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Multifactorial Assessment of the Bioenergetic Potential of Residual Biomass of *Pinus* spp. in a Rural Community: From Functional Characterization to Mapping of the Available Energy Resource

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Abstract: The generation of biomass residues in different productive activities of rural communities in Mexico represents an area of opportunity for the generation of bioenergy for various purposes. Solid biofuels (SBF), for example, are an alternative for the exploitation of these residues. The present study shows a comprehensive proposal for the analysis of residues of *Pinus* spp. generated by the artisanal sector of a rural community in Mexico. The proposal is based on four stages: a) characterization of the physico-chemical and functional properties of the residues, by Scanning Electron Microscopy (SEM), Infrared (FTIR) and Raman Spectroscopy, Thermogravimetry (TGA-DTG), determining the calorific coefficient and polymeric compounds present by fiber analysis; (b) spatial, temporal and dimensional analysis of the waste generated in the town studied; (c) assessment of the energy potential available in space and time; (d) definition of guidelines for the management of solid biofuels for the community through collection, processing and final disposal centers. The results of the assessment of timber residue from 50 artisan workshops that represent 25% of the total in the community show that the identified heating value of the dry residue ranges from 17.6 MJ/kg to 18.1 MJ/kg, attributed to the presence of polymeric compounds such as cellulose, hemicellulose and lignin, the latter in the order of 28%, which contributes to a high energy potential, and whose compounds were identified by TGA-DTG analysis, FTIR, SEM and fiber analysis. The energy potential was estimated at approximately 7 TJ/year for the analyzed workshops. In which case, the economic savings obtained from unburned firewood would amount to about $20,000 USD/year. As regards the reduction in firewood consumption due to the use of residues for energy purposes, about 350 Tn/year would be mitigated, which would reduce the community's emissions by more than 76 $TnCO_2$/year. A strategic management proposal was also established, aimed at providing spaces for the collection, processing and final disposal of solid biofuels from wood residues, which in sum represent an energy alternative that is sustainable in environmental, economic and social terms, for the same community.

Keywords: biomass; bioenergy; biofuel; renewable energy; sustainability; wood; energy mapping

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1. Introduction

The growing demand for energy, linked to population growth, has most certainly threatened energy sustainability and the satisfaction of society's needs in recent years [1]. Renewable energy sources represent an alternative to promote more affordable, fair and sustainable scenarios [2,3]. Additionally, in recent years, human activity, accompanied by our modern lifestyles, has contributed to the problem of global warming and, consequently, to climate change [4]. Economic growth and the growing energy dependence of the commercial sector on fossil fuels worldwide also contribute to this issue; these fuels are used in activities that generate significant pollution and greenhouse gas emissions. As a consequence, in recent years, various reports of pollution and future climate changes have been taken into account for current decision-making, with greater relevance for climate services, to improve adaptation and resilience to climate change and curb greenhouse gas emissions in pollution from different sources such as fossil fuels [5–7].

The expansion of industrialization has also caused a considerable increase in waste, which poses a significant problem for its final disposal. Much of this waste can be reused in the production chain of new materials or products, as is the case of agribusiness and biofuels [8,9].

Currently, renewable energy resources such as biomass can provide thermal energy, which is a promising energy source and has enormous potential to meet the energy needs of various sectors [10,11], as it offers great energy potential to reduce dependence on fossil fuels. Additionally, this resource is affordable for some rural areas, and an alternative energy source that is environmentally friendly [12,13]. To assess the energy contained in the biomass, first, it is necessary to assess the energy potential, understood as the chemical energy of the biomass that can be transformed for energy use [14,15]. Biomass energy has the potential to create significant impacts on the most pressing development challenges such as rural poverty and environmental damage [11].

In Mexico, renewable energy made up 11.25% of primary energy, with biomass being one of the sources with the greatest potential as it is increasingly used for bioenergy generation, accounting for a total of 6.34% of the share for primary energy (SENER 2020) [16]. According to some estimates, the elevated potential of bioenergy is somewhere between 2228 and 3459 PJ per year, which could satisfy about half of Mexico's total primary energy consumption [17]. This context gives rise to a possible scenario for the generation of solid biofuels for bioenergy generation. Therefore, Mexico has great potential for the generation of solid biofuels (pellets and/or briquettes) derived from lignocellulosic materials such as wood residues of *Pinus* spp. [18–21].

Consequently, it is necessary to develop sustainable alternatives to non-renewable energy sources [22–24]. Since these renewable sources will be required to complement the supply of primary energy globally in the coming years, together with the increase in population and industrialization, they will lead to increased demand for fuels. Since they are renewable, they can be integrated into the production chain and the current economy, but with more sustainable and resilient practices, which in sum generate long-term socio-environmental benefits such as those that have been stated in the case of bioenergy [25].

Thus, the wood residues derived from the artisanal industrialization of a rural community can be a sustainable alternative for energy supply, mainly thermal, through biofuels [26] and this in turn can be used locally to meet thermal energy needs where the supply of forest-derived fuels is required. The use of wood residues transformed into biofuels could combat the immoderate felling of forests and the resources of which are being used as conventional fuels in various rural areas of the country [27]. In this way, the production of solid biofuels provides an energy option for the satisfaction of basic needs [28,29]. These second-generation derived biofuels can be manufactured from lignocellulosic biomass or from woody crops, mostly from forest waste or residues [30].

In this regard, the present investigation highlights the energy potential of timber residues in the Indigenous community of San Francisco Pichátaro in the Mexican state of Michoacán. In this area, there is a high concentration of forest vegetation (*Pinus* spp.) which is used for conversion into rustic furniture, from which the timber residue is released [31–33], residue that is currently burned outdoors [34]. Therefore, this research proposes to use this residue to generate solid biofuels, validating its feasibility through a characterization of its morphological, physico-chemical and functional properties, while also determining its relevance through an assessment of current and available energy potential by types of timber waste.

This research complements an extensive methodology that aims to determine the production of *Pinus* spp. residue and its energy potential in an Indigenous village in Mexico. Reference has been made to previous work that showed the proximal analysis of *Pinus* spp. residue from the community of the study in order to determine the feasibility of producing solid biofuels. Likewise, their respective elemental analysis has been reported to determine the elemental composition (C, H, O, N and S). A multicriteria quantitative analysis was presented where the analyzed material was compared in chemical, physical and energetic terms with other residues such as from *Pinus* spp. (species in general) and *Quercus* spp. (species in general). Additionally, a forecast of the potential for energy generation in the community using residue from pine trees was presented [35].

For this investigation, the morphological, physico-chemical and structural characteristics were determined by scanning electron microscopy (SEM) and infrared spectroscopy (FTIR) to quantify the polymeric components such as hemicellulose, cellulose and lignin, and these results were contrasted with thermogravimetric analysis. Together, these characterization techniques make it possible to confirm the amounts of polymeric compounds more accurately, and they are also useful for knowing the potential for the manufacture of pellets or briquettes.

Finally, an analysis of the spatial and temporal energy potential available in the location of the study is shown via energy mapping. This analysis shows the energy potential by artisan workshops, and by micro-regions, which makes it possible to identify the geographical areas where centers for collecting and processing timber waste, manufacturing solid biofuel and points of sale to the public can be installed.

This proposal integrates a broad analysis to promote the generation of local bioenergy sources through the self-management of timber waste. In addition, it completes a research project raised from basic science to its application as an energetically self-managed local social impact project. Therefore, it represents an investigation with potential for replicability in areas with characteristics like those of the town analyzed.

The proposed methodology is based on four components: waste identification, physico-chemical analysis, spatiotemporal energy potential assessment and guidelines for the management of solid biofuels. It is also a way to integrate scientific-technical aspects with local problems of waste management and propose locally sustainable energy alternatives.

The manuscript focuses on a methodological proposal, from the identification of residues to the assessment of the energy potential available from its characterization. This proposal is linked to a case study, but the methodology is expected to be replicated in other communities with characteristics similar to those of the town analyzed.

2. Materials and Methods

2.1. Community of the Study

This proposal is based on the analysis of the production of timber residues in the Indigenous community of San Francisco Pichátaro (latitude: 19.55°, longitude: 101.8°), located in the state of Michoacán, Mexico (Figure 1a). The methodology used for this research is shown in Figure 1b. In general terms, it consists of four stages: (a) characterization of the physico-chemical and functional properties of the residues; (b) spatial, temporal and dimensional analysis of the waste generated in the study site; (c) assessment of the available energy potential; (d) definition of guidelines for the management of solid biofuels from a sustainability perspective, considering the economic, social and environmental dimensions.

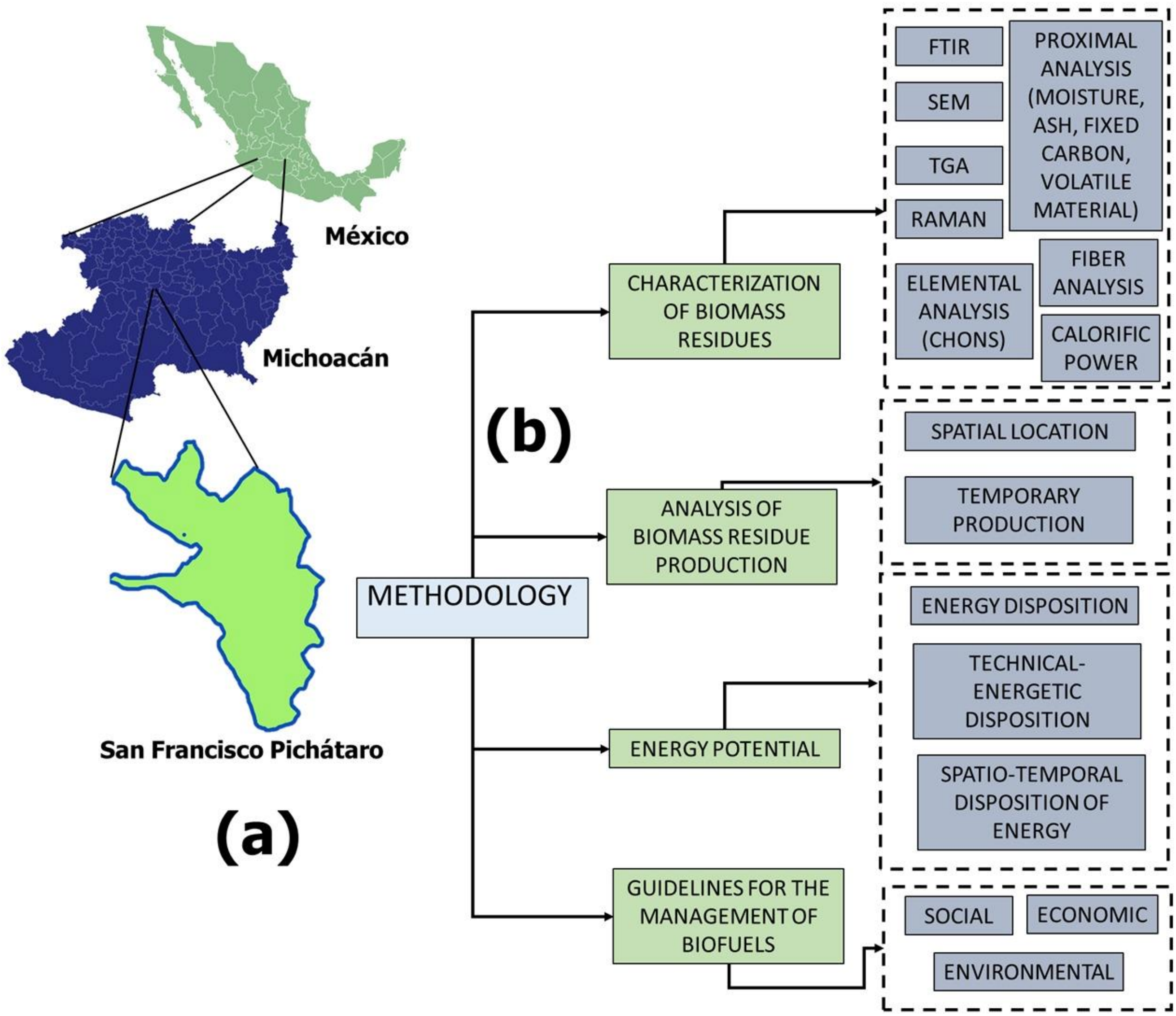

Figure 1. (**a**) Geographic location of the study community (**b**) Methodology applied.

Given that the productive fabric of the community relies on the use of forest biomass, residues were studied from their collection at the production site to the performance of the prospective analyses described below.

2.2. Physico-Chemical Characterization of Pinus spp.

Samples of biomass residues from 50 different workshops were collected in order to analyze the general characteristics in terms of physico-chemical, morphological and functional properties. The following physico-chemical characterizations were determined for this investigation.

2.2.1. Moisture Content

The initial moisture content of the timber residue was determined in triplicate by the dehydration method according to the UNE-EN 14774-1 standard [36].

2.2.2. Ash Content

The ash content of the timber residues was determined according to the EN 14775 standard [37]. In this case, completely dry 40-mesh woodmeal was used.

2.2.3. Volatile Matter

Estimates of the amount of volatile matter were performed according to the ASTM E872-82 standard [38] using a LINDBERG muffle furnace, for which completely dry 40-mesh woodmeal was also used.

2.2.4. Fixed Carbon

Fixed carbon refers to the residual fraction of the fuel that remains once the volatile matter has been pyrolyzed during an experimental test. For this analysis, it was calculated by difference, subtracting the content of ash and volatile matter from 100% [39] according to Equation (1).

$$FC = 100 - AC - VM, \tag{1}$$

where

FC = the fixed carbon content of the dry base (%)
AC = the ash content of the dry base (%)
VM = the volatile matter content of the dry base (%)

It is noted that of the 50 workshops identified, in each one four points were taken were randomly taken where the samples were collected for the proximal analysis.

2.3. Structural and Functional-Energetic Characterization of Pinus spp.

The carbon, hydrogen and nitrogen content were measured in an elemental analyzer (Model 4010; Costech International SpA, Milan, Italy) according to the UNE-CEN/TS 15104 EX (2008) standard [40]. In this case, the biomass was sieved in a completely dry 40 mesh, and the oxygen was calculated by difference [41]. Fourier Transform Infrared (FTIR) spectroscopy was required for the identification of the functional groups in the biomass residues, carried out using the Thermo Scientific Smart Orbit accessory with the Thermo Scientific Nicolet 6700 spectrometer (measurements taken by ATR; Waltham, MA, USA). A total of 96 scans (with resolutions of 4 cm^{-1}) were performed, in a range of 4000 to 400 cm^{-1} and 3 analyses were carried out for each sample. Thermo Scientific OMNICTM software (Version 2013; Waltham, MA, USA) was used to determine the bands. Raman spectroscopy was also used with a SENTERRA apparatus, Bruker brand, with a 532 nm laser.

The morphology and elemental composition of the *Pinus* spp. timber biomass was analyzed by scanning electron microscopy (SEM) using a Jeol JSM 7600F model equipped with field emission (Tokyo, Japan). The chemical composition of the main polymeric components of *Pinus* spp. (cellulose, hemicellulose and lignin) was determined by fiber analysis using the Van Soest gravimetric method and α-amylase [42]. For this analysis, 0.5 g samples of dry wood meal with a homogeneous particle size (passed through a 60/40 mesh, 0.274/0.516 mm) were used. This step was performed in triplicate for each of the 30 samples, using an ANKOM-200 fiber analyzer (Macedon, New York, NY, USA) [43].

To calculate the heating value, a mathematical model referred to in the research for lignocellulosic materials [44,45] was used. In this case, based on the chemical analyses developed herein, prediction models based on elemental analysis were used, substituting the values in the following indicators and based on Equation (2):

$$HHV = 0.335C + 1.423H - 0.154O - 0.145N, \tag{2}$$

where

HHV = High Heating Value (MJ/kg)
C = Carbon
H = Hydrogen
O = Oxygen
N = Nitrogen

Having substituted the values of Equation (2), the next step was to substitute the values (the proximate analysis) [46] of Equation (3):

$$HHV = 0.3543FC + 0.1708VM, \quad (3)$$

where
HHV = High Heating Value (MJ/kg)
FC = fixed carbon
VM = volatile matter
After obtaining the values of Equations (2) and (3), the formula was simplified by obtaining the HHV, subtracting the ash content [47] as shown in Equation (4):

$$HHV = 19.914 - 0.2324A, \quad (4)$$

where
HHV = High Heating Value (MJ/kg)
A = ashes
At the end of the previous procedure, the heating value was obtained.

A thermogravimetric and differential analysis (TGA-DTG) was also performed to identify the polymeric compounds and contrast this analysis with complementary techniques. To obtain the data and subsequent analysis, the dried sample of *Pinus* spp. with uniform particle size was placed in a PerkinElmer Simultaneous Thermal Analyzer STA 6000 thermogravimetric analyzer (PerkinElmer, Waltham, MA, USA). The first stage of mass degradation was carried out in the 25–105 °C range. The sample was left in isotherm for 30 min. Then, its temperature was raised again to 700 °C, remaining in isotherm for another 20 min. The heating rate was 15 °C/min. In this stage, argon was used as high-purity inert gas (99.99%) with a flow rate of 150 mL/min. The second part of the heating ramp was carried out in the air with a flow rate of 50 mL/min and was kept in isotherm for 20 min. Then, cooling was performed at 30 °C/min from 700 °C to room temperature (28 °C). In order to reduce the effects of mass and heat transfer, a ceramic crucible was used in the thermobalance of the apparatus, where approximately 6 mg of the *Pinus* spp. sample was placed. It is important to mention that before carrying out each experiment, an argon purge was carried out for 25 min with a flow rate of 80 mL/min. The pyrolysis process was carried out in triplicate.

2.4. Analysis of Waste Production

In order to assess the production of *Pinus* spp. biomass residues that are generated in the town, a georeferenced spatial map of the Indigenous community of San Francisco Pichátaro was produced using Google Earth [32]. The preliminary map serves the purpose of diagnosing the main active workshops in the village of the study. In this Indigenous community, there are approximately 200 artisan workshops, transforming wood into rustic furniture that is then distributed throughout Mexico [35]. In order to map waste production, only 50 community workshops were taken as a representative sample, representing approximately 25% of the total number of workshops (Figure 2a), but those with uninterrupted operations were strategically identified.

Within the community of the study, of the 50 diagnosed workshops, only four were chosen in such a way that the samples were different from one another because they were collected from different workshops located to the north, south, east and west of the community. In the same community, the workshops were selected in this way to improve the accuracy of the results shown here and to ensure that the timber residue was not only from one workshop but from different workshops in their respective locations. A total of 5 kg of wood residue in the form of *Pinus* spp. sawdust was collected for each of the four workshops. This was then used to conduct the remaining analyses in a laboratory, according to the various standards in order to characterize the material that is described in the rest of this investigation.

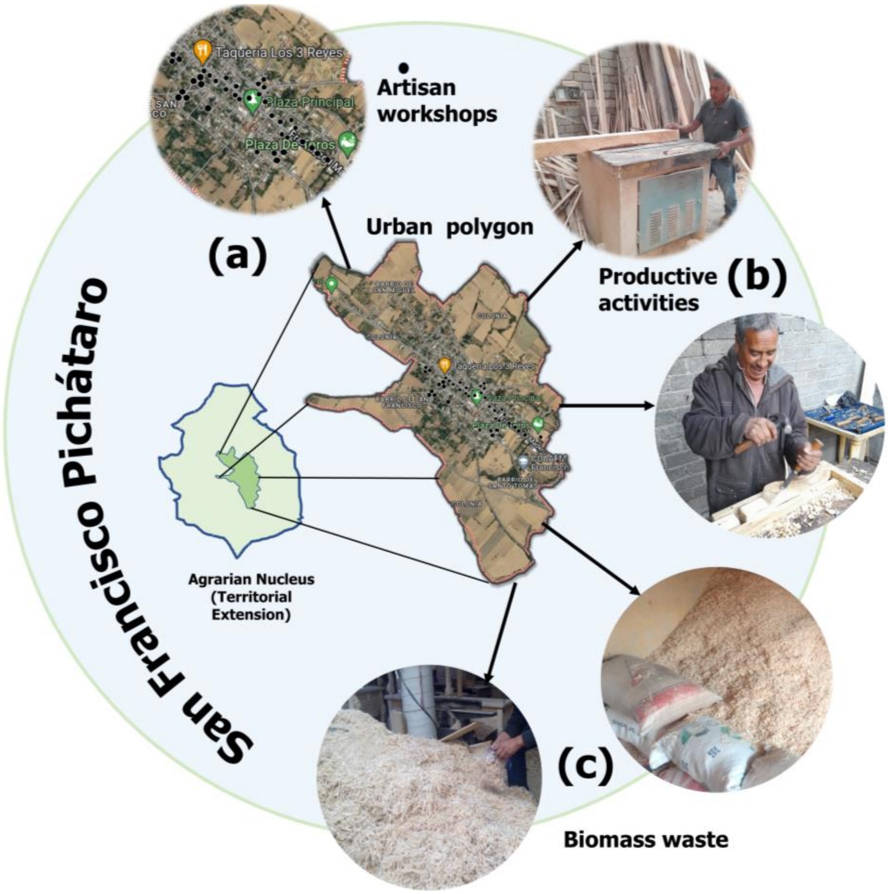

Figure 2. (**a**) Spatial location of the workshops that produce biomass residues, (**b**) productive fabric of the community and (**c**) biomass residues generated in the workshops.

Figure 2 shows an overview of the identification of the artisan workshops that generate waste, the productive activities of timber harvesting in the forests (Figure 2b), as well as the volume of waste generated in a working day (Figure 2c). Of the 50 workshops analyzed, the waste production that is usually generated was quantified weekly for one month by means of private visits to each workshop, with the help of a basic diagnostic instrument and a digital hook scale. It is important to mention that these workshops are the ones with the largest volume of operations throughout the year. The sampling of residues was carried out estimating the daily weight for one week from each workshop. For the experimental, physico-chemical and heating value analyses, samples from each workshop were analyzed.

2.5. Analysis of Energy Potential

Using the data from the previous analyses, it was possible to obtain the amount of energy available in the generated waste. This study addresses the specific case of the town, where the generated waste is mostly dry, and two types are generated: sawdust and chips. Therefore, the heating value resulting from the characterization process was extrapolated to all the residual biomass available on a weekly, monthly and annual basis, for each workshop and for all the studied workshops, as well as for all the workshops in the community. Also, the available technical potential was estimated considering the combustion technologies used in the town, which are mainly open-air stoves without insulation, with an average thermal efficiency of 10% [48,49].

Additionally, a map of the energy potential available by point of spatial location in the community was generated, based on waste production. The study site (San Francisco Pichátaro), located in the municipalities of Tingambato, Nahuatzen, Erongarícuaro and

Pátzcuaro, in the state of Michoacán, has a surface area of 9088.054756 ha [50], with a single homonymous population center.

Thus, to produce the map, an Excel database was fed with 50 sites that correspond to the analyzed workshops. Identification information, biomass production and available energy were included, in addition to spherical geographic coordinates in decimal format. The geographic space of the community was visualized using the QGis program [51]. In the same program, the geographic data were saved as vector files of point geometry in "shape" format, to later be reprojected to the UTM system for processing purposes in metric units.

An inverse distance weighted interpolation analysis (IDW) was performed, where the sampling points are weighted with a function of the inverse of the distance so that the influence between points decreases with the distance [52]. For this, the "IDW interpolation" plugin was applied in QGis, where both the biomass production (chips and sawdust) and the available energy were used as interpolation attributes, in such a way that three raster files with a resolution of 15 m were generated. The generation of isolines was applied to each raster layer to clearly delimit the categories that were generated by the interpolation analysis. These were generated in intervals of 10 for biomass and 0.1 for energy. Finally, for rendering purposes, each raster file was converted to shape polygons using the "raster pixels to polygons" plugin and reclassified using equal intervals and 10 classes.

2.6. Guidelines for Local Management of Biofuel

In this section, the sustainability, social, economic and environmental dimensions are discussed. The results of the previous sections are addressed to show some of the advantages of the use of solid biofuels and their management at the level of collection, processing and final disposal. In addition, the mitigation that could be generated if all available waste is used for energy purposes was analyzed. For this analysis, an emission factor for firewood of 2.3 $KgCO_2$/kg was considered, according to the national emissions inventory of Mexico [53], and biomass was not considered as a resource of neutral emissions. The heating value of firewood for conventional use was estimated under the analogous scheme of residues as original substance/dry matter with a heating value of 19 MJ/kg [54–56]. Regarding the cost analysis, a local purchase price for this resource was estimated in the order of $0.052 USD/kg, at the official exchange rate for the Mexican peso in January 2023. An analysis of possible jobs was also carried out for the briquette manufacturing process, considering three employees for each work unit: technician, day laborer and salesperson.

3. Results and Discussion

3.1. Characterization

Table 1 shows the different proximal analyses determining the technical feasibility of producing solid biofuels. The samples analyzed had an anhydrous moisture content. Four such samples were used, described in the table as sample 1 (M1), sample 2 (M2), sample 3 (M3) and sample 4 (M4).

Table 1. Proximate analysis of biomass from *Pinus* spp. timber residues (%).

Analysis	Wood Residue Samples			
	M1	M2	M3	M4
Moisture	10.75 (±0.07)	9.54 (±0.78)	17.34 (±3.05)	13.11 (±0.36)
Ash	0.526 (±0.49)	0.352 (±0.09)	0.474 (±0.05)	0.394 (±0.03)
Volatile matter	86.258 (±0.05)	90.882 (±0.38)	82.892 (±0.07)	87.792 (±1.04)
Fixed carbon	13.215 (±0.78)	8.765 (±0.70)	16.633 (±0.75)	11.812 (±0.72)

As regards the proximal analyses, the moisture content was established in a range from 9.54% (±0.78) to 17.34% (±3.05); similar moisture levels for pine wood residues have been shown in a moisture range from 17.7% to 20.3% [57]. The relationship between moisture and the heating value of the material analyzed for this investigation shows that the low moisture content determined in this investigation is low compared to other pine wood residues, which makes it a suitable material for densification.

In this investigation, the result found for the ash content was from 0.352% (±0.09) to 0.526% (±0.49); similar studies report ash from 0.1% to 1.1% [58]. The volatile matter was from 82.892% (±0.08) to 90.882% (±0.38); similar studies report volatile matter in the order of 79.6 to 90.9% [59]. Finally, the fixed carbon was from 8.765% (±0.70) to 16.633% (±0.75); other studies report fixed carbon in the range from 9.10 to 20.44% [44]. This study demonstrates that the results obtained in the different analyses are similar to those reported in other investigations related to the generation of solid biofuels.

The results of the elemental analysis of pine timber residues can be seen in Table 2.

Table 2. Ultimate analysis of the samples of timber residues (%).

Samples	C	H	O	N	S
M1	48.79	5.98	44.79	0.41	<0.01
M2	47.78	5.99	45.60	0.60	<0.01
M3	48.12	6.09	45.37	0.40	<0.01
M4	47.96	6.05	45.56	0.41	<0.01
Average	48.16 (±0.44)	6.02 (±0.05)	45.33 (±0.37)	0.45 (±0.09)	<0.01

The results are similar to those reported in previous investigations for C = 42.3%, N = 0.63%, H = 5.61%, and S = 0.07% [60]. Others report C = 46.5%, H = 6.7%, O = 46.4%, N = 0.13%, and S = 0.029% [61], which corroborates that these timber residues can be used for energy purposes.

The morphological analysis of the *Pinus* spp. residues was carried out using scanning electron microscopy, which made it possible to identify the micrometric size of the crushed residual wood agglomerates that were collected after the manufacture of wooden furniture (Figure 3a).

Additionally, using infrared spectroscopy (Figure 3b), it was possible to identify the functional groups present in said timber residues (*Pinus* spp.). The FTIR analysis (Figure 3b) made it possible to identify the presence of polymeric compounds such as cellulose, hemicellulose and lignin, as well as some extractives with high energy content [62]. This analysis shows a strong and broad absorption band at 3406 cm^{-1} and the mid-peak at 1408 cm^{-1} [63–66] attributable to said polymeric compounds. Bands were also identified at 887 cm^{-1} for C-H corresponding to bending of the cellulose, 1042 cm^{-1} for C-O stretching in cellulose and hemicellulose, 1464 cm^{-1} for stretching by CH_2 bending in lignin and xylan, 1738 cm^{-1} for non-conjugated C=O in xylans (hemicellulose) and in bands of 3400 cm^{-1} for stretching in O-H [67]. The 1628 cm^{-1} band represents the C=C stretch and suggests the presence of lignin and aromatic compounds. The band at 1055 cm^{-1} is indicative of COC stretching in the xylan of the hemicellulose [63–66].

The infrared spectroscopy analysis was contrasted with the Raman spectroscopy, which complements the characterization of the timber residue and shows bands in the regions between 1000 and 1700 cm^{-1} and between 2900 and 3400 cm^{-1} (Figure 3c) [68]. These bands correspond to the presence of polymeric compounds such as cellulose, compounds formed by carbon, hydrogen and oxygen: CH_2, C-O-H, C-C-H, O-H and C-H [68]; thus, the bands at 2940, 1597, 1140 and 1334 cm^{-1} correspond to the presence of lignin, a compound that contributes to a high heating value [69].

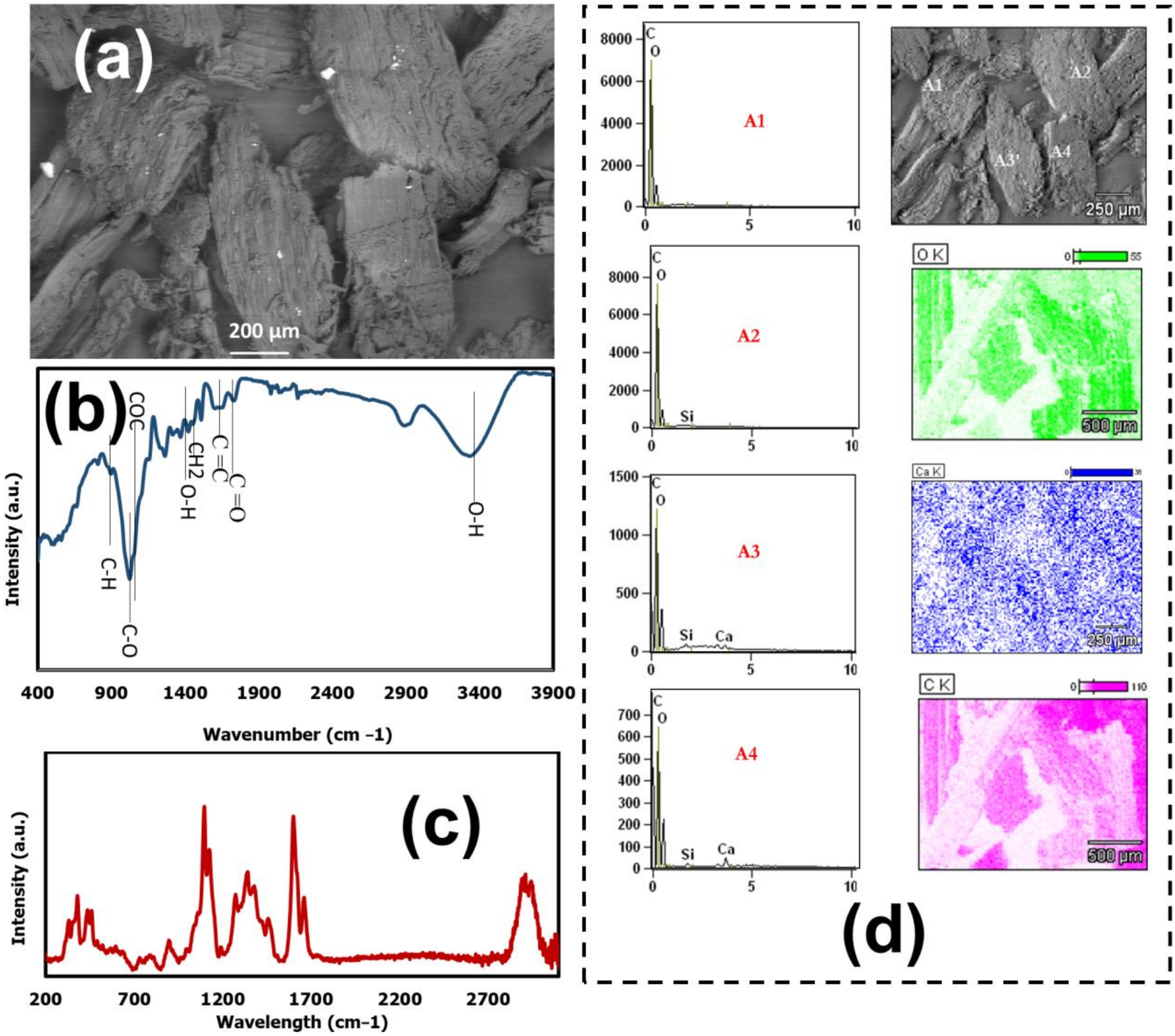

Figure 3. Physico-chemical characterization: (**a**) SEM, (**b**) FTIR, (**c**) Raman Spectroscopy, (**d**) SEM-EDS.

On the other hand, Figure 3d shows a semi-quantitative elemental analysis, which made it possible to identify the distribution and content percentage of elements such as carbon (C), oxygen (O), silicon (Si) and calcium (Ca), in representative proportions. This analysis is complemented with the data in Table 3, that shows the mass percentage of the chemical elements present in the *Pinus* spp. residues.

Table 3. Mass percentage of the elements present in the biomass of *Pinus* spp.

	Mass %			
Sample	**C**	**O**	**Si**	**Ca**
M1	71.33	28.36	0.09	0.22
M2	71.19	27.94		0.51
M3	69.26	28.47		1.82
M4	70.63	26.34		2.68
Average	70.60 (±0.81)	27.77 (±0.85)	-	1.30 (±0.99)

The previous results show a significant content of polymeric and extractable compounds, which can be linked to the energy content of these residues. Likewise, the morphological structure of the typical fibrous texture of sawdust could favor biomass agglomeration and, consequently, would produce an increase in compressive strength. Biomass waste studies help to predict its agglomeration properties for briquetting [70].

The characterization by FTIR and SEM is consistent with the determination of polymeric compounds by the fiber method. These results are presented in Table 4 as values in determined ranges for each compound with reference to the samples collected for this investigation, which is consistent with the previous characterization.

Table 4. Chemical composition of the main polymeric components of *Pinus* spp.

Samples	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Extractives (%)
Pinus spp.	48.16–54.87	9.12–17.34	24.66–28.01	5.84–11.76
Standard deviation	2.21	2.52	0.97	1.90

The amount of wood waste generated in the community of the study shows prominent energy characteristics for the generation of energy through solid biofuels, since the heating value found in the material analyzed for this research is adequate and very similar to those reported in the scientific literature, as shown in Table 5.

Table 5. Heating value and similar data of residues of *Pinus* spp.

Samples	Heating Value Found	Comparative Heating Value (References)
M1	18.0 MJ/kg	17.33 to 18.03 MJ/kg [71]
M2	18.1 MJ/kg	18.37 to 18.58 MJ/kg [72]
M3	17.6 MJ/kg	19.09 to 20.42 MJ/kg [73]
M4	17.8 MJ/kg	17.95 to 18.93 MJ/kg [74]

From the above, the calorific coefficient is similar compared to the values reported in previous research for *Pinus* species, for which the calorific coefficient found is equal to or greater than those previously reported, which makes it a suitable material for the generation of solid biofuels. In addition, this parameter is directly related to the moisture content, but in previous research for this material, a moisture value of 14.21% ($\pm$0.16) to 21.9% ($\pm$0.29) was found [35], which indicates that this material is suitable for the generation of thermal energy through solid biofuels.

On the other hand, Figure 4 shows the thermogravimetric curve (TGA) and the curve of its derivative, that is, the differential curve (DTG) in an inert atmosphere of argon. A characteristic behavior of lignocellulosic materials is observed. In this sense, it can be considered that hemicellulose (first stage) decomposes at a lower temperature (190–380 °C) than cellulose (second stage) which degrades between 280 and 400 °C. Finally, lignin, considered a more complex compound, decomposes between 170 and 800 °C in a third stage; it decomposes at a slower rate due to the association with the phenolic hydroxyl group [75,76].

As can be seen, the area of greatest degradation occurs between 250 and 400 °C, where there is the maximum loss of hemicellulose and cellulose due to the release of most of the volatiles, favoring the formation of charcoal at the end [77]. The highest rate of degradation (DTG) is also observed in this intermediate stage. When comparing the peaks of hemicellulose (shoulder), at approximately 325 °C, and cellulose ($\approx$360 °C), it is observed that they have a different heights and positions, which indicates the influence of the distribution of organic and inorganic compounds in the thermal degradation process of pine.

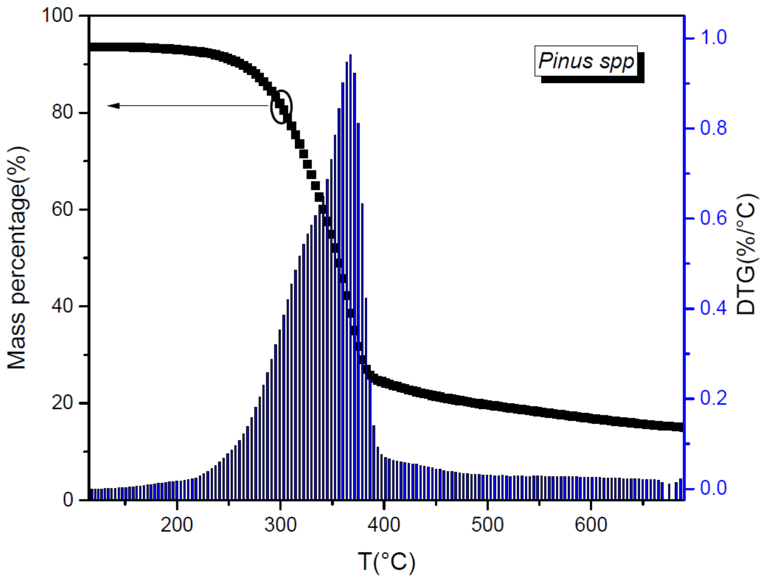

Figure 4. TGA-DTG curves of *Pinus* spp. in an atmosphere of argon and air.

3.2. Production, Energy Potential and Guidelines for the Management of Solid Biofuels

As regards the production of waste in the analyzed workshops, some of the most common types are highlighted, the generation of which is attributed to the dimensions, the technology used and the operation time of the workshop. Figure 5 shows the geographical location of the study site (Figure 5a), the identification of workshops (Figure 5b), and the intensity of production of sawdust and chips in the analyzed workshops (Figure 5c,d). Sawdust production ranges from 10 to 250 kg/week per workshop, while chip generation ranges from 10 to 132 kg/week.

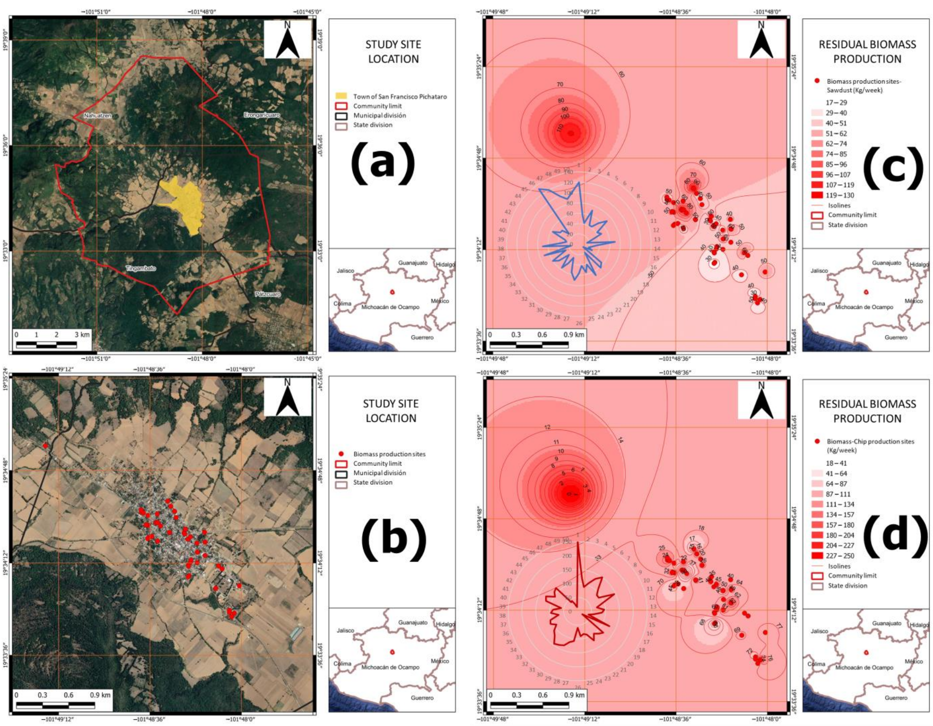

Figure 5. Spatial analysis: (**a**) location and spatial distribution of the study site, (**b**) spatial location of the production workshops, (**c**) intensity of production of sawdust in the studied workshops and (**d**) intensity of production of chips in the studied workshops.

According to the residents who own the artisan workshops, the COVID-19 pandemic significantly impacted the levels of wooden furniture manufacturing, and consequently, also the generation of waste. And, although the pandemic is coming to an end, the truth is that it has left an economic impact on local production levels, as well as changes in the productive fabric, migration and assistance provided by various social programs. There are no precise data on the levels of reduction in the productive fabric of the community, but they were greater than 30%.

However, this analysis shows the distribution of waste generation in the different workshops, as well as its dispersion, which is minimal because it is a small town. The low dispersion in waste generation makes it feasible to manage, as has been addressed in some investigations [78]. In this sense, the collection of biomass takes place over small distances, so the construction of collection centers does not represent a challenge associated with the disposal of residual biomass.

The energy potential available in each workshop was estimated using the waste production in each workshop and considering the heating value of 17.6 MJ/kg for sawdust and 18.1 MJ/kg for chips. This analysis considered the sum of the energy from both types of waste generated.

Figure 5 shows the spatiotemporal distribution of the energy potential of sawdust and chip residues in the workshops of the community of the study.

The spatial distribution by workshop and gradient of energy disposal can be seen in Figure 6a, where the presence of areas with higher and lower energy intensity associated with waste generation can also be seen.

The distribution of energy potential is also associated with a neighborhood organization called "barrios", which is how the community's homes are grouped locally.

Figure 5b shows the distribution of energy available from workshop waste by "barrios". There are seven of these "barrios" in which the community homes are integrated; thus, all the analyzed workshops, cumulatively, have an available energy potential that amounts to approximately 7 TJ/year (Figure 5c). When extrapolating this analysis proportionally as a preliminary analysis, an energy potential of approximately 28 TJ/year can be assumed for all the workshops that exist in Pichátaro (Figure 5d).

This mentioned energy potential does not consider end-use technologies; however, in the analyzed town few sophisticated technologies are used for cooking food and heating water [49]. In particular, traditional cooking devices (tripartite bases of stone or brick in whose center the combustion is carried out) are mainly used for these activities.

If the available energy were used to manufacture solid biofuels to be used in traditional stoves (10% efficiency) [48], and these could preserve the calorific coefficient analyzed in this research, a projection of the technical potential for the 50 workshops can be inferred at between approximately 7 TJ/year and 28 TJ/year, which could satisfy the energy demand of many families [79]. For example, the demand of 140 families could be satisfied, considering some previous studies (199 GJ/year) [49].

The use of wood residues can also generate economic and environmental benefits. In economic terms, each family that uses solid biofuels for all its energy consumption, for cooking food and heating water, can save more than $600 USD/year, which for some families represents their entire income of several months. On the other hand, the use of solid biofuels burned in efficient wood-burning stoves can generate health benefits: (a) minimizing the physical demand on housewives who carry firewood, which is sometimes extracted from the forest and carried several kilometers on their backs and (b) reducing emissions and avoiding smoke inhalation if biofuels are burned in wood-saving stoves. In addition to the environmental aspects, these benefits combine to optimize family income and provide access to affordable, renewable, sustainable and modern forms of energy.

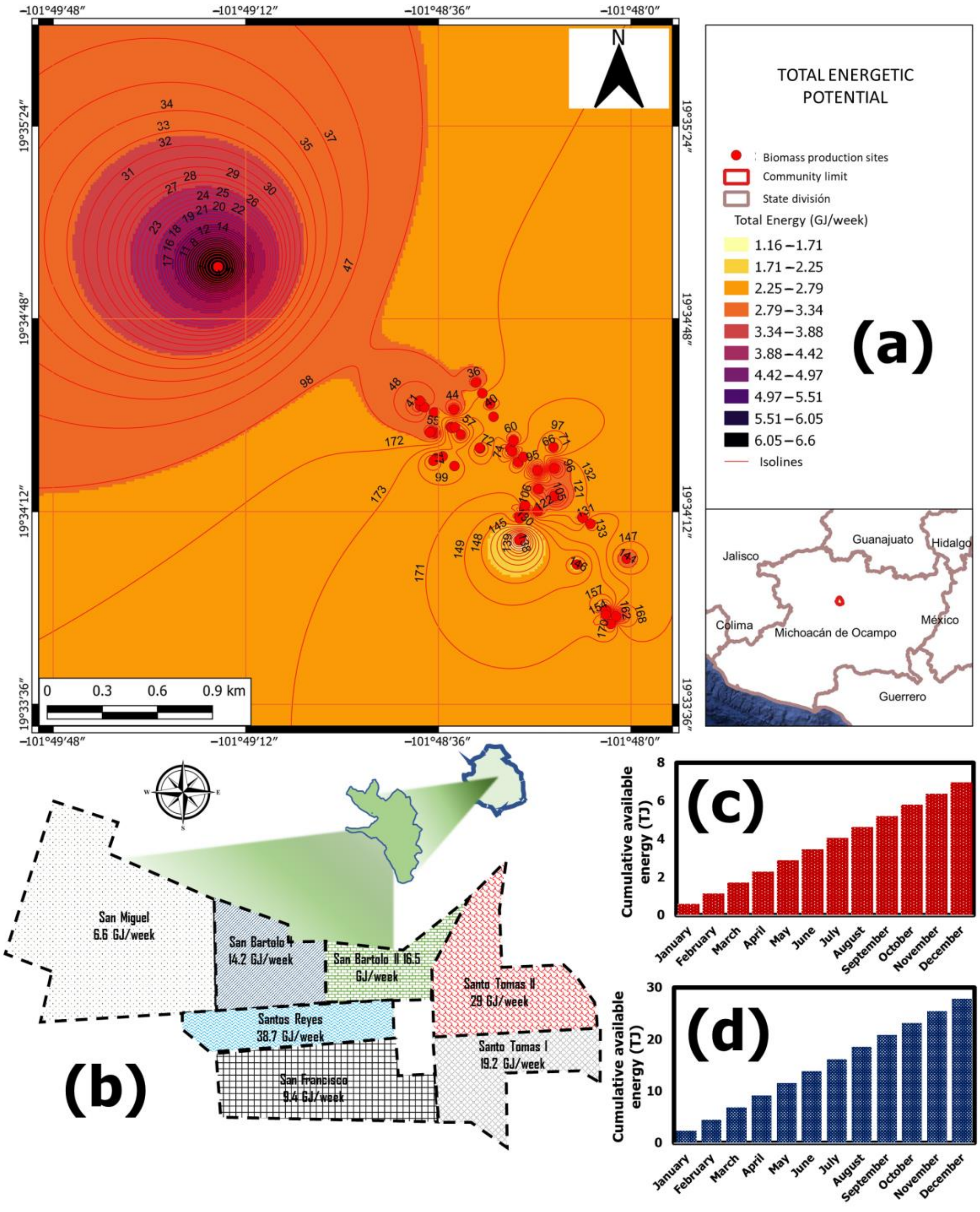

Figure 6. (**a**) Spatial distribution of energy potential, (**b**) distribution of energy potential by "barrios" in the community, (**c**) accumulated energy potential for the 50 workshops analyzed, (**d**) accumulated energy potential extrapolated to all the workshops in the community.

Also, it is important to mention that the energy potential is a way of knowing the energy available in the wood residues. The greater the heating value and the amount of waste, the greater the energy potential will be. In rural communities such as the one in this study, the total energy demand per family, which includes cooking, mobility and electric power, is estimated at 199 GJ/year [49], from which the relevance of the aforementioned available potential can be inferred. In addition, knowing this potential makes it possible to suggest strategies for using various types of fuels, the relevance of waste processing or the implementation of new technologies that complement the use of energy from waste. Therefore, it is useful to know the energy potential in order to ensure sustainable management of energy.

From the previous analysis, it is possible to identify the “barrios” and areas in the town where there is a greater concentration of workshops, and therefore, greater waste production. The southwest district is where the highest rates of biomass waste generation can be found.

At the same time, according to the analysis of spatiotemporal energy potential, strategic points can be identified for the management of solid biofuels. Figure 6a shows two critical areas with the highest waste generation, the central area of the community and the western area. Due to this condition, it is suggested that a collection and processing center be established in zone 1 for the generation of solid biofuels. While zone 2 requires a collection, processing, and final disposal center for all the inhabitants of the community, receiving the biofuels generated in zone 1. It is important to mention that some strategies have already been proposed for the production of solid biofuels from the artisan manufacturing [54], so this research is complemented by the results that are shown herein.

A comprehensive comparison of the general results that have been obtained is shown in Figure 7b,c. For a linear projection of the 50 workshops that generate biomass waste (Figure 7b), as well as for all the community workshops (Figure 7c), the theoretical and technical available energy potential can be seen. It also shows the economic savings that could be invested in equipment for the process of producing solid biofuels, obtained from unburned firewood, resources that amount to about \$20,000 USD/year and \$80,000 USD/year, for the case study and all the workshops, respectively.

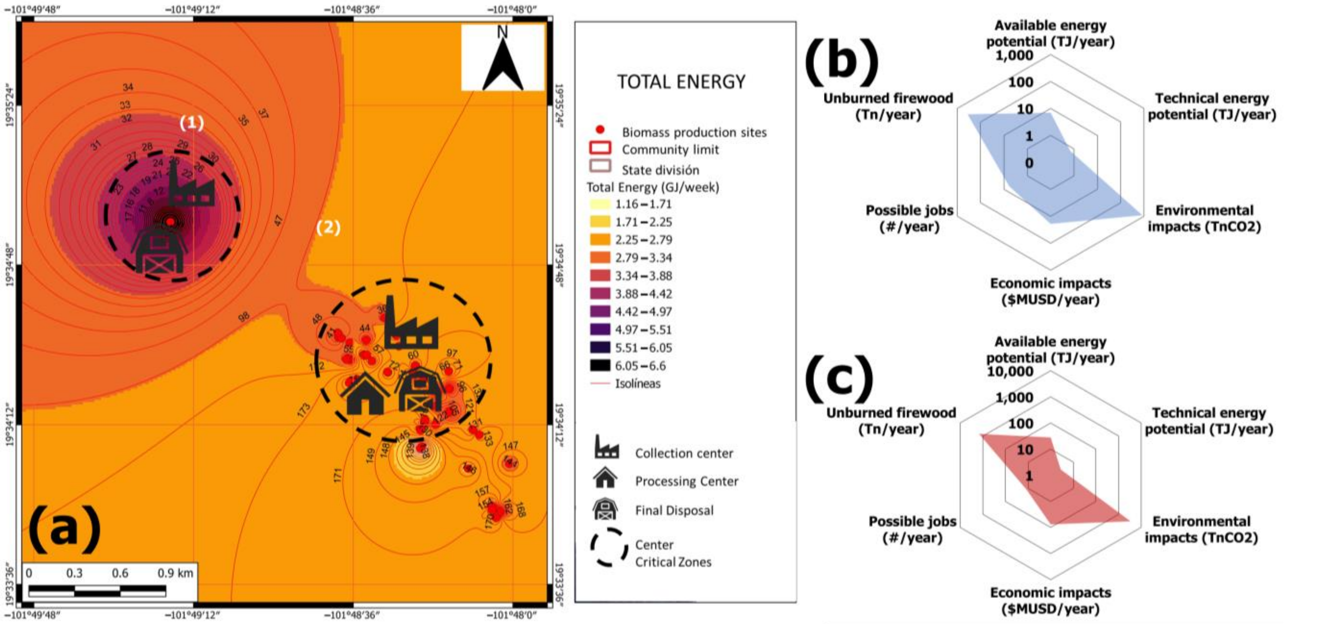

Figure 7. (**a**) Spatial management of the infrastructure for the management of solid biofuels. Integrated analysis of the biofuel management scenarios: (**b**) for the 50 workshops analyzed, (**c**) for all the workshops in the community.

As regards firewood consumption, it would be mitigated by approximately 350 to 1400 Tn/year (for particular and general cases), which would lead to a reduction of emissions in the community of more than 76 $TnCO_2$/year. In addition, if a solid biofuel manufacturing strategy is implemented, an alternative production chain would be generated that would require staff. This staff, due to the two critical bioenergy areas that were identified, needs to be of at least 6 employees for the case of the workshops and at least 12 for the general case. Depending on the technical specifications of the management strategy, staff may consist of full-time or part-time employees. This would at least slightly diversify the productive fabric of the town.

The solid biofuel management strategy is not only linked to the disposal of biomass residues, the energy potential, and the technical processing strategies. Some other aspects linked to the dimensions of sustainability should also be considered, most notably the following:

Environmental. The collection of timber waste in two strategic centers is feasible given the low dispersion of waste generation. However, it is necessary to limit transport through low-emission vehicles. The processing can be powered by passive technologies with mechanical or artisan functionality, or with low-power systematized equipment so that its energy consumption can be provided by locally available alternative energy sources. In addition, the use of these alternative fuels can be complemented through eco-technologies, such as wood-saving stoves [80,81].

Economic. It is feasible to use existing biomass residues in the community. Although they currently do not have added value, once their use becomes visible, they will no longer be free, so it is necessary to develop a fair and affordable alternative for buying and selling these resources. Additionally, all the processes for obtaining biofuels must be carried out locally and with the greatest number of local resources (raw materials/energy resources), to maintain a local, supportive economic scheme, as well as to avoid increasing the final prices of these energy products due to dependence on external agents, since local production is an important factor.

Social. Two operating schemes are required to ensure the management and sustainability of the project: (a) the generation of local ventures that provide economic incentives for this proposal in its initial stage and encourage the development of energy associations or cooperatives that can locally manage a solid biofuel production chain, and (b) the initiative of the local authorities that maintain an Indigenous self-government scheme, which receives and administers economic resources from the Mexican government to guide the local affairs of the community and to have a local public administration, which is governed by the traditional system of "usos y costumbres". The self-management of a local biofuel production chain would not only optimize the use of local residues, but it would also generate an affordable energy supply scheme for the entire population, helping mitigate the burning of wood and other fossil fuels. In any case, the strategy aims to build an affordable, fair and sustainable value chain that is economically profitable, ecologically viable and socially acceptable [82].

This research has brought to light some alternatives for the use of wood waste from the community of San Francisco Pichátaro. However, bioenergy use is still facing a number of challenges and limitations that are mentioned in this research:

- The production of waste depends on the market for wooden furniture, which has decreased considerably in recent years.
- The transformation of waste into solid biofuels requires community participation. The people need to assimilate and appropriate the processes to use the energy from locally available waste. The population must become greatly interested in these alternative fuels.
- The disposal of wood waste is currently free; however, when a production chain is defined, the waste will have a cost and a price will have to be established that can compete with the firewood that is consumed locally.
- The greatest potential for the use of waste will be achieved in efficient wood stoves. These end-use devices come at a cost that not everyone can afford.
- One area of opportunity for the use of waste for bioenergy lies in defining the energy mitigation cost, the investment cost and the retail cost of the biofuels that are generated, while establishing a system that can compete with conventional fuels such as firewood and L.P. gas.
- Employment management strategies that encourage the implementation of the collection, processing and final disposal centers for solid biofuels should also be explored.

An additional contribution of this research is based on two scopes according to the proposed methodology: (1) for the academic sector, the identification of technical-energy feasibility is determined from the estimation of waste production and laboratory analysis, but it is complemented with the participation of the inhabitants of the community, specifically of the artisan workshops in which the study was carried out; and (2) the estimation of the spatiotemporal energy potential is analyzed based on the participation of the artisans and through community diagnoses, in addition to defining guidelines for the possible management of locally available energy alternatives such as solid biofuels.

In summary, an agreement between the researchers and the community is key for determining joint proposals that will have a social impact. This type of research is currently motivated by persons in the community who are linked to groups of university researchers and are requesting support to find strategies for improvement in their community. Some of the authors of this research paper reside in the community of the study, so the alternative paradigm is the management of knowledge from local groups, aimed at empowering the community of the study and encouraging the management of local energy alternatives.

It is also important to mention that the implementation of these investigations establishes models for linking the community with the academic sector, which will allow them to be replicated in the future by more communities with similar characteristics, of which there are many in Mexico. Therefore, this research cements the possibility of implementing these biofuel management strategies, with the possibility of being applied in more rural communities.

4. Conclusions

This research establishes the feasibility of extracting the available energy potential of *Pinus* spp. timber residues as an alternative energy source within a rural community called Pichátaro. The data found on the timber biomass of the community provide an alternative, profitable, and environmental mitigation strategy, which can initially be inferred by projecting the technical potential of the 50 workshops, approximately 0.7 TJ/year to 2.8 TJ/year, to satisfy the energy demand of the population, following a linear projection of the 50 workshops of the same community.

The analyzed samples of timber residues had a heating value of 17.6 MJ/kg to 18.1 MJ/kg, while the proximal analyses determined an ash content of less than 0.6%, a volatile matter content of less than 90% and a fixed carbon content of less than 16%. The polymeric compounds were estimated as follows: cellulose less than 55%, hemicellulose less than 18% and lignin less than 28%. These compounds were corroborated by semi-quantitative chemical analysis, X-ray diffraction and infrared spectroscopy. Thus, the chemical composition also displayed average values of carbon at 48.16% ($\pm$0.44), hydrogen at 6.02% ($\pm$0.05), oxygen at 45.33% ($\pm$0.37), nitrogen at 0.45% ($\pm$0.09) and sulfur at <0.01%. These results are relevant because they are useful for determining the feasibility of using wood residues as raw materials for the manufacture of solid biofuels in the analyzed community.

The economic savings that could be invested in equipment for the solid biofuel production process were obtained from unburned firewood, resources that amounted to about $20,000 USD/year.

As regards the environment, firewood consumption would be reduced by about 350 Tn/year, which would reduce community emissions by more than 76 $TnCO_2$/year.

Finally, there is a need to generate and improve knowledge and awareness of the use of biomass as a renewable energy source and SBF as a new product that can replace or compete with fossil fuel in terms of price, energy savings and CO_2 emissions, in addition to the availability of resources, which avoids energy dependence. Therefore, identifying energy potential is important when exploring new ways to meet energy demand in communities like the one described.

For these reasons, this research highlights the potential of an Indigenous community in Mexico to satisfy its demand for thermal energy using *Pinus* spp. timber residues that are processed within the same community and densified as SBF, supplying energy locally, efficiently and sustainably.

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