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Characterization of Agricultural Residues of *Zea mays* for Their Application as Solid Biofuel: Case Study in San Francisco Pichátaro, Michoacán, Mexico

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Citation: Morales-Máximo, C.N.; López-Sosa, L.B.; Rutiaga-Quiñones, J.G.; Corral-Huacuz, J.C.; Aguilera-Mandujano, A.; Pintor-Ibarra, L.F.; López-Miranda, A.; Delgado-Domínguez, S.N.; Rodríguez-Magallón, M.d.C.; Morales-Máximo, M. Characterization of Agricultural Residues of *Zea mays* for Their Application as Solid Biofuel: Case Study in San Francisco Pichátaro, Michoacán, Mexico. *Energies* **2022**, *15*, 6870. https://doi.org/10.3390/en15196870

Academic Editors: Diego Luna and Attilio Converti

Received: 13 July 2022
Accepted: 14 September 2022
Published: 20 September 2022

Abstract: This proposal evaluates the energy potential of agricultural residues of *Zea mays* from an indigenous community in Mexico. The study consists of four stages: (a) evaluation of residue production in all community farming areas (b) morphological and physicochemical characterization, using scanning electron microscopy (SEM), as well as infrared spectroscopy (FTIR) and Raman (c) the proximal and functional evaluation of the residues, through fiber analysis, determination of fixed carbon, humidity, estimation of calorific value, ash microanalysis and elemental analysis, and (d) evaluation of energy potential and multicriteria analysis. The results show that *Z. mays* residues have initial moisture values of less than 10%, ash content below 20%, fixed carbon around 14% and a calorific value of 17.6 MJ/kg associated with polymeric compounds and carbohydrates, as well as a percentage of extractable compounds of the order of 40%. The production of these residues on the 249 hectares (ha) of cultivation used would generate 23 TJ/year, whereas if the total number of hectares available were cultivated, the total energy generation would be 330 TJ/year, which is enough to satisfy the wood fuel demand of approximately seven communities with the characteristics of the study community. Due to this potential, as well as the results of the characterization, the agricultural mentioned residues are an energy alternative to meet the energy demand in communities in Michoacán, Mexico.

Keywords: rural energy; solid biofuel; sustainability; *Zea mays*

1. Introduction

Currently, the interest of the world population in the new renewable alternative energy sources that can be made available in each country in a local and decentralized manner represents a response to the constant rampant and unsustainable energy consumption and is a way of trying to guarantee the supply of energy both locally and to satisfy energy needs at a global level. That is why, in recent years, there has been a growing interest in researching, producing and applying new forms of sustainable use of energy through renewable fuels that can replace conventional non-renewable fuels in the short term. The foregoing contributes to the reconstruction of a resilient and sustainable global economy, which can currently no longer depend on fossil fuels and non-renewable energy sources, the latter of which, in addition to being expensive and volatile in their prices, are a high-quality satisfier of growing environmental impact. Thus, the pressing need for new forms of energy has given rise to a rapid eco-technological and energy development from all existing renewable sources in the world. It is expected that these developments will lead to important technological advances, which will be reflected in a greater capacity to produce clean, affordable, non-polluting energy and will also help to generate reductions in production costs for the benefit of the population, which in sum contribute to the fulfillment of the 2030 agenda [1]. In environmental terms, there is a growing demand for energy and the need for a significant reduction in greenhouse gas (GHG) emissions, which in recent years has generated a high accumulation of mainly CO_2, methane, particulate matter $PM_{2.5}$ and some other pollutants, which have severely damaged the environment; some damage is due to the burning of fuels, and some is due to the different activities of the human population [2].

It is, therefore, necessary to develop sustainable alternatives to non-renewable energy sources [3], as these renewable sources will be able to complement the world's primary energy supply, which in the coming years, together with population growth and industrialization, will lead to an increase in the demand for fuels, and because they are renewable, they can be integrated into the production chain and current economy, albeit with more sustainable and resilient practices, which, in sum, generate long term socio-environmental benefits [4]. Among the renewable resources referred to, biomass is a fuel that has become very important in the last decade, considered as a waste with energy potential, since it has several advantages, such as its availability (residual, forest and agricultural biomass), its neutral emission of carbon in most cases where there are sustainable management systems for natural resources and its easy combustion for solid biofuels that make it a source of bioenergy that can help meet future energy demand [5]; in addition, it is a resource that is easy to use and is distributed in various latitudes and can formulate decentralized use and local energy supply strategies. The use, potential and improvement of the energy efficiency of biomass depends on its physicochemical characteristics, and these, in turn, depend on the type and region of origin to improve thermally operated waste conversion processes, which is a contemporary energy strategy throughout the world [6]. Thus, the energy that can be used from any residual biomass resource represents a low-cost alternative because it comes from waste and usually has a low environmental impact. Agricultural residues derived from corn plantations, for example, can be a sustainable alternative for supplying energy, mainly thermal, through biofuels, without altering the purpose for which they were cultivated, which is food and in some cases forage; however, because it is a residue in its "corn stubble" stage, it can be used locally to meet thermal energy needs, where the supply of forest-derived fuels is required. The use of transformed agricultural residues as biofuels could combat the immoderate logging of the forest whose resources are used as conventional fuels in different rural areas of the country [7]; in this way, the use of agriculture would not only provide food security but also energy options to satisfy basic needs. These second-generation derivative biofuels can be manufactured from lignocellulosic biomass or woody crops, mostly from forest residues or waste but also from agroforestry and/or agriculture [8]. In this sense, the present research shows a case study in a rural indigenous community called San Francisco Pichátaro in the state of Michoacán, Mexico; in this area, there are a large number of corn crops for edible use; when the corn plant becomes stubble (*Zea mays* Residue), it is burned in the open to leave the land clean for new cultivation, and what is not burned is milled for forage use, with it being a small percentage of those who use it; therefore, this research proposes the use of this residue for the generation of solid biofuels, validating its feasibility based on the morphological, physicochemical and functional and proximal properties characterization, as well as the determination of its relevance through an evaluation of the current and available energy potential by total cultivation areas. Finally, a multi-criteria analysis is carried out to compare the competitiveness of agricultural residues with conventional local fuels.

2. Materials and Methods

The methodology used for the evaluation of the potential of agricultural residues for solid-type biofuels integrates the following aspects: the evaluation of the potential of biomass for the production of biofuels, including availability; laboratory tests and estimation of the current available energy potential in the cultivation; and harvest extension areas with all available areas, see Figure 1.

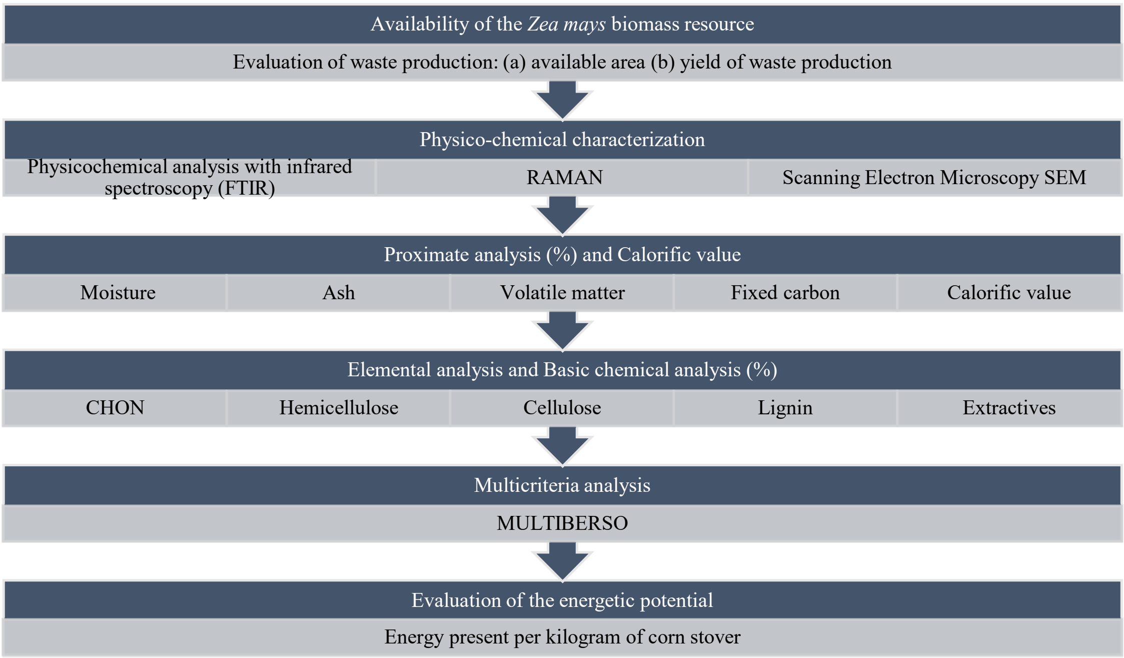

Figure 1. Methodology proposed for the research.

2.1. Availability of the Biomass Residue of Corn Stubble

This research is proposed as a case study in the community of San Francisco Pichátaro, Michoacán, which is part of the Purépecha plateau, located at 19° 34″ N and 101° 40″ W, at an altitude of 2350 m above sea level. The main economic activities of this community are forestry and agricultural. Studies show that in the basin of the Pátzcuaro Lake, where Pichátaro is located, around 20 local varieties of corn are planted of a mixture of eight races, of which the farmers of Pichátaro make use of 75%. Currently, the community has 249.25 ha of corn [9] that are frequently cultivated, but according to data of the Instituto Nacional de Estadística y Geografía (INEGI) and the Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO) [10], there are 3576.19 ha available for cultivation that are currently not producing corn. Due to the diversity of corn, the yields are varied; however, for this investigation a yield of 3500 kg/ha is assumed. Corn production is seasonal, that is, it is only produced subject to the rainy season in summer, which provides sufficient resources for crop growth, while the harvest period runs from the months of November to February of the following year; in that time interval the disposal of *Z. mays* residues is for forage or burned in the open to clean the cultivation areas, although in the first case it is a small percentage of farmers who take advantage of it because the community does not have a representative livestock vocation. The samples that were analyzed were collected from the cultivation areas and those characterization procedures are described below.

2.2. Physico-Chemical Characterization

The morphology and semi-quantitative elemental composition of the stubble biomass of *Z. mays* was performed by scanning electron microscopy (SEM) using a Bruker equipment Model Jeol JSM 7600F with field emission. Complementarily, another part of the chemical analysis was performed by Fourier Transform Infrared Spectroscopy (FTIR), which was carried out using the Thermo Scientific Smart Orbit accessory with the Thermo Scientific

Nicolet 6700 spectrometer (measurements were made by ATR). A total of 96 scans were performed at 4 cm-1 resolutions, operating over a range of 4000 to 400 cm-1 and 3 analyses were performed for each sample using Thermo Scientific OMNICTM software to determine the bands. Raman spectroscopy was also used with a SENTERRA equipment, Bruker brand, with a 532 nm laser. For this analysis, 2 kg of stubble were collected in four different parcels with respect to the four cardinal points, obtaining four samples on average of 125 g each.

2.3. Proximate Analysis and Calorific Value

The initial moisture content of the stubble was determined in triplicate according to UNE-EN 14774-1 Standard [11], was determined in triplicate by the dehydration method. The ash content of agricultural residues was determined according to the EN 14775 (2010) standard [12] and the content of volatile matter according to the ASTM E872-82 standard [13]. For this case, absolutely dry 40 mesh stubble meal (CS) was used. Fixed carbon was calculated by difference, subtracting the ash content and the volatiles by 100% [14]. The calorific value of the stubble samples was determined using a semi-automatic calorimeter (LECO AC600, MI, USA, Durango Mexico) in accordance with the EN-14918 standard [15]. For this purpose, absolutely dry 40 mesh stubble meal (CS) was used, and the analysis was performed in triplicate for only two collected samples.

2.4. Elemental Analysis and Basic Chemical Analysis

The content of carbon, hydrogen and nitrogen was measured in an elemental analyzer (Model 4010; Costech International SpA, Milan, Italy) following the UNE-CEN/TS 15104 EX (2008) standard [16]. For this case, biomass was used that was sieved in an absolutely dry 40 mesh, and the oxygen was calculated by difference. The percentage of cellulose, hemicellulose and lignin were determined via fiber analysis based on the Van Soest gravimetric method using α-amylase in an ANAKOM-200 device [17]. As for the extractives, they were determined by differentiation of cellulose, hemicellulose and lignin, and corrected for ash content [18]. For this purpose 0.5 g of 40-mesh absolutely dry stubble (CS) was used [19]. For the above, the corn stubble was milled before finally proceeding to sieve, in a RO-TAP apparatus using ASTM E-11 (2020) [20] standard meshes (numbers 20, 40 and 60), the 40-mesh meal (425 µm) according to the T 264 cm-97 standard (TAPPI 2000) [21].

2.5. Multicriteria Analysis

Multi-criteria analysis is a methodology that allows the use of sustainability indicators to comprehensively evaluate processes, technologies, systems and, in particular, fuels. This approach has been used in integrated assessments of technologies using renewable and eco-technical energy sources, the use of this methodology is with the objective of knowing the strengths that the biofuel derived from agricultural corn waste may have, which will be compared with other biofuels in different parameters; such as energetic, chemical, physical and matter of use. For this analysis, the MULTIBERSO program was used [22].

2.6. Evaluation of the Energetic Potential

The energy potential of the biomass was obtained from the relationship between the mass of dry residue (Mrs) and the energy of the residue per unit mass (E), also known as calorific value (PC). Equation (1) expresses the relationship between the variables and proposes an approximate mathematical model [23].

$$PE = (Mrs) * (E) \tag{1}$$

where:

PE: Energy potential [TJ/year]
Mrs: Mass of dry residue [t/year]
E: Energy of the residue per unit mass [TJ/t]
CV: Calorific value (MJ/kg)

For the substitution in the formula regarding the number of hectares cultivated with corn, 249.25 hectares registered in PROAGRO 2014 were taken as reference [9].

To make the previous estimate, a stubble production yield of 1.5 kg/kg of corn was considered [24].

2.7. Statistical Analysis

In the case of the analyses that were performed more than once, in order to compare the data obtained, an analysis of variance was performed at 95% statistical confidence and the mean values were compared using the multiple range test with the method of least significant difference (LSD) [25]. The data obtained were processed using Statgraphics Centurion 19.2.01. In all cases, the mean value and standard deviation are reported.

3. Results and Discussion

3.1. Physicochemical Charactarization

The analysis with infrared spectroscopy (Figure 2a) allowed us to identify the functional groups present in the corn residue (stubble). The presence of polymeric compounds, such as cellulose, hemicellulose and lignin can be specified, as well as some extractables, are suitable for the generation of a good biofuel, since they contribute to providing a high energy content. Using FTIR it was possible to identify bands at 898 [26] for C-H, corresponding to the deformation in cellulose, 1055 [27] for C–O stretch in cellulose and hemicellulose, 1115 and 1116 [28] C–O–C for stretching and symmetric vibration of the ester bond and CH stretching in aromatics ring (syringyl), 1158 [29] for C–O–C vibration for cellulose and hemicellulose, 1463 for deformation stretching of CH_2 in lignin and xylan, 1734 [30] for unconjugated C = O in xylans (hemicellulose), 2930 [31] for asymmetric CH_2 (guaiacyl-syringyl) vibration and at 3400 for O–H stretching [32]. Infrared spectroscopy was contrasted with Raman spectroscopy, which complements the characterization of corn stubble and shows bands in the regions between 1000 and 1300 cm^{-1} and 1500 and 1700 cm^{-1} [32], that correspond to Glucose and Cellulose, compounds formed by carbon, hydrogen and oxygen: CH_2, C-O-H, C-C-H, O-H y C-H (Figure 2b) [33]. Thus, the presence of polymeric compounds and carbohydrates, such as glucose, contribute to the calorific value of this biomass resource.

The micrometric morphology of the laminar and agglomerated type of *Z. mays* residues can be seen in Figure 2c. Additionally, the compounds present in the functional groups and polymeric and glucose compounds are appreciated in the semi-quantitative chemical mapping in Figure 1d–h. In the identification of chemical elements, the presence of Carbon (C), Oxygen (O), Magnesium (Mg), Aluminum (AI), Silicon (Si), Phosphorus (P), Potassium (K) and Calcium (Ca) are observed. This analysis is complemented by the data in Table 1, which shows the percentage by mass of the chemical elements present in the corn residues of the analyzed samples, with the presence of carbon with a maximum of 78.42% and a minimum of 62.99, with the presence of oxygen with a maximum of 36.83% and a minimum of 18.11, magnesium has a presence of a maximum of 0.27% and a minimum of 0.05%, aluminum has a maximum of 0.27% and a minimum of 0.13%, silicon is found with a maximum of 8.78% and a minimum of 0.2%, phosphorus has a maximum of 0.10% and a minimum of 0.04%, chlorine has a maximum of 2.45% and a minimum of 0.34%, potassium has a maximum of 8.13 % and a minimum of 0.45%, calcium has the presence of 1.63% maximum and a minimum of 1.63% and molybdenum. Of the various samples that were tested, the results were quite similar. The analyses in Figure 2 articulate with each other to show the identification of polymeric compounds and the presence of carbohydrates, such as glucose, which can be inferred by the presence of certain functional groups due to the characterization by FTIR (Figure 2a) and RAMAN (Figure 2b) that contrast with the elemental chemical identification obtained by SEM (Figure 2h). These compounds contribute to the calorific value of biomass and allow it to be considered as an energy source.

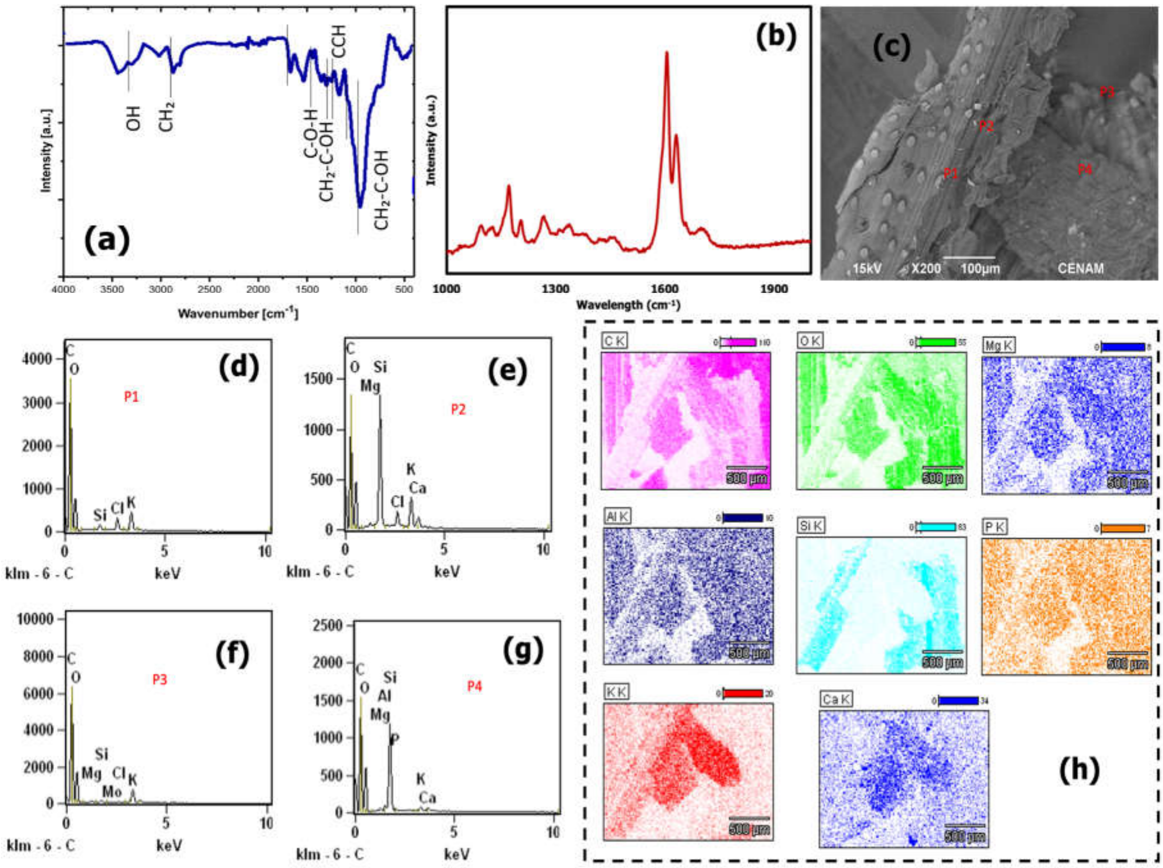

Figure 2. (**a**) FTIR (**b**) Rama spectroscopy (**c**) SEM, semi-quantitative chemical analysis: (**d**) point 1 (**e**) point 2 (**f**) point 3 (**g**) point 4 (**h**) chemical mapping.

Table 1. Mass percentage of the elements present in the biomass of corn stubble (%).

Sample	*C-K*	*O-K*	*Mg-K*	*Al-K*	*Si-K*	*P-K*	*Cl-K*	*K-K*	*Ca-K*	*Mo-L*
P1	66.34	25.01			0.67		2.45	5.53		
P2	62.99	20.39	0.19		8.78		1.74	4.28	1.63	
P3	53.52	36.83	0.27		0.53		0.34	8.13		0.39
P4	70.90	22.14	0.09	0.27	5.76	0.10		0.45	0.30	

The scanning electron microscopy in the corn stubble residue (CS) reported in this research shows the presence of elements, such as Carbon (C), Oxygen (O), Magnesium (Mg), Aluminum (AI), Silicon (Si), Phosphorus (P), Potassium (K) and Calcium (Ca); other investigations show the detailed inorganic components of corn stubble fractions, the contents of inorganic elements varied and K, Si, Cl, Ca, Mg and S were the main components inorganics in corn stubble fractions [34]. According to the findings of other investigations in corn stubble, shown in spectra, indicate that it contains elements, such as carbon 53.9%, oxygen 44.4%, potassium 1.0%, chlorine 0.3%, calcium 0.1%, magnesium 0.1%, silicon 0.1%, and aluminum 0.1%, in various amounts [35], while this research reports carbon with a maximum of 78.42% and a minimum of 62.99, with the presence of oxygen with a maximum of 36.83% and a minimum of 18.11%, magnesium has a maximum of 0.27% and a minimum of 0.05%, the aluminum maximum is 0.27% and minimum is 0.13%, silicon is found with a maximum of 8.78% and a minimum of 0.2%, phosphorus maximum is 0.10% and minimum is 0.04%, chlorine maximum is 2.45% and minimum is 0.34%, potassium maximum is 8.13% and minimum is 0.45 %, calcium with the presence of 1.63% maximum and a minimum of 1.63% and molybdenum, indicating these percentages are higher than those reported in the other investigation. The above results show that a representative content of extractives compounds and glucose, which can be linked to the energy content of these residues. This will be discussed later.

3.2. Proximate Analysis and Calorific Value

Table 2 shows the result of the proximate analysis of the stubble samples. The initial moisture found in the samples (CS) ranged from 7.04% (±0.62) to 8.43% (±0.50) with an average value of 7.99% (±0.55). The result of the analysis of variance indicates that there are statistically significant differences between the collection sites. The average moisture value found is lower than the range reported in other research for this same type of material (12.01 to 12.44%) [36]. Prior to a densification process, approximately 10% moisture content is suggested [37]. Moisture content below 50% can be used for direct combustion; if it is higher, drying operations are necessary, which increases the costs for its use. Moisture is an important starting parameter, since the energy conversion of the positive residue will be either positive or negative at the time of combustion [38]. The average moisture content of the stubble samples of this research indicate an excellent raw material for densification, as they do not require pre-treatment by drying or oven drying, which entails the integration of economic resources to establish the moisture content, as they do not present this situation; it is an optimal material due to its characteristics for the densified material.

Table 2. Proximate analysis of biomass of corn stubble (%).

Analysis	Corn Stover Samples			
	CS1	CS2	CS3	CS4
Moisture	8.30 (±0.26)	8.O7 (±0.02)	7.04 (±0.62)	8.11 (±0.48)
Ash	9.52 (±0.22)	7.38 (±0.31)	7.45 (±0.06)	14.57 (±0.33)
Volatile matter	76.37 (±0.30)	82.65 (±0.51)	82.07 (±0.37)	72.69 (±0.06)
Fixed carbon	14.10 (±0.51)	9.96 (±0.81)	10.46 (±0.35)	12.77 (±0.27)

As for ash content, significant differences were found, where CS2 and CS3 are different from CS1 and CS4, as these samples come from different batches. The ash content was found in a range of 7.38% (±0.31) with a mean value of 7.28% to 14.57% (±0.33) with a mean value of 14.19%. (Table 2); the percentage variation may be a function of where the plant grows and where it was collected [39]; investigations reported in the scientific literature on corn stubble show results through a pyrolysis process in an atmosphere of CO_2, with a value of 6.8% [40]. Through grinding for generation, the ash content was 7.46% [41]. According to Pierre-Luc Lizotte (2015) [42], the stubble ash content in corn in its standing growth stage averaged 4.8% in a cold crop heat unit zone, 7.3% in a warmer zone, even a deep analysis shows that the highest ash content is present in the leaves of the plant with values of 7.7% to 12.6% [42]. Regarding the ash content found for this research, it is shown that the results obtained are similar to other investigations with an average value of 11.64%, which is high, but it is still adequate due to its calorific value and moisture content; it is suitable for the generation of solid biofuels, and its high ash content can be used for other types of biofuels, such as biorefining.

Regarding the volatile matter, the results obtained from the corn stubble (CS) in this research were of a range of 72.69% (±0.06) to 82.65% (±0.51) (Table 2). The results obtained here are similar to those of these previous investigations, so the high volatile content confirms its potential for conversion into a high yield of bio-oil by fast pyrolysis [27], as well as for the generation of other biofuels.

Regarding the content of fixed carbon, the results found show a variation that ranges from 9.96% (±0.81) to 14.10% (±0.51) (Table 2). The analysis of variance indicates that there are no statistically significant differences. Finally, an investigation of samples of agricultural residues and pine sawdust reported 15.54% of fixed carbon [7], a combination for the generation of pellets. Therefore, the fixed carbon found in this investigation turns out to be lower, compared to other similar investigations; this will mean that in the final combustion stage in a final use device (burner), the total remainder due to the ignition of the fuel is, in percentage, low or lower, compared to other stubble residues.

The calorific value of the stubble samples (CS) ranged from 17.7 MJ/kg to 17.9 MJ/kg. The results found for the calorific value of the stubble in this investigation turned out to be similar to other investigations. Within the study community there are two wood fuels that are used for the generation of thermal energy that are called Pine firewood (*Pinus* spp.) and Oak firewood (*Quercus* spp.) whose maximum calorific value reported in the scientific literature for these species is 20.92 MJ/kg [43] and 19.5 MJ/kg [44], respectively; even an investigation of *Pinus* spp. waste briquettes is reported, where the calorific value found was 17.6 MJ/kg [45]. Compared with other biofuels present in the study community, the stubble residue turns out to be competitive and viable for the production of densified materials, since the variation in calorific value is little compared to pine and oak firewood, but with briquettes it even turns out to be to higher, which confirms that this biomass residue is suitable for the production of solid-type biofuel due to its considerable calorific value.

The foregoing is inferred from the fact that the detected moisture content of the stubble material turns out to be adequate for the manufacture of solid-type biofuels, since being low, the content will not affect the generation of energy. On the other hand, the high content in the stubble can affect the combustion equipment and the users of the residential sector due to the cleaning process; even so, it is a good material for densification. Finally, the high content of volatiles can be beneficial in combustion because the mixture allows the ignition temperature to increase and, therefore, the calorific value indicates that the product with a high percentage of volatile material and low content of fixed carbon reduces friability and brittleness; it also increases its resistance to compression and cohesion.

3.3. Elemental Analysis and Basic Chemical Analysis

The average results obtained from the elemental analysis of the corn stubble samples are as follows: carbon 42.48% (±0.44), hydrogen 6.06% (±0.11), oxygen 50.93% (±0.50) and nitrogen 0.83% (±0.50).

According to Medic [46] the milled stubble at torrefaction temperature (°C) and a gas residence time of 60 s (s), the elemental analysis found was for C = 46.27 (±0.22), H = 5.81 (±0.24), N = 0.63 (±0.06) [46]. The results found here are similar to other reported investigations, even below what is reported, which indicates that it is a good parameter for the environmental issue, since in the matter of carbon, at the time of oxidation in combustion it is converted into CO_2, which could become carbon neutral, and on the N side, it turns out to be low, compared to other agricultural crops or biomass residues [47], which makes it a parameter and not so harmful to the environment.

The average results obtained from the basic chemical analysis of maize stubble samples are as follows: hemicellulose 26.96% (±0.60), cellulose 26.87% (±3.64), lignin 5.07% (±2.43) and extractives 31.35% (±5.45). Investigations concerning chemical analysis show the following results: cellulose 32.75%, hemicellulose 31.08%, lignin 10.07% [48], cellulose 37.57%, hemicellulose 27.0%, lignin 17.99% [49], cellulose 30.4%, hemicellulose 21.4% and lignin 17.2% [50]. Another study shows that corn stover, when pretreated and washed, contains 60.01% cellulose, 27.33% hemicellulose and 6.87% lignin [51]. The results of our chemical analysis are similar to those previously reported for corn stover, which can be used for biofuel generation as a renewable energy source. The presence of these compounds is consistent with the characterization data by means of SEM, FTIR and Raman, since it allows confirmation of the presence of said polymeric and extractives compounds to which some glucose derivatives are linked, and which are closely linked to the high power calorific value that has been estimated. Therefore, in terms of energy, they represent a viable alternative available locally.

3.4. Multicriteria Analysis

This multicriteria analysis is a comparison that is based on a comprehensive assessment to define the strengths and opportunities of the different fuels analyzed; the parameters and indicators used are shown in Table 3.

Table 3. Parameters and indicators used in the multicriteria analysis.

Parameter	Indicator
Energetic	Calorific value (MJ/kg)
Proximate analysis	Moisture (%) Ash (%) Volatile matter (%) Fixed carbon (%)
Chemical composition	Lignin (%) Cellulose (%) Hemicellulose (%) Extractives (%)

The value of the indicators used has been reported in other investigations [43–45].

Weighting with maximum and minimum values that define the best and worst scenario, the data of the maximum value are obtained from the scientific literature, see Table 4.

Table 4. Values of the indicators.

Indicator	Maximum Value	Minimum Value
Calorific value (MJ/kg)	26.03	0
Moisture (%)	15	0
Ash (%)	10.7	0
Volatile matter (%)	80.40	0
Fixed carbon (%)	31.79	0
Lignin (%)	21.7	0
Cellulose (%)	57.4	0
Hemicellulose (%)	31.11	0
Extractives (%)	53	0

The multicriteria methodology is not a tool *per se*; it must always be comparative. In this study, the following residues were analyzed for comparison, since they are the ones found in the study community: (1) pine residue (*Pinus* spp.), (2) oak residue (*Quercus* spp.) and the corn agricultural residues (*Zea mays*) of this research. The actual evaluation of the indicators for the two case studies is shown in Table 5.

Table 5. Evaluation of the indicators.

Indicator	Corn Residue (*Zea mays*)	*Pinus* spp. Residue	*Quercus* spp. Residue
Calorific value (MJ/kg)	17.6	20.92	19.5
Moisture (%)	7.99	15	25
Ash (%)	7.3	0.64	0.95
Volatile matter (%)	72.57	82.9	87.33
Fixed carbon (%)	9.19	8.9	8.88
Lignin (%)	5.07	22.5	4.9
Cellulose (%)	26.87	54.73	38.4
Hemicellulose (%)	26.96	13.14	24
Extractives (%)	41.09	20.55	6.94

Note: The values of the wood residues of *Pinus* spp. and *Quercus* spp. were obtained from the scientific literature.

These values (Table 5) are normalized to establish a scale from 0 to 10. Where 0 represents the worst possible scenario and 10 the best. The normalized values can be seen in Figure 3 that show the multi-criteria analysis and sustainability indicators.

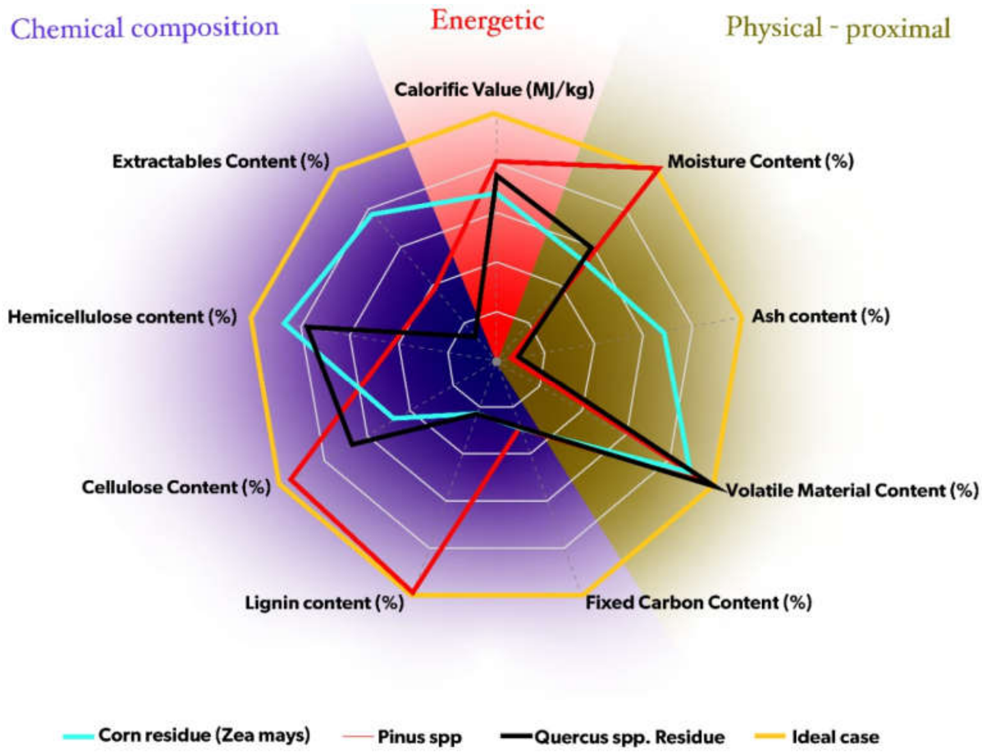

Figure 3. Formulation of indicators with different parameters.

The different indicators that intervened in the respective analysis are shown in Figure 3 through which the potential of the agricultural residue of *Zea mays* can be identified, compared to the wood residues of *Pinus* spp. and *Quercus* spp. present in the same study community, strengths and weaknesses can be seen graphically in different aspects, from an energetic, physical-proximal and chemical composition approach.

The calorific value indicator shows a similarity, compared to the other two types of residues present in the community (*Pinus* spp. And *Quercus* spp.), given that this parameter is fundamental and having a considerable calorific value makes it an excellent material for the generation of solid-type biofuels.

In the moisture content, the *Z. mays* residue is lower, compared to the moisture content of the *Pinus* spp. and *Quercus* spp. Being of a low percentage, no prior drying is required to stabilize the samples at a moisture content that allows the production of solid biofuels; the final moisture that it has makes it an excellent raw material for densification.

Regarding the ash content, that of corn stubble turns out to be high, compared to the other two residues involved, which may be a parameter for certain end-use devices where combustion is required; a high ash content is generated in this process, for which device maintenance will be required or its application in devices may be sought to remove the ashes without complications.

In the content of volatile material, the results are similar, there is a minimal difference, only the sample of the residue of *Quercus* spp. contains a higher content of volatile material that can be harmful to the environment.

Regarding fixed carbon, there is no significant difference between the three residues (Average: 9.73%).

For the lignin content, the highest percentage turns out to be the residue of *Pinus* spp., which directly influences the calorific value, which may be higher in this type of residue, compared to *Quercus* spp. and *Z. mays*, although its content in the stubble is low, and it does not interfere with the calorific value detected as such, which is usually like the other two residues.

In the case of the content of extractives, the *Z. mays* residue has a high content of extractables, which compensates for the low content of lignin, since this content can directly influence the combustion of the densified material and generate a high calorific value, compared to the other two residues, which have a low extractable content; in the case of cellulose *Z. mays* the content is low, and for hemicellulose its content is similar to *Quercus* and higher than *Pinus*.

In summary, agricultural residues, such as *Z. mays* corn stubble, represent an abundant and competitive raw material, compared to other residues, such as timber, *Pinus* spp. and *Quercus* spp. in energetic aspects, physical-proximal and chemical composition, and it is seen as a raw material for the generation of bioenergy with sustainability indicators.

3.5. Evaluation of the Energy Potential

In this research, two scenarios have been considered, the first identifying the total energy potential that exists in the community based on the identified calorific value, the yield of the corn crop, the generation of waste per kilogram of corn and the hectares cultivated at this time (2022); in this case, the production potential between the months of November and February reaches a total of 23.42 TJ/year of energy (Figure 4a). However, the total available cultivation area exceeds 3000 ha, which, if cultivated with corn, would have an energy potential in the order of 336.07 TJ/year (Figure 4b). Quantitatively and without processing, it is not clear to measure the scope of the energy potential, however, considering previous research that has shown that the rate of consumption of timber forest resources in indigenous communities of Michoacán is around 6.9 Tn/year for families of five people [52], it is possible to identify the final energy demand, assuming a calorific value of 19 MJ/kg of firewood; therefore, in this case, the use of the total energy potential of the entire cultivation area could provide, during the months that corn residues are generated, the satisfaction of the demand for wood fuel of about 7797 families. Considering that each community has about 1000 families, the energy resources would cover a region of about a little more than seven communities.

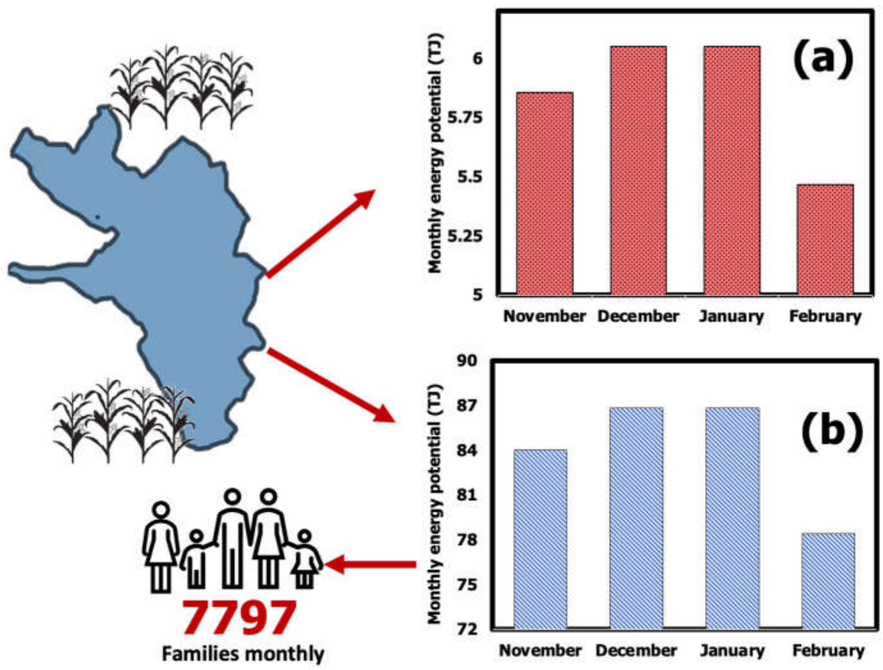

Figure 4. Energy potential of *Zea mays* residues, in the community of San Francisco Pichátaro: (**a**) in the currently cultivated area (**b**) in the totally available agricultural area.

From the foregoing, the opportunities that the use of these agricultural residues possesses can be inferred, and while although in this investigation they have limited themselves to evaluating the technical feasibility and energy potential, it is possible that in future works, the economic, environmental benefits and social aspects of the use of these possible fuels are investigated. Waste can also be transformed to generate densified materials, such as pellets or briquettes, that establish production chains with added value and potential for replicability in other communities. Finally, these resources represent a sustainable energy alternative, viable due to its local availability, efficient because it can be used as a fuel that satisfies needs and that can eventually satisfy the demand for thermal energy, as well as being profitable because, although at this time it does not have an associated cost, its local availability and abundance anticipate economic feasibility.

Since the main source of energy used in the community is thermal, the use of *Z. mays* residues as solid biofuels could be even more efficient with the use of end-use technologies, for example, biomass-saving stoves, such as the Patsari. This would reduce conventional consumption by approximately 30% and project the satisfaction of the needs of up to 10,136 families. Gasification thermoelectric plants could also be implemented that will use these residues and satisfy the demand for electrical energy. The use of these biomass residues is versatile and can contribute to generating a local energy system with the use of these technologies, promoting community energy self-sufficiency [53].

3.6. Final Remarks

The use of *Zea mays* residues represents an alternative for valuing local resources. In addition, it encourages self-sufficiency and energy sovereignty and helps us to generate strategies to address some relevant aspects that the study community and neighboring indigenous communities have, among which the following stand out:

- The change of land use, for the production of exogenous crops that generate negative impacts of an environmental and socioeconomic nature. This, coupled with the low economic profitability that this crop has experienced in recent years, promotes the abandonment of corn production practices. However, if it is reactivated, the evaluation of waste could be encouraged to satisfy the demand for local energy, which mainly depends on forest biomass, so there is a little explored area of opportunity. Reactivating the planting of corn at this time would generate double benefits; on the one hand, recovering an ancestral production system that is necessary and that provides food sovereignty in addition to low environmental impacts to the ecosystem, and on the other hand, because the community does not have a significant livestock vocation, the use of corn residues would contribute to the generation of clean, economic and local energy.
- Coordination with government programs. Currently, the Government of Mexico has programs to reactivate local production systems; one of them, "Sembrado Vida", generates economic incentives to promote the cultivation of corn. If this type of program were spread even more, the active cultivation area would be larger, which would generate a possible and representative use of residues that have high energy potential, as previously mentioned.
- Previous studies have already been carried out that show the feasibility of using forest biomass residues for the production of solid biofuels (Briquettes), which can be manufactured locally and that, in efficient end-use technologies, would generate benefits for this locality study. Therefore, it is suggested to explore the technical feasibility of *Z. mays* residues as biofuels, with the aim of diversifying the matrix of energy production from these local resources. In addition, unlike the forest, the production of agricultural residues has a faster and more periodic generation capacity, which by exploiting large areas of cultivation could significantly satisfy, in a complementary way, the demand for thermal energy at the local level.
- This locality (Pichátaro) is governed by the indigenous self-government scheme, which is economically and legally managed locally, with subsidies from the Mexican govern-

ment to meet their basic needs. Therefore, the generation of energy locally is a way to strengthen their processes of self-sufficiency and self-determination. They also have local programs that can disseminate efficient energy consumption practices regulated from their community decisions, which makes the energy transition based on energy production through their local energy resources attractive.

Additionally, the community maintains a close link with a group of academics who are studying the possibility of inserting sustainable technologies, which could use the agricultural residues of *Z. mays*, which would contribute to generating an efficient, economical, resilient, local energy consumption process that is sustainable. The latter will be shown in future research.

In this way, it can be highlighted that the use of *Z. mays* residues as an energy resource at the local level is attractive because it can promote the formulation of sustainable rural energy systems, which are managed from their forms of local government. In addition, it is a resource with energy potential (high calorific power) and with wide scalability due to the available cultivation areas and the null valuation of this residue. It cannot be an immediate substitute for the forest fuels that are used (not to say whether it is better or worse than firewood), but it can gradually complement the matrix of local energy demand, be economically profitable because it is waste, and encourage the use of new end-use technologies, including electricity production plants, such as biomass gasifiers.

If practices of energy use of this residue are implemented in indigenous communities, such as the one analyzed, more communities could replicate the consumption scheme of their local agricultural resources and diversify the use to satisfy their most pressing needs.

4. Conclusions

The study carried out in the present research shows the technical feasibility of using an agricultural biomass residue, as well as its available energy potential, which can represent an alternative energy source within the community of Pichátaro; the data found from the biomass generated from *Zea mays*, from the community, represent a resilient, profitable and environmental mitigation alternative.

The average moisture value found in the stubble was 7.99%, being a low percentage, compared to other moisture contents that turn out to be higher, compared to the one reported here, since it does not require an artificial drying pretreatment to stabilize the moisture content and more easily produce solid-type biofuels (BCS), for which this residue turns out to be viable to produce this type of fuel. The average calorific value found in the stubble samples was 17.6 MJ/kg, which, when compared to other biofuels present in the study community, the difference is little (±1 MJ/kg), compared to pine and oak firewood, which confirms that this biomass residue is suitable to produce BCS due to the energy released at the time of his combustion.

Finally, it was identified that the total available cultivation area in this study community exceeds 3000 ha, which, if cultivated with corn, would have an energy potential of the order of 336.07 TJ/year, with which the demand of various communities could be satisfied.

The use of these residues together with the use of efficient technologies can generate an efficient, economical, resilient and sustainable local production and consumption chain. Therefore, identifying energy potential is important to explore new ways of satisfying energy demand, which in communities, such as the one described, is mainly thermal energy.

That is why this research shows the energy potential that an indigenous community in Mexico can have to meet the demand for thermal energy through its native corn crops, which in its residue stage (stubble) can be used as material for the densification of BCS, since meeting the thermal needs of the community with its own waste represents a form of local, efficient and sustainable energy management, and encourages the formulation of alternative energy systems that have replicability potential in communities with similar characteristics.

Author Contributions: Conceptualization, C.N.M.-M., L.B.L.-S. and M.M.-M.; Data curation, J.C.C.-H., S.N.D.-D., M.d.C.R.-M., L.F.P.-I., J.G.R.-Q., L.B.L.-S. and M.M.-M.; Formal analysis, L.B.L.-S., J.C.C.-H., M.M.-M., A.L.-M. and L.F.P.-I.; Funding acquisition, L.B.L.-S., S.N.D.-D., M.d.C.R.-M., J.C.C.-H., J.G.R.-Q. and M.M.-M.; Investigation, C.N.M.-M., L.B.L.-S. and M.M.-M.; Methodology, C.N.M.-M., L.B.L.-S., J.C.C.-H. and M.M.-M.; Project administration, S.N.D.-D., J.C.C.-H., M.d.C.R.-M., A.A.-M., A.L.-M., J.G.R.-Q. and M.M.-M.; Resources, L.F.P.-I., A.L.-M., J.C.C.-H., M.M.-M., M.d.C.R.-M., A.A.-M. and L.B.L.-S.; Software, L.B.L.-S., J.C.C.-H., C.N.M.-M. and M.M.-M.; Supervision, M.d.C.R.-M., S.N.D.-D. and J.G.R.-Q.; Validation, L.B.L.-S. and J.G.R.-Q.; Visualization, A.A.-M., M.M.-M., A.L.-M., J.G.R.-Q., S.N.D.-D. and M.d.C.R.-M.; Writing—Original draft, L.B.L.-S., A.A.-M., C.N.M.-M. and M.M.-M.; Writing—review & editing, L.B.L.-S., J.C.C.-H., A.A.-M. and J.G.R.-Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank the Indigenous Community of San Francisco Pichátaro, the Intercultural Indigenous University of Michoacán, the Michoacán University of San Nicolás de Hidalgo and the National Metrology Center, M.C. Margarito Álvarez Jara and de PRODEP 2021 program for their support in carrying out this research.

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

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