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Avocado Tree Pruning Pellets (*Persea americana* Mill.) for Energy Purposes: Characterization and Quality Evaluation

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Abstract: The energy use of fruit tree pruning represents a current alternative to achieving an energy transition toward clean biomass resources, which can substitute for fossil fuels and mitigate polluting emissions. In Mexico, avocado is one of the most important fruit crops, with approximately 260,000 ha planted. The pruning of avocado trees generates large amounts of biomass that are not fully exploited, lacking studies that analyze in depth the energy potential of pruning. This study aims to determine the potential energy use of avocado pruning as densified solid biofuels. The physical, chemical and energetic properties of two pruning fractions defined as class B (branches) and class BAL (branches and leaves) were determined. From class B, pellets were made, and their physical and mechanical properties were determined. Subsequently, the evaluated parameters of the pellets obtained were compared to European quality regulations to determine their quality and identify their potential uses. The characterization of avocado pruning indicates that class B generally has better physicochemical characteristics than class BAL to be used as solid biofuel. It was found that class B has a high calorific value (19.61 MJ/kg) and low ash content (1.2%), while class BAL contains a high amount of ash (7.2%) and high levels of N (1.98%) and S (1.88%). The manufactured pellets met most of the quality requirements for immediate use in the residential, commercial and industrial sectors at the regional level.

Keywords: fuel pellet; densified solid biofuels; lignocellulosic residues; ash characterization; thermogravimetric analysis (TGA-DTG)

Citation: Soria-González, J.A.; Tauro, R.; Alvarado-Flores, J.J.; Berrueta-Soriano, V.M.; Rutiaga-Quiñones, J.G. Avocado Tree Pruning Pellets (*Persea americana* Mill.) for Energy Purposes: Characterization and Quality Evaluation. *Energies* **2022**, *15*, 7514. https://doi.org/10.3390/en15207514

Academic Editor: Dino Musmarra

Received: 10 September 2022
Accepted: 9 October 2022
Published: 12 October 2022

1. Introduction

The sustainable energy transition based on renewable energies places bioenergy as an alternative that plays an important role in achieving a reduction in the consumption of fossil fuels and global patterns of production and consumption [1]. The use of agricultural and agro-industrial residues for energy production can represent a reduction in dependence on the use of fossil fuels but also a decrease in environmental pollution [2]. The use of this type of waste avoids the use of agricultural land, which prevents the generation of competition with the food sector [3], in addition to producing lower greenhouse gas (GHG) emissions during its life cycle [3–5]. Currently, large amounts of agricultural residues are often left in the field to rot or to be burned in the open air, ultimately releasing carbon dioxide into the atmosphere [5,6].

Recently, the use of residues generated from fruit tree pruning for energy purposes has gained increased interest. These lignocellulosic materials can be used in gasification processes, or cellulose and hemicellulose hydrolysis processes to obtain bioethanol, however, they are mostly used as solid biofuels [3] due to their lower production cost. Mexico has a wide variety of fruit tree crops, of which are mainly orange, mango, avocado and lemon [7], but there is currently little knowledge regarding the use of pruning residues generated for this type of crop. Avocado is one of the most important fruit crops in terms of cultivated area in the country, with approximately 260,000 ha planted, where the state of Michoacan is the main producer with an area of approximately 183,000 ha [8]. Regarding avocado, many studies focus on the use of seeds and peels for the production of liquid and gaseous biofuels [3], without considering pruning residues as raw material. Avocado pruning residues currently do not have a proper use; in many cases, they are moved to the outskirts of the orchards to await degradation or are simply burned, which not only lacks benefit but accrues costs through management and the generation of polluting emissions. Recently, for the avocado growing region in Michoacán, Mexico, the availability of pruning residues has been estimated between 780 and 1245 kg/ha of biomass on a dry basis per year, considering an average number of 100 trees per ha [9]. However, planting density can be up to 180 trees/ha [10], so the amount of biomass generated could be even higher.

Fruit tree prunings, like other agricultural residues, are an important source of biomass that could be used for the production of solid biofuels; however, despite being able provide large volumes of usable biomass with consistent properties, they are limited in their use due to their low density, which translates into high transportation costs [2,11], difficulty in storage, and, given its high moisture content, becomes an unsuitable material for direct use [12]. Given the characteristics of agricultural biomass, it is an ideal candidate for the use of densification technology in pellet format, where in addition to reducing transportation and storage costs, it is possible to improve the properties of the biofuel [2,12,13]. In Mexico, densification technology has been considered an efficient technology alternative for the use of bioenergy as part of the "Transition Strategy to Promote the Use of Cleaner Technologies and Fuels in Mexico" [14]. However, the use of biomass pellets is still in its infancy within Mexico, and there is a lack of information about agricultural and fruit tree pellet production.

Recently, some estimates have been made regarding the availability of avocado pruning residues in the avocado growing region of Michoacán, Mexico [10]; however, no studies focus on the characterization and utilization of avocado pruning residues as feedstock for densified solid biofuels for energy purposes. In the present study, biomass from avocado tree prunings (branches) was used to produce densified solid biofuels (pellets). The main goal was to characterize the biomass, as well as the elaboration and evaluation of the quality of the pellet based on the criteria of international standards [15,16], to finally identify its potential use.

2. Materials and Methods

2.1. Study Site and Biomass Origin

Figure 1 shows the map of the study site, which is located in the municipality of Salvador Escalante, Michoacán, Mexico. The map shows the distribution of the area planted with avocado, and the boundaries of the study area are outlined in red.

The sampled orchards are located at an elevation between 1880 and 2230 m above sea level. Sampling was conducted between October and December 2020. Ten orchards were sampled, and biomass samples were collected from 30 different trees at random. Biomass collection was carried out immediately after each pruning. All the orchards sampled were Hass variety trees, and the orchards were conventionally managed (using agrochemicals as part of their management). The age of the trees sampled ranged from 15 to 30 years. A total of 30 samples were collected from two different pruning fractions: class B (branches with diameters greater than 2.5 cm) and class BAL (branches less than 2.5 cm and leaves). These two biomass fractions are those normally generated during pruning operations. Only class B was considered for the pelletizing process because class BAL is usually shredded and spread around orchards.

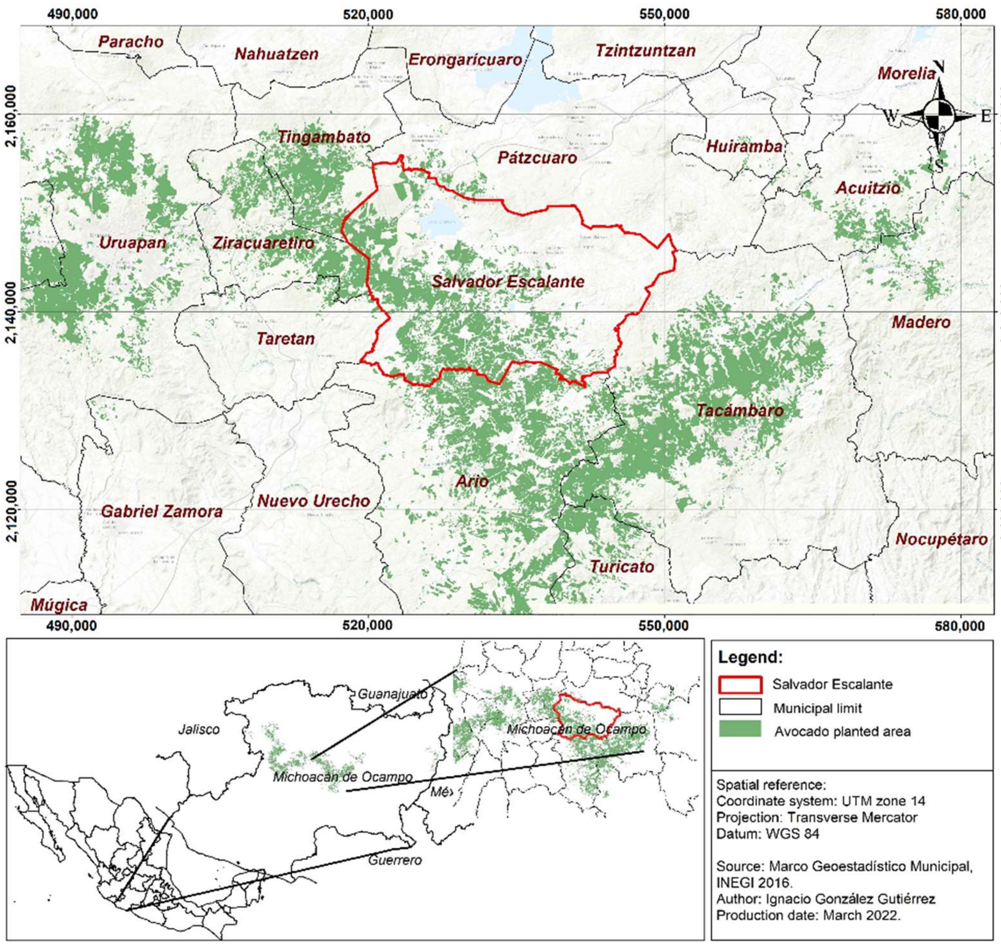

Figure 1. Study site: Salvador Escalante, Michoacán, México.

2.2. Analysis of Pruning

2.2.1. Sample Preparation

Class B and BAL biomass samples were reduced in size and then allowed to air dry and ground in Micron equipment (Micron Mixer, Model K20F, series 236, Micron S.A. de C.V., Mexico City, Mexico). After grinding, the samples were sieved (40 mesh, 425 micron) using ROTAP equipment (Model RX-29, W.S. Tyler, Mentor, OH, USA). This biomass meal was used for chemical and energy analyses, and moisture content was determined in triplicate using a thermobalance (Adam Equipment, model PMB53, Adam Equipment Inc., Oxford, CT, USA). The total moisture content of freshly cut samples was determined in triplicate based on EN 18134-2 [17] in a forced flow oven (Binder GmbH, model BD 260, Tuttlingen, Germany).

2.2.2. Proximate Analysis and Higher Heating Value

Proximate analysis was determined for class B and class BAL: ash content [18], volatile matter content [19] and fixed carbon (determined by difference). The higher heating value (HHV) was determined only for class B based on EN 18125 [20] using a calorimeter (Calorimetric Thermometer Parr, Model 67272, Parr Instrument Company, Moline, IL, USA). These analyses were carried out in triplicate.

2.2.3. Basic Chemical Analysis, Elemental Analysis and Ash Microanalysis

The chemical composition (cellulose, hemicellulose and lignin) of class B and class BAL biomass was determined in duplicate on a fiber analyzer (ANKOM Fiber Analyzer, model ANKON200, ANKOM Technology, Macedon, NY, USA) using α-amylase, based on the method described by Van Soest et al. [21]. The extractive content was calculated by the difference in the ash-free percentage. The percentages of carbon, hydrogen, nitrogen and sulfur were determined by the modified Dumas method [22] using an elemental analyzer (Thermo Fisher Scientific, model Flash 2000 series, Fischer Scientific Inc., Wellesley, Waltham, MA, USA). This analysis was performed only once, and the oxygen content was calculated using the difference in the ash free weight percentage. Ash microanalysis was performed using a Varian Agilent (Model 730-ES, Varian Inc., Mulgrave, Australia) inductively coupled plasma atomic emission spectrophotometer (ICP-AES) [23]. From this methodology, the presence of 29 chemical elements was traced. The concentration of Cl in the biomass was determined volumetrically. The analysis was performed only once.

2.2.4. Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA-DTG) was only performed for class B biomass to analyze the thermal behavior of wood with and without bark. For this purpose, two fractions were separated and denoted as "branches with bark" and "branches without bark". An approximate amount of 30 mg $\pm$ 5 mg of sample (40 mesh) was used and was uniformly placed in an alumina crucible for each test. A simultaneous thermal analyzer (STA 6000, Perkin Elmer Inc., Wellesley, Waltham, MA, USA) was used. Pyrolytic conditions were maintained using reagent grade nitrogen gas (99.99% purity; INFRA, Mexico City, Mexico) with a flow rate of 30 mL/min. A linear heating program was made from 25 to 850 °C at a rate of 10 °C/min and then maintained in isotherm at 850 °C for 10 min. Each test was performed in triplicate. Heating ramps were also performed in triplicate only when the conversion difference was greater than 5% or the data resulted in considerable background noise. OriginPro [24] software was used for data management.

2.3. Pellet Production and Characterization Pruning

For the pelletizing process, approximately 150 kg of branches between 2.5 and 10 cm in diameter (Class B) were collected. These samples were ground and left to air dry. Subsequently, the particle size distribution [25] was determined using a sieve shaker (RO-TAP®, model RX-29, W.S. Tyler, Mentor, OH, USA). Prior to pelleting, sawdust moisture was determined using a Benetech moisture meter (Benetech Inc., model Gm640, Aurora, IL, USA). Finally, pelletizing was carried out with Meelko equipment (type ZLSP200C, Meelko Co., Opa Locka, FL, USA) with a processing capacity of 80 to 120 kg/h. Approximately 70 kg of pellets were obtained.

Length and diameter were determined on a sample of 10 pellets obtained using a digital Vernier (Steren, model HER-411, Azcapotzalco, Edo. de Mexico, Mexico) (EN 17829, 2016) [26]. Moisture content was determined in duplicate on a 1 g sample of pellets using a thermobalance (Adam Equipment, model PMB53, Adam Equipment Inc., Oxford, CT, USA). Particle density was determined using 10 pellets [27], and bulk density was determined in triplicate [28]. The mechanical durability was obtained in triplicate using the overturning test [29].

2.4. Pellet Quality Assessment

The quality of the pellets obtained was evaluated considering the main physical, chemical, energetic and mechanical properties determined in this study, for which the reference values of the ENplus® certification manual [15] and the Spanish standard EN 17225-2 [16] for residential, commercial and industrial use were taken.

2.5. Potential Pellet Uses

The potential uses of pellets were evaluated based on the criteria and recommendations of ENplus [15] and EN 17225-2 [16] for uses in the residential, commercial and industrial sectors. For this purpose, threshold values for each of the evaluated parameters were compared. Additionally, a proposal for the final use of pellets was generated for the study region.

2.6. Statistical Analysis

Statistical analysis of the data was performed using Statistica software [30]. The Shapiro-Wilk test and Levene's test were used to test the normality and homoscedasticity of the data, respectively. An independent Group t test was performed to test for statistically significant differences between biomass classes for proximate analysis and basic chemical analysis. The significance level was $\alpha = 0.05$.

3. Results and Discussion

3.1. Analysis of Pruning

3.1.1. Total Moisture Content

The total moisture content obtained for class B (63.47 $\pm$ 1.65) and class BAL (68.41 $\pm$ 1.37) indicates a statistically significant difference. These results agree with previous reports that reported moisture content values are higher than 60% in samples obtained from freshly cut prunings [31]. Moisture content and calorific value have an inversely proportional linear correlation with each other, so high moisture levels are not favorable [32]. Moisture is a limitation for directly used biofuel because it affects parameters, such as density and calorific value, in addition to its influence on combustion efficiency [2,5].

3.1.2. Proximate Analysis and Higher Heating Value

Table 1 shows the results of proximate analysis for class B and class BAL and shows significant differences for moisture, ash and volatile matter. The ash content of the B class differs from the BAL class by 6% (Table 1). The higher percentage of ash found in the BAL class is attributed to the presence of leaves. Ash content has been reported for branches (0.88–3.4%) [9,33], branches with leaves (6.3%) and leaves (6.9%) [9], where samples with leaves have the highest concentrations. A high ash content is undesirable for most thermal utilization systems, as it can cause fouling, corrosion, slagging or scaling in equipment and can also decrease equipment efficiency [34,35]. In domestic boilers, they can cause scaling issues and decrease their efficiency or even damage them [34].

Table 1. Proximate analysis of both classes of biomass samples (%).

Class	Moisture	Ash	Volatile Matter	Fixed Carbon
B	6.57 $\pm$ 0.27 a	1.22 $\pm$ 0.04 a	83.87 $\pm$ 0.64 a	8.34 $\pm$ 0.55 a
BAL	7.39 $\pm$ 0.26 b	7.22 $\pm$ 0.10 b	75.80 $\pm$ 1.84 b	9.59 $\pm$ 1.96 a

Different letters in column denote a statistically significant difference, determined from Student's t test ($p < 0.05$).

In the literature, the content of volatile matter for avocado wood has been reported to range from 79.4 to 82.4% [33], which is lower than that obtained here for the B class (Table 1). High levels of volatiles favor the thermal conversion of biomass [36], which makes it an appropriate material for energy utilization [37].

The fixed carbon content for both biomass classes was found to be below 10% (Table 1). For avocado pruning wood, values ranging from 10.9 to 13.8% have been reported [33], and for other types of wood, they range from 15.13 to 19.57% [38–40]. These two ranges of reported values are above the result obtained here for class B (Table 1).

Table 2 shows the results obtained from the determination of the calorific value for class B of the present study, as well as some values reported in the literature for different fractions of woody and nonwoody biomass of the avocado tree. The higher heating value determined for class B (19.61 MJ/kg) is within the range of values reported in the literature for avocado tree woody biomass and below that reported for leaves (Table 2). The value obtained here is very close to the typical average value found for virgin woody materials from cutting residues, specifically for hardwood (19.7 MJ/kg), according to the EN 17225-2 [16] classification. On the other hand, the higher heating value for class B is in the upper portion of the range of values reported for woody biomass from different types of fruit trees:

olive, almond, cherry, kiwi, lemon, loquat, orange, apple, pear, hazel, guava, chicozapote and mango (16.30–20.27 MJ/kg) [31,38–43].

Table 2. Higher heating value for class B biomass and other values reported in the literature for avocado tree biomass.

Biomass	Specification	HHV (MJ/kg)	References
Avocado	Class B	19.6	This study
	Branches	19.2–19.7	[9,33]
	Branches with leaves	19.7	[9]
	Leaves	20.1	
Other fruit trees (olive, almond, cherry, kiwi, lemon, loquat, orange, apple, pear, hazel, guava, chicozapote and mango	Branches	16.30–20.27	[31,38–43]
Pinus spp.	Sawdust	19.69–19.85	[39]
Vid	Branches	18.95	[44]

3.1.3. Basic Chemical Analysis, Elemental Analysis and Ash Microanalysis

Table 3 shows the results of the basic chemical analysis of the two biomass classes studied. Significant differences were found for cellulose, hemicellulose and extractive contents. The BAL class is a pruning fraction containing leaves, which could explain the differences with respect to the B class.

Table 3. Basic chemical analysis for the two biomass classes (%).

Class	Cellulose	Hemicellulose	Lignin	Extractives
B	46.75 ± 1.11 a	20.62 ± 0.21 a	14.45 ± 0.87 a	16.97 ± 0.45 a
BAL	37.55 ± 0.53 b	18.37 ± 0.37 b	13.62 ± 0.01 a	23.24 ± 0.15 b

Different letters in column denote significant difference, determined from Student's *t* test ($p < 0.05$).

Paniagua et al. [33] determined the chemical composition of avocado pruning wood, and they reported a range of values for cellulose (38–45%), hemicellulose (28–37%), lignin (15–27%) and extractives (2–10%). As shown in Table 3, the cellulose content of class B is very close to the upper value reported, while the amount of hemicellulose is below the lower value. The lignin content is very close to the lower limit of the range reported by these researchers.

The lignin concentration in class B biomass is relatively low, compared to values reported for softwoods (25.6–39.4%) and hardwoods (17.6–31.8) [45]. Lignin content may play an important role in some of the pellet quality parameters [46], and it has been reported that pellets made from woody materials with high lignin concentrations and low amounts of extractives also showed high mechanical durability [47]. The results obtained here for class B biomass in extractives and lignin content could explain the relatively low mechanical strength of pellets made from this biomass.

The results of the elemental analysis are shown in Table 4 and generally agree with data reported for various types of lignocellulosic biomass [48]. Class B biomass contains low N and S concentrations (Table 4), which is desirable in biomass that will be used as solid biofuel [16,32], while class BAL contains higher N and S concentrations (Table 4). These results agree with Tauro et al. [9] who, for biomass from avocado prunings, indicated that branches with leaves contain 2.2% N and 0.13% S, while leaf biomass contains 2.6% N and 0.16% S. On the other hand, in pruning residues from guava, hazelnut and olive trees, a range of values between 0.59% and 1.24% for N and between 0.01% and 0.08% for S has been found [31,43,49].

Table 4. Ultimate analysis of both types of biomass samples (%).

Class	C	H	O	N	S
B	46.95	5.95	46.27	0.81	<0.01
BAL	46.26	6.01	43.84	1.98	1.88

The N content is associated with increased NOx emissions [50]; in addition, the N content can also be related to the formation of nitrous oxide (N_2O), which is a greenhouse gas (GHG) [32]. On the other hand, the S content is associated with the generation of emissions and increased corrosion in energy utilization systems [14,51], which can occur when there are high concentrations of SO_2 in flue gases [32].

Figure 2 shows the results of the microanalysis of the ashes. It is known that the ash content in biomass is one of the most important parameters, but it is also relevant to know the microanalysis of the ash, since some chemical elements can cause sintering problems, corrosion of equipment and generation of particulate matter in combustion processes [32]. For the majority of elements, the descending order, P > K > Ca > Fe and K > P > Fe > Ca, is observed for class B and class BAL, respectively (Figure 2a). The chemical elements with the highest concentrations in both biomass types are P and K. The presence of K, Ca and P has also been reported in ashes from residues of other fruit trees, such as branches and leaves of lemon trees and branches of orange trees, where for both cases, the highest concentrations of elements in descending order were K (235,380–281,157 ppm), Ca (22,220–24,031 ppm) and P (5,811–29,480 ppm) [39]. For guava pruning biomass, the presence of K (12,874.41 ppm), P (6640 ppm) and Ca (4289.36 ppm) has been reported [31]. The concentration of Cl in biomass B and BAL is low (Table 5) and complies with the recommended value (<0.02%) of the ENplus [15].

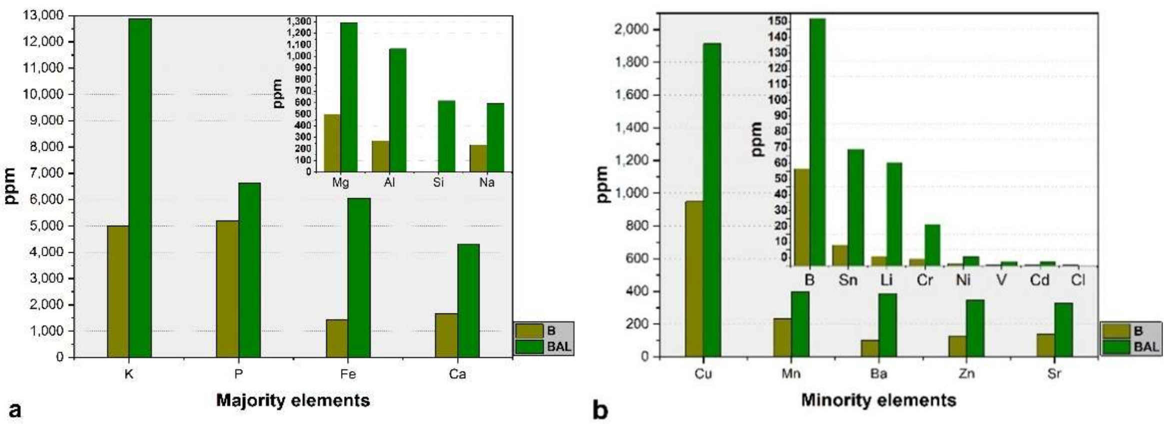

Figure 2. Ash microanalysis of class B and BAL. (**a**) Concentration of major elements, (**b**) concentration of minor elements.

The presence of some heavy metals, such as Cd, Cr, Cu, Sn and Zn, was detected (Figure 2b). The concentration of Cu stands out, compared to other elements, both for class B (948 ppm) and for class BAL (1911 ppm). For pruning biomass from other types of fruit trees, Cu (23.83–113.7 ppm) and Zn (50.92–166.30 ppm) contents have been reported [31,39], where the Cu content is lower than the concentration determined here for class B. The Zn content in class B is within the range of values reported in the literature; however, the BAL class presented high concentrations in Cu and Zn (1911 and 345 ppm, respectively), with respect to the B class. It has been reported that when high Zn concentrations are present, there is a risk of significant impact on human health [52]. The high ash content in the BAL class (Table 1) makes this type of biomass unsuitable for use as solid biofuel. On the other hand, Cu and Zn, as well as other heavy metals, such as Cd and Pb, have been identified as the main aerosol formers that increase the emission of particulate matter in biomass combustion and are also associated with corrosion problems and deposit formation in combustion equipment [53]. Table 5 shows the actual microanalysis concentrations of ash in ppm and the concentration in mg of the element per kg of fuel.

Table 5. Ash microanalysis of class B and BAL.

Element	Concentration in Ash (ppm)		Concentration in Fuel (mg/kg)	
	Class B	Class BAL	Class B	Class BAL
Ag	ND	ND	ND	ND
Al	272.8	1066.12	3.32	77.00
As	ND	ND	ND	ND
B	61.6	156.8	0.75	11.33
Ba	100.5	387	1.22	27.95
Be	ND	ND	ND	ND
Ca	1666.68	4289.36	20.31	309.79
Cd	0.5	2.4	0.01	0.17
Co	ND	ND	ND	ND
Cr	4.1	26.2	0.05	1.89
Cu	948.2	1911.68	11.55	138.07
Fe	1440.17	6061.43	17.55	437.78
K	5017.51	12,874.41	61.13	929.83
Li	5.96	65.4	0.07	4.72
Mg	498.6	1289.31	6.07	93.12
Mn	235.3	398.8	2.87	28.80
Mo	ND	ND	ND	ND
Na	236.7	594.0	2.88	42.90
Ni	1.2	5.6	0.01	0.40
P	5202.63	6640.97	63.39	479.63
Pb	ND	ND	ND	ND
Sb	ND	ND	ND	ND
Se	ND	ND	ND	ND
Si	ND	616.6	ND	44.54
Sn	13.2	73.8	0.16	5.33
Sr	137.7	330.7	1.68	23.88
Tl	ND	ND	ND	ND
V	0.5	2.4	0.01	0.18
Zn	124.4	345.2	1.52	24.93
Cl	0.51	0.17	0.006	0.012

ND = not detected.

It is not known if the high concentration of Cu detected in the samples studied is due to the nature of the biomass or if it could be related to the use of pesticides, which are part of the phytosanitary control of avocado cultivation. Burgos et al. [54] reported that the pesticides used in avocado orchards in the state of Michoacán are usually synthetic, mainly used by producers who maintain a conventional type of cultivation, which is the type of management most used, in comparison with organic management. In addition, some fungicides used for phytosanitary control contain Cu and are foliar applied [55]. However, to relate a high Cu content in avocado biomass to the use of pesticides or other external agents, more specific studies are needed.

3.1.4. Thermogravimetric Analysis (TGA)

Figure 3a shows the weight loss experienced by the bark-covered branches, with respect to temperature. It can be observed that initially, the weight loss up to approximately 117 °C was 6.3%, and this weight loss is attributed to the moisture content of the sample. It can be observed that the greatest weight loss occurred in the temperature range of approximately 175 to 390 °C, with a loss of 64.6%. Finally, near 400 °C onward, thermal decomposition took place in a less important way toward the end of the process at 850 °C.

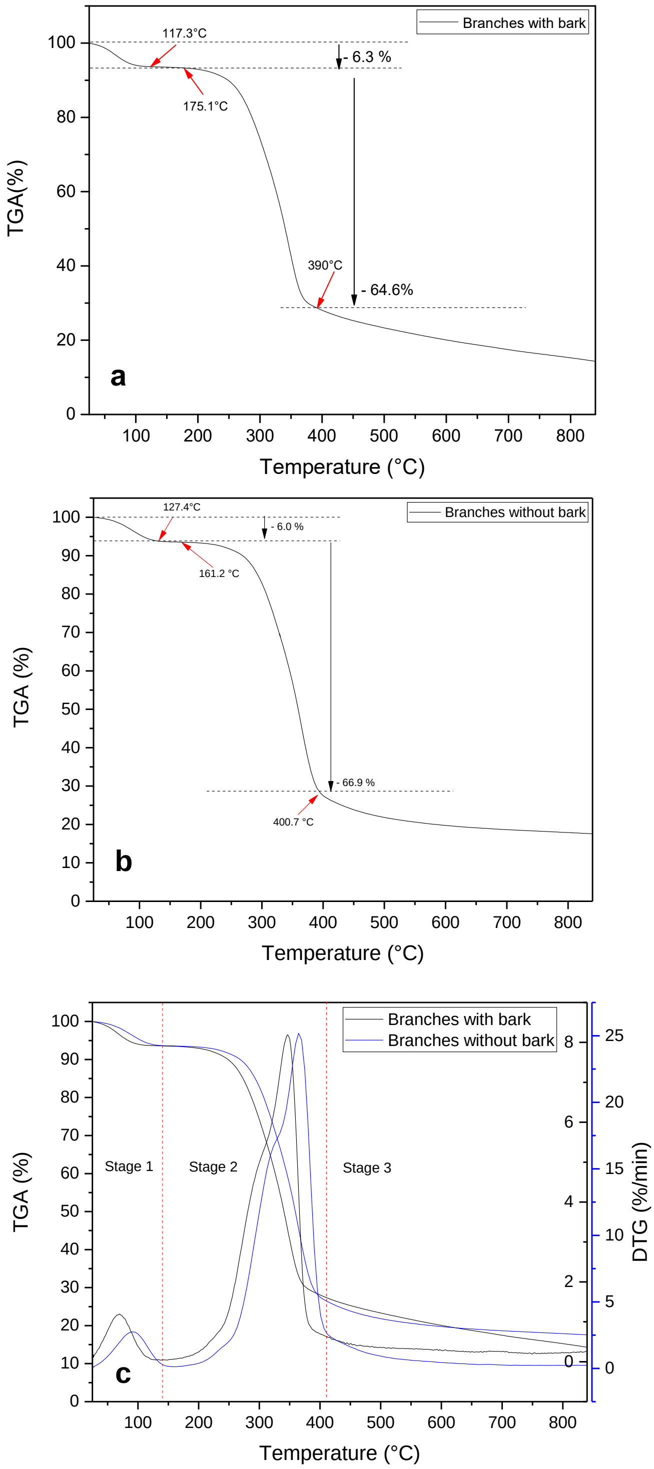

Figure 3. (**a**) TGA curve of branches with bark, (**b**) TGA curve of branches without bark, (**c**) TGA-DTG curves of branches with and without bark and the three stages of the thermal conversion process identified. This is a figure. Schemes follow the same formatting.

The weight loss of the branches without bark (Figure 3b) was 6%, which occurred up to approximately 127 °C; this loss was due to moisture. The most important mass degradation took place in the temperature range of 160 to 400 °C, with 66.9% mass loss. Several authors have reported the initial mass reduction during pyrolysis processes experienced by some woods, with such a reduction between 60 and 85%, that is, for both hardwoods and conifers [56,57].

From the analysis of the TGA–DTG curves, three stages of the thermal conversion process were identified, which are shown in Figure 3c. Stage 1 shows the elimination of moisture, and the smallest peak is observed. In stage 2, the highest peak is located in the region between 280 and 420 °C, where, according to the literature, hemicellulose depolymerization occurs, which despite the different composition of this constituent depending on the specific biomass source, usually occurs from 150 to 350 °C [58], with the main conversion range being 200 to 350 °C [59]. In the DTG plot, a small deformation in the main peak can be observed at a temperature of approximately 300 to 330 °C (Figure 3c). It has been found that for different types of lignocellulosic biomass, such deformation in the main peak is given by the partial superposition of two peaks and is associated with hemicellulose degradation [60,61].

During the second stage, cellulose conversion usually occurs in the range of 275 to 350 °C [58]. In this sense, it has been reported that for the range of 300 to 350 °C, cellulose is generally degraded in some hardwoods [56]. This same stage also presents part of the thermal decomposition of lignin, where the first conversion step is carried out in a range between 200 and 450 °C, where the highest rate of lignin decomposition is usually in the range of 360 to 400 °C [61]. In step 3, a more gradual decomposition was observed as temperature increases, which is attributed to a slower degradation, mostly of lignin, where, according to Kim et al. [58], this range can range from 250 to 500 °C, although it can extend up to 700 °C [56].

According to Figure 3c, for the two fractions studied, different DTG profiles can be observed in both the height of the main peak and the observed horizontal displacement. Since the experimental conditions were the same, the variations are attributed to the presence or absence of crust. In this sense, Arteaga-Pérez et al. [62] found differences in the DTG profiles of the mass degradation of eucalyptus wood and bark under pyrolysis conditions; here, the authors suggest that the difference in the main peak heights can be attributed to a higher ash content, coupled with the different composition between wood lignin and bark lignin. The horizontal shift to the left of the branches with bark can be attributed to a higher content of extractives, particularly tannins, as suggested in the literature [63], or, as reported for the case of *Pinus pinaster*, bark is the more reactive species; therefore, as it decomposes at a lower temperature than wood, it can produce this type of shift, which is attributed to a lower lignin content [64].

3.2. Pellet Production and Characterization

The particle size of class B biomass, obtained prior to pelletizing, is shown in Table 6. According to the results obtained, the fraction representing the highest percentage is 0.50 mm (23%), followed by the 1.40 mm (17.50%) and 2 mm (15.5%) fractions, which together represent approximately 56%. The lowest proportion corresponds to the fines fraction (3.98%). In general, the particle size distribution of this biomass can be considered good for the pelleting process, and it is known that particle sizes smaller than 4 mm can produce pellets with acceptable mechanical properties [37].

Table 6. Class B biomass sawdust particle size distribution.

Mesh (mm)	Retained Fraction	Mean Retained Value (%)	Standard Deviation
3.15	>3.15	7.49	1.27
2.80	2.80–3.15	7.00	0.63
2.00	2.00–2.80	15.52	1.45
1.40	1.40–2.00	17.50	1.28
1.00	1.00–1.40	14.94	0.26
0.50	0.50–1.00	23.07	1.61
0.25	0.25–0.50	10.50	2.01
Tray	<0.25	3.98	1.01

The average pellet length obtained was 15.69 mm (±8.9 mm) (Figure 4). Pellet lengths of different biomass types have been recently reported in the literature, with values ranging from 10.47 to 35.10 mm [37,40,43,48], indicating wide length variability. Values of 47.7 mm have even been reported for apple tree pruning pellets [40]. However, according to ENplus [15] and EN 17225-2 [16], the percentage of pellets with lengths greater than 40 mm should be less than 1%. In Figure 5, it is observed that the largest portion of pellets is in the length ranges > 12 mm and >25 mm (81% in total). In the pellets obtained, the percentage of fines (<3.15 mm) and the percentage of pellets with lengths greater than 40 mm were less than 1%.

Figure 4. Pellets obtained from class B biomass.

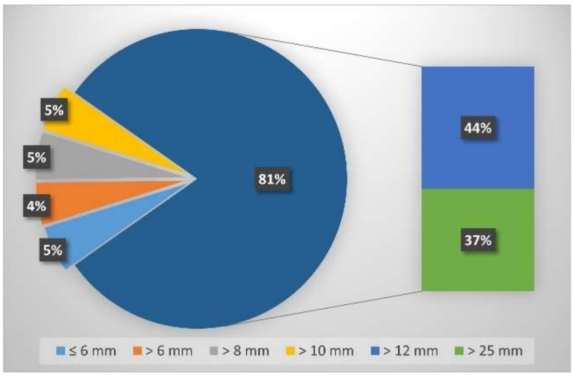

Figure 5. Pellet length distribution.

The average diameter of the pellets obtained was 6.09 mm (±0.03 mm). The pellet diameter is defined by the size of the holes in the extrusion die used in pelletizing [40,50]. However, depending on the type of biomass used, pellets can have slight variations in the final diameter. For example, Carrillo-Parra et al. (2021) [40] reported the quality of 17 types of biomass from different agricultural and forestry sources, where the range of diameters ranged from 5.80 to 6.14 mm.

The results of the physical and mechanical characterization of the pellets are shown in Table 7. The final moisture content of the pellets is slightly above the range of values recently reported in the literature for pellets obtained from fruit tree prunings (4.56–8.68%) [31,40,43,48,65]; such values are below 10%, which is favorable for utilization by combustion [16].

Table 7. Physical and mechanical characterization of pellets.

Parameter	Mean	Standard Deviation
Final moisture content (%)	8.85	0.22
Particle density (g/cm^3) (g/cm^3)	1.19	0.02
Bulk density (kg/m^3) (kg/m^3)	580.97	4.14
Energy density (GJ/m^3) (GJ/m^3)	11.39	0.08
Mechanical durability (%)	86.68	0.19

Particle densities are slightly above those reported for pellets made from apple tree prunings (1.06 g/cm^3) [38] and guava tree prunings (1.05 g/cm^3) [31] but are within the range of values reported for different forest and agricultural sources (1.02–1.37 g/cm^3) [40,64]. According to Mediavilla et al. [66], particle nudity can influence combustion behavior and burning time.

Bulk density is lower than the range of values determined for pruning pellets from olive, pomegranate and guava trees (603.50–749.40 kg/m^3) [31,43,65], but it is higher than the results obtained for apple tree pruning pellets, even higher at different proportions in a mixture with pine wood (506–558 kg/m^3) [38]. The bulk density of the pellets obtained here is outside the range, although very close to the minimum quality value ($600 \leq DG \leq 750$ kg/m^3) of EN 17225-2 [16].

The energy density obtained is close to the range of values reported for pine wood pellets and some commercial pellets (11.8–12.9 GJ/m^3) [67].

The mechanical durability is lower than the values reported for pellets from olive, pomegranate and hazelnut tree prunings (96.60–98.4%) [43,48,65]. Research from de Souza et al. [45] suggested that higher mechanical durability and reduced cracking in pellets may occur due to higher lignin content; thus, the low percentage of lignin found in avocado biomass (Table 3) could be related to the low mechanical durability found in the obtained pellets. However, there are other factors that influence both the low mechanical durability and bulk density; such factors are moisture content, particle size and pelletization temperature [68].

3.3. Pellet Quality Assessment

Table 8 compares the values obtained for class B biomass pellets with the values set by ENplus [15] for residential and commercial use, as well as those set by EN 17225-2 [16] for industrial use. The different classifications, according to their use, are presented. It can be observed that the pellets obtained meet most of the quality requirements for residential, commercial and industrial use. However, in the case of mechanical durability and bulk density, they do not meet the values suggested by European standards.

Mechanical durability and pellet density are the main parameters describing quality in terms of physical properties [69]. Low mechanical durability can imply higher mechanical wear of pellets, producing fine particles or dust during transportation, transshipment and storage, which increases material losses and disrupts boiler feed systems [69,70]. Fine particles can cause combustion processes to be less homogeneous [69], reduce combustion efficiency and increase emissions [71]. There is also an increased risk of fires or explosions during handling, shipment or storage due to the presence of fines [71]. On the other hand, low bulk density has implications for the operational costs of transporting, storing and handling pellets [14,32,50].

The formulation and optimization of biomass blends from different sources is an alternative to obtain better quality pellets [48]. Some authors have indicated the effectiveness of the optimal formulation of mixtures with pine wood to improve the mechanical durability and bulk density of pellets [44,72]. Mechanical durability can be optimized from the variation in particle size and moisture content [14,73]. Considering the above, the mechanical properties of the pellets made from class B biomass could be improved.

Table 8. Compliance with pellet quality parameters adapted from ENplus [15] and EN 17225-2 [16]. The symbol • indicates that the pellets are included in at least one classification (A1, A2, B,..., I3), and the symbol ◊ indicates that they are not included in any.

Property	*ENplus* [15] (Commercial and Residential Use)			EN 17225-2 [16] (Industrial Use)			Class B Biomass Pellets	
	A1	A2	B	I1	I2	I3		
Diameter (D, mm)		6 ± 1 or 8 ± 1			6 ± 1 or 8 ± 1		•	6.09
Length (L, mm)		$3.15 < L \leq 45$ *			$3.15 < L \leq 40$ *		•	15.68
Moisture (% wt, as)		≤10			≤10		•	8.31
Ash (% wt, db)	≤0.7	≤1.2	≤2.0	≤1.0	≤1.5	≤3.0		1.2
Mechanical durability (% wt, as)	≥98.0	≥97.5		≥97.5		≥96.5	◊	86.7
Net calorific value (MJ/kg, as)		≥16.5			≥16.5		•	18.11
Bulk density (BD, kg/m^3, as)		$600 \leq DA \leq 750$			≥600		◊	580.97
N (% wt, db)	≤0.3	≤0.5	≤1.0	≤0.3		≤0.6	•	0.81
S (% wt, db)	≤0.04	≤0.05			≤0.05		•	<0.01
As (mg/kg, db)		≤1			≤2		•	0
Cd (mg/kg, db)		≤0.5			≤1.0		•	0.006
Cr (mg/kg, db)		≤10			≤15		•	0.1
Cu (mg/kg, db)		≤10			≤20		•	11.6
Pb (mg/kg, db)		≤10			≤20		•	0
Hg (mg/kg, db)		≤0.1			≤0.1		•	0
Ni (mg/kg, db)		≤10			-		•	0.01
Zn (mg/kg, db)		≤100			≤200		•	1.5

Notes: as = as received, db = dry basis. * Pellets with L > 40 mm: maximum 1%. Pellets > 45 mm are not allowed.

3.4. Potential Pellet Uses

Good quality pellets, such as those that are certified through the ENplus (A1) scheme, can be easily adopted for energy utilization in virtually any end-use technology, such as in residential boilers, gasifiers and industrial boilers [74]. Generally, pellets obtained from class B biomass meet most of the values required by ENplus [15] for residential or commercial use. The only values that fall outside the ranges established by the standards are mechanical durability and bulk density. Based on this general trend of conformity, the low mechanical durability and bulk density of the pellets obtained favors the use at the local level, so an option for this type of pellet would be to use them within short transport radii, where the low density is not as impactful in terms of logistical costs.

The Cu content determined for pellets from Class B biomass is greater than 10 mg/kg but less than 20 mg/kg (Table 8), so the recommended use according to EN 17225-2 [16] is in the industrial sector, where more advanced controls and flue gas cleaning are usually in place. In this sector, pellet could be technically feasible to replace 883 PJ/year (18% of the final energy demand at the national level) and mitigate 66 million tons of CO2e (MtCO2e) [75]. However, from an economic standpoint, the use of pellets would be viable to replace liquefied petroleum gas (LPG) (24 USD/GJ), diesel (32 USD/GJ) and fuel oil (11.4 USD/GJ) (price calculated in dollars from net calorific value) [76,77] and mitigate 35 MtCO2e. These calculated values of total mitigation by substitution of LPG, diesel and fuel oil for the industrial sector in Mexico have been obtained from estimates made by Tauro et al. [75]. These fuels are widely used in the agroindustrial sector to generate process steam. Although the determination of pellet production costs entails an exhaustive analysis and is not part of the objectives of this study, following the methodology of Tauro et al. [75] it was possible to estimate a cost of 8.5 USD/GJ, lower than the cost used in our work.

The mixture of biomasses with high ash levels and pine wood, which generally has low concentrations, can reduce the content of some heavy metals, such as Cu [71], so the mixture of avocado pruning and pine wood could be an alternative to improve the quality of pellets for residential use. In this sense, class B biomass pellets could see use in the residential sector for cooking or heating tasks. From an economic point of view, a pellet production cost of 10 USD/GJ [75] in plants has been estimated, which would be viable when compared to the high cost of LPG of approximately 24 USD/GJ [76,77]. Further maturity of efficient cooking technologies is required for the energy use of pellets in the residential and commercial sector, where up to 73% of LPG use could be substituted [75,78]. It is still necessary to promote the use of biofuels together with governmental economic support to favor the competitiveness of bioenergy options, as stated by Martínez-Bravo and Masera [78]; however, this type of technology is promising for residential use in water heating or food cooking [79].

The energy utilization of pellets, although they are usually intended for thermal applications or for the generation of electricity from direct combustion, can also be used for the generation of lean gas through a gasification process, where such gas can be burned directly or purified to synthesize transportation fuel [74]. On the other hand, solid biomass can also be subjected to a pyrolysis process, heating between 300–600 °C in the absence of air to generate products, such as biochar and bio-oil [74]. TGA-DTG is essential to determine the temperature and heating rate of the pyrolysis process that has been carried out in this investigation; such temperature is the most important parameter that can determine the performance of products, such as biochar or bio-oil. In this sense, TGA-DTG is useful for predicting mainly the yields of such products through kinetic analyses with the determination of parameters, such as the activation energy, the frequency factor and the reaction order, in particular, as well as thermodynamic, proximal and primary composition analyses derived from the mass degradation of the pellets, which allow the optimized manufacture of a pyrolytic reactor. A more detailed analysis of these parameters would clarify optimal potential use to be defined.

The local use of pruning residues in the Mexican avocado-growing region could be a viable alternative for the use of pellets as an energy source; however, it requires organization on the part of the producers. In this sense, the participation of organizations, such as the local plant health boards can play an important role, since they are auxiliary organizations that maintain close communication with avocado producers. Waste management could be centralized in geographically strategic sites for the collection, conditioning and production of pellets, where the same existing communication routes for the transportation of the avocado harvest facilitate access. The use of pellets can be a market opportunity for producers and local communities. There are several agro-industries in the study region that could replace fossil fuels with pellets, generating economic savings by substituting fuels and mitigating polluting emissions. A case in point is the mezcal and tequila distilleries, which are currently intensive users of firewood, LPG and fuel oil and are interested in alternatives to reduce their emissions [9].

Finally, the integration of pellets could contribute to the generation of formal jobs and the promotion of job creation in the regions generating these inputs and, therefore, promote social development in addition to CO_2 emissions reduction [12,80]. On the other hand, it is important to understand energy needs, since, as suggested by Quiñones-Reveles et al. [80], this contributes to technological innovation, which, in turn, contributes to the acceleration of the energy transition.

4. Conclusions

In this study, the potential energy use of avocado prunings as densified solid biofuels was determined. The physical, chemical and energetic properties of two pruning fractions defined as class B (branches) and class BAL (branches and leaves) were determined. Woody biomass (class B) can be part of the resource base potentially usable as solid biofuels, as it exhibits high calorific value (19.61 MJ/kg) and low ash content (1.2%). The chemical composition of branches and leaves (class BAL) limits their use due to high concentrations of N and S, high ash content and the presence of heavy elements, such as Cd, Cu and Zn. Pellets obtained from class B meet most of the quality requirements analyzed for residential, commercial and industrial use, except for mechanical durability and bulk density, whose values are below the minimum threshold. However, pellet production costs are estimated at

8.5 USD/GJ, much lower than fossil fuels costs. Additionally, for residential or commercial use, the Cu content (11.6 mg/kg) is outside the ENplus quality specification (10 mg/kg) but acceptable for industrial use. From the TGA-DTG analysis, it was possible to observe the different stages of the thermochemical decomposition process of the avocado pruning woody fraction, in relation to the main components of the biomass, namely, cellulose, hemicellulose and lignin. As a perspective for future studies, a more detailed analysis of the kinetic parameters and thermodynamic parameters would allow the design and manufacture of equipment, revealing an important alternative for the use and application of this type of biomass in pyrolytic reactors.

Author Contributions: Conceptualization: J.A.S.-G., R.T. and J.G.R.-Q.; Methodology: J.A.S.-G., J.J.A.-F., V.M.B.-S. and J.G.R.-Q.; Writing—original draft: J.A.S.-G., R.T., J.G.R.-Q. and V.M.B.-S.; Writing—review and editing: J.A.S.-G., J.J.A.-F. and J.G.R.-Q.; Funding acquisition: J.G.R.-Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by FSE-SENER-CONACYT (CEMIE-Bio) Grant No. 246911.

Data Availability Statement: Not applicable.

Acknowledgments: Authors thank the support of UMSNH, GIRA and CONACYT (Consejo Nacional de Ciencia y Tecnología).

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

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