficial for the quality of the pellet [36].

The particle size plays an important role in the durability and density of the pellets, since it contributes significantly to the hardness [35] as a result of the increase of the interatomic adhesion forces (van der Waals forces, dipole–dipole forces, and hydrogen bonds) [36]. On the other hand, finer particles tend to absorb more moisture than longer particles, requiring prolonged conditioning processes [33,68], while the spaces between larger particles can result in a thermal insulator that reduces the heat transfer during the pelleting process [45]. In contrast, Mani et al. [25] and Lehtikangas [29] did not find a significant effect of particle size distribution on pellet density. Although our study aim was not to know the relationship between particle size and density or durability, future studies might analyze such relationships, together with its possible impact on energy consumption, pellet energy consumption, or combustion rates [43].

Several authors [33,35,46] recommended the use of sawdust with different particle sizes and with different raw materials, since the pellet quality could be improved because of stronger bonds generated between large and small particles, reducing the spaces between them.

The bulk density is another important factor of pellet quality, since higher bulk densities of sawdust lead to better transport efficiency, smaller storage spaces, and a higher density of the pellets produced [69,70].

The barked sawdust of the four *Quercus* species showed higher bulk density than debarked sawdust (Figure 2). This is due to the presence of fewer spaces in the internal structure of the bark

particles, so they are denser than bark-free wood particles [39]. In solid wood, Lerma-Arce et al. [14] and Miranda et al. [40] mentioned that neither the tree fraction nor the presence of bark have a significant influence on bulk density, which depends mainly on species. However, Şen et al. [71] indicated that the complexity of the structural tissue of wood and bark are key features that must be taken into account when contemplating the uses of the bark.

Values of the bulk density of *Quercus* species were within the range reported for other species. For example, Baptista et al. [72] reported a bulk density of 209 kg/m³ for *Tectona grandis* bark. Miranda et al. [73] reported values of 227 kg/m³ and 169 kg/m³ for the bark of *Betula pendula* and *Eucalyptus globulus*, respectively. They also documented for spruce and pine barks mean bulk densities of 258 kg/m³ and 202 kg/m³ [67]. Ferreira et al. [74] presented an average bulk density of 197 kg/m³ for the bark of *Pseudotsuga menziesii*. On the other hand, Sette et al. [75] reported bulk density values for bark and wood from *Eucalyptus urograndis* of 250 kg/m³ and 260 kg/m³ respectively.

It must be taken into account that density is a physical property that could affect the compaction process [2] and cannot be modified in its values (unlike moisture content or particle size). This because it is a peculiar characteristic of each material when is processed [45], and results from the inherent physical structure of the raw material [76].

4.2. Immediate Analysis

Values in moisture content (Figure 3) were lower than 5.5% to 6.6%, as reported by Filbakk et al. [37] and Relova et al. [45], as well as the within the range of 9%–11% reported for pine wood with bark by Agar et al. [77]. On the other hand, Lerma-Arce et al. [14] found that the moisture content is significantly influenced by the presence of bark, because the barks are known to be less hydrophilic than wood, which could mean less water absorption [42]; however, the above was not observed in this investigation.

The moisture content is one of the most important parameters for the mechanical durability of pellets [78]. The moisture content of the raw material is always higher than that of the pellets manufactured, which is due to the evaporation produced by the heating of the matrix in the process of pelletization [79]. On the other hand, moisture content has different effects: if the moisture content is too low, the friction between the sawdust and the matrix will be high, which will increase the energy consumption. Also, the sawdust in the matrix could burn out and the holes in the matrix might be clogged, or thermal insulation could occur, which prevents heat transfer [45]. On the contrary, if the moisture content is high, it will increase the costs and the drying time (when it is done at open air). In addition, the raw material becomes slippery and cannot be easily compacted [29]. After all, the moisture content of sawdust is a variable that can and should be optimized [14,78].

The values of volatile material for barked and debarked sawdust were found to be in the range of 82% to 91% (Figure 4), and they were similar to values reported by different authors [6,75,80–83]. Values below the average reported here were found by Forero-Núñez et al. [84] (76.82%) and Demirbas [85] (66.6%). The fact that barked sawdust had less volatile material was reported by Feng et al. [86]. This can be attributed to the presence in the bark of significant amounts of lignin and extracts [29,37], which have a slow devolatilization rate [87], occurring in higher temperature ranges than those recorded during pelleting [88,89]. It is known that volatile matter takes part in the combustion process of biomass, directly affecting the performance and physical stability [50,84]. Thus, a high content of volatile matter would imply a rapid ignition of the biofuel, but also its conversion into powder [6,84], which is a disadvantage. On the other hand, lower values of volatile matter will create difficulties in the ignition process of biofuel. For example, Graham et al. [90] mentioned that a decrease in volatile matter can contribute to a weakening of interfacial forces, adhesion and cohesion forces, solid bridges, and interlocking forces.

The ash content was below 0.5% for both barked and debarked sawdust of the four species of oak (Figure 3c), which is in accordance with the requirement specified by the standard EN 14961-2 [91] for its conversion into non-industrial pellets and with class A1 ($\leq 0.7\%$). The values reported for the ash

content for oaks are diverse; Rutiaga-Quiñones et al. [92] reported a value of 0.9% for *Q. candicans*. Ruiz-Aquino et al. [93] found values from 0.3% to 0.95% for *Q. laurina* and *Q. crassifolia* species. Herrera-Fernández et al. [94] mentioned that the ash content for some species of oaks reaches 1.0%.

Some studies presented differences in ash content between barked and debarked wood: Barmpoutis et al. [95] reported values of 1.62% and 1.14% for wood and 12.18% and 9.15% for *Q. coccifera* and *Q. ilex* barks, respectively. Also, Fernández et al. [44] found for *Q. ilex* wood a value of 1.8%. Serret-Guasch et al. [96] mentioned an ash content of 0.5% to 2.0% for sawdust from the forestry industry. Also, Gil et al. [81] reported values in the range from 0.2% to 0.5%. The variation in the ash content may be due to physiological adaptations to the soil hydric potential conditions of different species [53].

The ash content is, by itself, a parameter that helps to determine quickly the quality of the biofuel. High ash contents are associated with low energetic values, and can negatively affect combustion [18,97,98]. Several authors have attributed the high ash content to the proportion of bark [14,37,82,86,94], causing slag formation, fouling, and sintering [34,59,99], and negatively affecting the milling and pelletizing equipment. However, in the present work, ash contents were low for the barked sawdust of the four oak species. This can possibly be attributed to the fact that the logs analyzed had low percentages of bark (Table 1). In this sense, Filbakk et al. [37] reported ash values of 0.45% in mixtures of 95% wood and 5% bark of *Pinus sylvestris*, which is consistent with the values reported here. In addition, Lerma-Arce et al. [14] found values of 0.46% for logs with diameters greater than 20 cm of *Pinus pinaster* with bark. Eimil-Fraga et al. [100] and Werkelin et al. [101] mentioned that the basal diameter has a significant effect on the ash content mainly because the bark content increases with smaller diameters [38]. In addition, Miranda et al. [40] reported for *Quercus pyrenaica* branches that lower diameters correspond to higher ash content. Qin et al. [41] also found no significant differences in the ash content in pellets produced with bark and without bark, and attributed it to the fact that the raw material had a bark proportion of less than 5%.

The fixed carbon values (Figure 3) were similar to those reported by Carrillo-Parra et al. [59], Gil et al. [81], and Miranda et al. [63] for oaks. However, they were lower than the reported value by Sette et al. [75] for wood and eucalyptus bark (17.3% and 16.7% respectively). They were higher than the values reported by Amirta et al. [80] for the bark of biomass residues (3.39%) and for olive wood reported by García-Maraver et al. [6] (1.0%).

Fixed carbon is the result of the release of volatile matter, excluding ash and moisture content [102]. Therefore, it is the most important parameter in terms of potential energy, because high fixed carbon contents are associated with high caloric powers [84]. On the other hand, low fixed carbon values are attributed to high ash contents [80]. Therefore, while the bark contains less volatile matter and a higher percentage of fixed carbon, higher calorific values would be expected in bark than in wood [86], which is consistent with the values reported here.

4.3. Calorific Value

The calorific value of the four studied oak species using barked and debarked sawdust (Figure 4) was higher than the lower limit established by the standard EN 14961-2 [91] (16.5 to 19.0 MJ/kg). Therefore, this species can be used as a raw material for transformation into densified biofuel for domestic or industrial applications. These results are in accordance with those reported by different authors [40,44,97,103,104]. Herrera-Fernández et al. [94] found values below those found here of ~17 MJ/kg for three species of oak. The values reported here for the calorific value were within the range proposed by Telmo and Lousada [3], ranging from 17.63 MJ/kg to 20.80 MJ/kg, for hardwoods.

The calorific value is a parameter that establishes the amount of energy released during the complete combustion of a given material [103]. Thus, this trait is used to evaluate the competition of several biofuels in the market [105]. The fact that barked sawdust has a higher calorific value than debarked sawdust can be attributed to the content of extractives and lignin in the bark, which have a better calorific value than cellulose [37].

5. Conclusions

The fuel quality properties analyzed of sawdust of barked and debarked *Q. sideroxylla*, *Q. laeta*, *Q. rugosa*, and *Q. conzattii* suggest good potential to produce densified solid biofuels. The particles are considered suitable for the densification processes, and immediate analysis values indicated good properties for their conversion into densified solid biofuels.

In this research, we used logs with diameters higher than 25 cm, which are common in the final harvest of oak forests. It is recommended that future studies might analyze the variations in fuel quality with tree diameter to establish fuel qualities expected for dominated trees or for material obtained through intermediate silvicultural treatments such as thinning, which is mainly performed in mixed pine-oak forests.

In general, the results presented of the energy characteristics were individual; however, because the species are not isolated the nature, the role of blending ratios of barked/debarked oak sawdust, combined with other feedstocks (e.g., pine sawdust) on the pelletizing process, pellet quality, and combustion behavior should also be analyzed in future studies.

Author Contributions: Conceptualization, V.D.N.-R. and A.C.-P.; Methodology, V.D.N.-R., C.-P., J.G.-Q.; Validation, C.W. and D.J.V.-N.; Formal analysis, V.D.N.-R.; Investigation, V.D.N.-R., A.C.-P., C.W., and D.J.V.-N.; Resources, A.C.-P.; Writing—original draft preparation, V.D.N.-R. and A.C.-P.; Writing—review and editing, C.W. and D.J.V.-N.; Supervision, J.G.-Q.; Funding acquisition, A.C.-P.

Funding: This research was funded by Fondo de Sustentabilidad Energética, grant number SENER-CONACYT 2014 246911 Clúster de Biocombustibles Sólidos para la generación térmica y eléctrica y CONACYT project 166444.

Acknowledgments: We thank CONACYT for the student scholarship and to Clúster de Biocombustibles Sólidos for funding.

Conflicts of Interest: The authors declare no conflict of interest.

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