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Briquettes from *Pinus* spp. Residues: Energy Savings and Emissions Mitigation in the Rural Sector

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Abstract: This study analyzes the household energy needs of the indigenous community of San Francisco Pichátaro, Michoacán, Mexico, and the use of *Pinus* spp. wood residues for the production of briquettes. The energy and emission performances of wood briquettes were evaluated on the field and in the laboratory. On-field surveys and measurements show that most users combine the use of fuelwood and LPG for cooking and heating water, and 65% of people use fuelwood daily (40% of houses consumed more than 39 kg per week). The use of biomass waste is an energy option in rural communities and contributes to reducing firewood consumption and mitigating GHGs. Briquettes gasification to heat water reduces 74% of GHG emissions, increases the thermal efficiency by 30%, and reduces pollutant emissions of CO, CH_4, and $PM_{2.5}$, NMHC, EC, and OC by 50% to 75% compared to a three-stone fire. The use of briquettes on the Patsari stove showed energy savings of 12% and a 36% reduction in CO_2e compared to the "U" type open fire. The briquettes could reduce the fuelwood consumption by 318 t/year. It is possible to produce briquettes at a cost similar to or cheaper than fuelwood and generate a local market (circular economy) with local benefits.

Keywords: biofuels; energy needs; co-design; local market; biomass residues; GHG

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1. Introduction

The use of residues from forestry and agriculture activities for bioenergy could contribute to climate change mitigation [1] while at the same time provide tangible economic and other benefits to rural areas, avoiding negative impacts, such as competition with land for food production or inducing land-use change [2].

In developing countries, the use of primary and secondary forest residues could also help reduce the currently very large demand for firewood for thermal energy [3]. Given the recent increase in Liquid Petroleum Gas (LPG) and electricity prices, the use of biomass becomes more attractive [4]. Moreover, biomass is the main—and many times the only household energy fuel—in many rural communities of developing countries.

One important limitation on the extended use of biomass residues for energy is the lack of detailed and reliable information about availability of raw materials, costs, and suppliers in Mexico [5]. Mexico has a very large bioenergy potential from forestry and forest residues [6]. Such is the case for the state of Michoacán, where there are communities whose main economic activity is the transformation of wood (mainly for furniture). This process generates large amounts of residues—such as sawdust, bark, and other types—that are not well managed and consequently constitute an environmental problem [7], but since the rates of generation of these residues are unknown, the potential for generating processed solid biofuels (SB) is also unknown [8], as well as the possible applications and benefits in rural communities with a focus on local use [9].

In Mexico, the development of SB has acquired importance in recent years, but its applications are rarely cited because most of the biomass consumption in rural communities relates to devices designed for conventional firewood [10]. Currently, there are several studies on the evaluation of energy performance [11], indoor [12] and ambient pollution [13] of fuelwood cooking devices, but evaluations that integrate processed SB, improved cookstoves and gasifying devices are almost non-existent. Chimney cookstoves have higher efficiency [14], ventilate emissions outside the kitchen, and reduce fugitive emissions of CO and $PM_{2.5}$ pollutants compared to open fires [15]. However, there are no studies for the energy and emission performance of briquettes in this type of device.

A previous study focused specifically on the process of making briquettes and the physicochemical characterization of the produced briquettes [8], but there are no known energy performances or emission factors, especially for pollutants such as methane and elemental carbon. In the rural communities of Mexico, there is no evidence of the use of biofuels from biomass residues [15]. A local production of solid biofuels could improve the economy of the communities (circular economy). The processes of development, transfer, and adoption of technologies to identify household energy needs in rural areas are currently poorly systematized [16]. The implementation and adoption of sustainable technologies have the purpose of minimizing environmental impacts and improving social wellbeing, but this requires more inclusive and effective efforts to understand basic energy needs, mainly in the rural sector, and thus to overcome the barriers that limit access and acceptance of new forms of energy [17]. Developing local studies with real potential for biofuels use is a need that is currently not covered. There are also no projections that show local benefits in terms of energy savings and emission mitigation [18]. Intervention programs to achieve an energy transition and help curb climate change require robust studies that consider the mentioned aspects.

This study aims to identify the potential of timber residues in the indigenous community of Pichátaro, Michoacán, Mexico, and to analyze how this wood waste, used from a local perspective, would diversify the range of household energy options, encouraging the use of new raw materials, and promoting the use of alternative fuels. In this paper, we evaluated household energy needs, biomass potential, and the production costs of briquettes. Furthermore, energy and emission briquette performance were tested on the field and in the laboratory to determine energy savings and GHG mitigation. Finally, this study shows a projection of briquettes and fuelwood consumption, revealing the realistic household impact of biomass residue consumption with a focus on the energy transition and climate change. This paper is a novel study where the users are part of the energetic solutions considering economic, technological, and social aspects. This research shows a detailed assessment of briquette production from biomass residues in a rural community.

2. Materials and Methods

The methodology for the production and evaluation of briquettes must integrate the following aspects: A community diagnostic to learn about the fuel type consumed and the mean tasks performed in the community; the evaluation of the biomass potential for biofuel production, including availability and production costs; laboratory and on-field testing to evaluate the biofuels performance in end-use devices; and the development of a projection of the energy savings and emissions mitigation for the use of this alternative fuel. These factors add to the quality of the briquette production, see Figure 1.

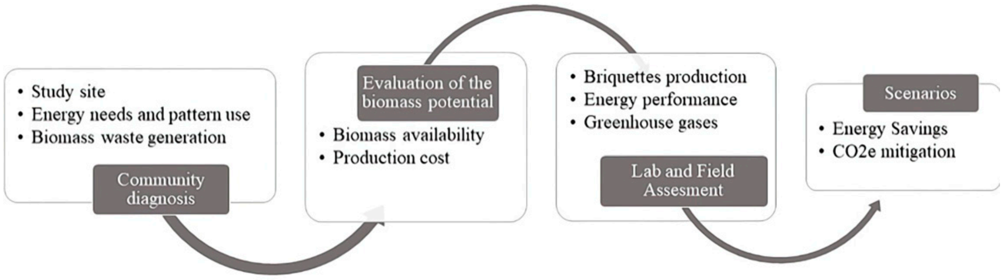

Figure 1. Comprehensive analysis of the production of briquettes from biomass residues.

2.1. Survey Campaign and Diagnosis of Needs

The aim is to identify the energy needs in order to understand the problem and consequently propose a solution. The study site was located in the indigenous community of San Francisco Pichátaro, which is a property that belongs to the municipality of Tingambato, Michoacán, Mexico (19°34″ N and 101°40″ W, and altitude of 2350 amsl) [19]. This community uses biomass to satisfy energy needs, and has a high rate of forest exploitation due to its various furniture manufacturing activities, which generate significant amounts of residual biomass. A community diagnosis was performed to estimate the potential of wood residues for the production of alternative fuels. Random surveys were carried out on 25 artisans to determine the wood consumption of the community. The manufacturers of wooden furniture represent 36% of the total number of artisans [20]. As part of the diagnosis, the types, uses, and the monthly amount of generated wood residues were identified. At the same time, end-user surveys were integrated into the diagnosis to find out their energy needs. This interaction was participatory, including users throughout the innovation process. To examine the energy consumption patterns in the residential sector, 30 houses were surveyed to learn about the fuel type and consumption, the frequency, and the devices used.

2.2. Biomass Potential Assessment

As part of the evaluation of the biomass potential, the available raw material for production of briquettes was estimated on a monthly and an annual basis. Additionally, the unit cost for the production of briquettes was calculated using the different types of raw material (residues) available in the community. The baseline for comparing the unit cost of the manufactured briquettes was the most widely used local fuel price (firewood). After the community diagnosis, a second campaign survey was carried out in the same 30 houses to find out if the users would be interested in using alternative fuels, the cost they would be willing to pay, as well as the desired yields. On the other hand, we analyzed whether the existing technology in the locality can maintain a constant production of briquettes [21].

2.3. Measurements

2.3.1. Laboratory

The performance of the briquettes was evaluated using a forced draft gasifier with 10 KW operating power, and firewood was used in a three-stone open fire for comparison. The forced draft gasifier (primary and secondary air) is a prototype in the region. Further details of the diagram are described in the work of Riegelhaupt et al. [22]. The ISO 19867-1 protocol was used for testing energy performance (thermal efficiency, fuel consumption, and cooking time) and emissions (Greenhouse Gas (GHG)). The briquettes were produced from wood residues of *Pinus* spp. (pine). The optimal mixture for production was previously reported in the literature [8]. The average size was 7 cm in diameter x 9 cm long with a humidity on a wet basis of 12 ± 2%, see Figure 2.

Figure 2. (**a**) Preparation of the mixture, (**b**) Compaction of the mixture, (**c**) Obtaining the briquettes, (**d**) Prepared briquettes for tests.

The firewood used was *Quercus rugosa* (hazel oak) with a humidity on a wet basis of 11 ± 1%. Both fuels were measured with a Protimeter Timbermaster Wood Moisture Meter (GE, USA) [12]. The firewood content was 46.55 ± 0.04 % of carbon (C), 6.13 ± 0.03 % of hydrogen (H), 47.13 ± 0.01% of oxygen, and 0.18 ± 0.01% of nitrogen (N). The elemental analysis was measured with an elemental analyzer (Thermo Fisher Scientific Inc., FLASH 2000, Waltham, MA, USA). The High Heating Value (HHV) was 18.3 ± 0.12 MJ/kg for the briquettes and 18.9 ± 0.10 MJ/kg for the fuelwood. The HHV was measured using a calorimeter Parr 6100. Soaked kindling with 95% isopropyl alcohol (15 g) was used as a fire starter. In all tests, the emission assessments were performed utilizing a Laboratory Emission Measurement System (LEMS) (APROVECHO Research Center, Cottage Grove, OR, USA). Real-time concentrations of CO_2 and CO were measured (Further details about sensors type and calibration are described in Ruiz-García et al. [12]). The $PM_{2.5}$ mass was measured gravimetrically with a sampling flow rate of 16 700 mL/min (using fiberglass filters, 102 mm of diameter) [23]. In parallel to the gravimetric system, a light scattering photometer was used to measure the $PM_{2.5}$ [24]. The filters were weighed on a balance with a precision of 1 µg. The filters were previously stabilized in a temperature range of 21 ± 2 °C and a relative humidity of 35 ± 5% (never less than 30%).

The samples of elemental (EC) and organic (OC) carbon were collected in quartz filters (flow rate of 3000 mL/min). The collected particles were measured with a carbon analyzer (Total Inorganic Carbon analysis, CM150, UIC Inc., Joliet, IL, USA). (Further details about measurements are described in Ortínez-Alvarez et al. [25]).

Methane (CH_4) and non-methane hydrocarbons (NMHC) were analyzed with a gas chromatograph (GC YL6500, Korea), and the GC has an ionized flame detector (FID). The sample injected was 2 mL, and helium was used as stripping gas. The GC column was 60 m in length and 0.320 mm in diameter, with lower and upper temperature limits of −80 °C and 260 °C, respectively (GS Gaspro, Agilent Technologies, Santa Clara, CA, USA). Calibration curves were determined using standard gases of 15 ppm, 100 ppm, and 200 ppm [26].

2.3.2. Field

The briquettes used on the field in the Patsari chimney-type cookstove had the same characteristics as in laboratory tests (Patsari cookstove is the most popular cookstove used in the community), and for comparison, *Quercus* spp. (White oak) firewood was used in both the "U" type open fire and the Patsari (See Figure 3). Further details of the diagrams are described by Medina et al. [13] and Berrueta et al. [14]. The humidity was determined using the same method as in laboratory tests [12]. The Controlled Cooking Test (CCT) was used to test cooking time and fuelwood consumption. In all tests, the emission measurements were carried out in the same way as described in the laboratory section. Emissions samples were collected into a light-shielded Tedlar bag of 5 L (SKC Inc., Covington, GA, USA), and used a sampling pump (224-PCXR4KD, SKC Inc., USA) with a flow rate of 100 mL/min. Three local cooks performed the task of making tortillas, and three repetitions were performed with each one (n = 9) to measure cooking time, dry fuel consumption, and char. All tests were started with 10 g of "ocote" (a very resinous *Pinus leiophylla* spieces). The tests were carried out in a kitchen of the community. This kitchen is representative of a typical kitchen of Michoacán (a volume of 36 m^3 and built with bricks and wooden boards) [12].

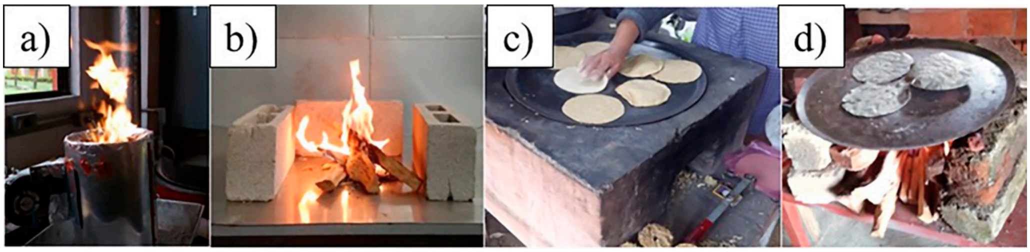

Figure 3. (**a**) Forced draft gasifier/briquettes, (**b**) Three-stone fire/fuelwood, (**c**) Patsari cookstove/briquettes, (**d**) "U" type/fuelwood.

2.4. Scenarios

2.4.1. Greenhouse Gas Mitigation

Gaseous sub-products of combustion are converted to CO_2, with their net contribution to global warming measured as CO_2e [15]. The global warming potentials used in this study to calculate CO_2e were: CO_2 = 1 [27], CO = 1.9 [28], CH_4 = 28 [27], NMHC = 12 [29], EC = 680 [30], and OC = −79 [30]. The first scenario follows the IPCC protocol and the second is the integration of all gases with global warming potential reported in the literature. To determine CO_2 emissions, the fraction of non-renewable biomass (fNRB) was 0.25 for south Mexico [31].

2.4.2. Energy Savings

The estimated energy savings were based on the consumption measured on the task of cooking tortillas. This task is carried out daily as a part of a typical cooking cycle of the region [13]. In this way, the annual energy savings compared to the use of conventional firewood were quantified.

3. Results

3.1. Diagnosis of the Generation of Timber Residue

The community diagnosis showed that *Pinus* spp. is the most used wood in the local industry. The residues were wood shavings and sawdust, and the weekly generation of these residues is 2277 ± 159 kg and 1657 ± 51 kg, respectively. Wood shavings represent 55 ± 4% of the community's biomass residues, while sawdust contributes 45 ± 3%. The applications of these residues are diverse, but it stands out that 33.0% is burned outdoors in uncontrolled combustions due to the inability to store it and the lack of demand. On the other hand, 18.5% is commercialized, while 14.8% is used as thermal energy to heat water (see Table 1). The San Francisco Pichátaro community is highly dependent on biomass to satisfy cooking tasks in the residential sector, but there is no use of locally generated biomass residues. 45% of the interviewed users cook with fuelwood exclusively, while 55% are mixed users (fuelwood and LPG). There is a potential opportunity to generate briquettes from wood residues and high possibilities of partially replacing the use of firewood. The surveys show that 65% of users use fuelwood daily to satisfy their energy needs. Table 1 shows that 40% of users had an average fuelwood consumption of >39 kg/week, and all the users consumed in average 23 kg/week. Regarding the fuelwood species used for heat generation in the residential sector, 45% corresponds to firewood from *Pinus* spp. (pine), followed by firewood from *Quercus laurina* (oak), which represents 33%, and 21% corresponds to other biomass fuels, such as wood chips, bark, branches, and debris (usually as the fire starter material). During cooking events, people use a mix of 50% pine and 50% oak. The 50 ± 3% of the population buys fuelwood, while 20 ± 2% extracts it from the forest.

Table 1. Biomass residue and consumption patterns in the residential sector of San Francisco Pichátaro.

Biomass Residue Uses									
Use type	Cooking	Heating water	Drying wood	Cleaning	Uncontrolled burning	Landfill	Fertilizer	Sale	Outdoor storage
(%)	5.6	14.8	9.3	5.6	33.0	3.8	3.8	18.5	5.6
Biomass residue generation									
Residue type			Wood shavings				Sawdust		
Generation (t/year)			9.1 ± 0.6				6.6 ± 0.2		
Energy consumption patterns in the residential sector									
Fuel type		LPG			Woodfuel			Both	
(%)		4.6			45.2			50.2	
Fuelwood use frequency in the residential sector									
Frequency		Daily			2 to 3 time weekly			2 to 3 time monthly	
(%)		65.3			25.1			9.6	
Woodfuel consumption									
Homes (%)		15			25		20		40
Range (kg/week)		15–19			20–23		24–27		>39
Supplying fuelwood									
Activity type		Buy			Gift			Forest extraction	
(%)		50 ± 3			29 ± 2 %			20 ± 2 %	

Note: *Pinus* spp. fuelwood had a humidity of 22 ± 5% and *Quercus* spp. fuelwood of 17 ± 3%.

3.2. Economic Evaluation of the Production and Use of Briquettes

Regarding the alternative fuel proposal, 65% of community users are willing to use another fuel derived from wood, but on the condition that it generates better combustion conditions than conventional fuelwood. In the specific case of briquettes, users are willing to use this type of biofuel to learn about its performance and benefits. In addition, they would even be willing to pay 25% more than the cost of conventional fuelwood if energy yields improve. In the community of San Francisco Pichátaro, fuelwood consumption is a priority, but the drastic deforestation (illegal logging) has caused the inhabitants to travel greater distances in the forests to extract fuelwood or buy it at a higher price. Our diagnosis shows that the most consumed species are pine and oak, both for consumption in the residential sector and in the wood industry. Table 2 shows the cost of conventional firewood and its comparison with briquettes made from wood shavings and sawdust. White oak fuelwood is 25% more expensive than pine firewood, and briquettes have a higher cost than pine and oak fuelwood if a binder is used. The briquettes used in this study were binder briquettes. The price of fuelwood is standard in the community. Pichátaro is a region with timber resources; therefore, the cost depends on the local market. In the case of the briquettes' cost, this study reports a low price for the sale of sawdust and shavings. These costs may increase in the future due to the rise in demand for this residue. In order for the briquettes to compete with firewood in terms of cost, the pelletizing machine must improve compaction to avoid the use of a binder. The binder is currently the main cost of the briquette.

Table 2. Costs of the briquettes type and conventional fuelwood.

Fuel Type	Briquette without Binder	Briquette with Binder	*Pinus* spp. Fuelwood	*Quercus* spp. Fuelwood
USD/t dry mass	31	282	182	224

Note: The costs were obtained from the community as part of the survey campaign.

3.3. Lab and Field Performance

3.3.1. Laboratory

Table 3 shows the results of energy and emission performance from the use of briquettes in the laboratory Water Boling Test (WBT). The three-stone fire burned fuelwood (open fire/fuelwood) and operated at a higher power and a higher burn rate than the gasifier that works with briquettes (briquette gasification) but performs the task in less time and with less efficiency. The thermal efficiency (power) was 24 ± 2% (6 ± 1 kW) for the briquette gasification and 17 ± 1% (8 ± 2 kW) for the open fire/fuelwood. Previous studies reported a similar thermal efficiency (power) of 15 ± 1% (11± 3 kW) [24] and 13 ± 3.7% (9 ± 1 kW) [14] for fire/fuelwood. Regarding briquettes gasification, Obi et al. [32] reported a thermal efficiency (power) of 33 ± 1% (5 ± 1 kW) using rice husk briquette and 12 ± 1% (9 ± 1 kW) using sawdust briquettes.

Power is defined as the fuel consumption used during the duration of the water boiling test. The fuel consumption of 413 ± 16 g and 629 ± 46 g refers to the fuel consumed to heat water from ambient temperature to the boiling point using briquettes and firewood, respectively. The thermal efficiency of the gasifier and the open fire considers the energy required to heat and evaporate water and does not consider the charcoal. In the case of the open fire, the energy performance using pine or oak is similar because both fuels have very similar HHV of 18,684 kJ/kg and 18,916 kJ/kg for pine and oak, respectively. The open fire tests were carried out with a mixture of pine and oak, as indicated by the consumption patterns on the field. The thermal efficiencies reported in this study are close to those reported by Obi et al. [32] using sawdust (18 ± 1%) and rice husk briquettes (15 ± 1%). On the other hand, the gasification process involves forced air (primary and secondary air) and allows the drying process, pyrolysis, volatiles, and finally gasification in a homogeneous way.

In all cases, the emission factors were lower in the briquette gasification than in the open fire/fuelwood. Regarding short-lived pollutants (SLCP), the open fire/fuelwood produces 4.2 times more elemental carbon and 3.1 times more methane than the briquettes gasification. With regard to OC, which is a compound that cools the atmosphere, the open fire/fuelwood emits 3.4 times more than the briquette gasification. Regarding $PM_{2.5}$, the gasification process helps to reduce this aerosol in the briquettes gasification by approximately half compared to the open fire/fuelwood. In the same way as the emission factors, the emission rates are higher for all the contaminants evaluated in the open fire/fuelwood compared to the briquettes gasification. The elemental carbon emission rates of the open fire/fuelwood are 3 times higher than the briquette gasification (see Table 3).

Table 3. Average energy and emission performance of briquette gasification and a three-stone fire fuelwood in a WBT (high power).

Energy Performance		
Parameters	Gasifier	Three-stone fire
Cooking time (min)	21 ± 6	24 ± 5
Burning rate (g/min)	20 ± 4	27 ± 7
Fuel consumption (g)	413 ± 16	629 ± 46
Power (kW)	6 ± 1	8 ± 2
Thermal Efficiency (%)	24 ± 2	17 ± 1
Emission Factor per Dry Fuel Consumption		
Parameter	Gasifier	Three-stone fire
gCO_2/kg	310 ± 75	1140 ± 123
gCO/kg	12 ± 5	32 ± 9
mg CH_4/kg	233 ± 124	716 ± 272
mg NMHC/kg	555 ± 285	1350 ± 680
mg $PM_{2.5}$/kg	1206 ± 580	2797 ± 979
mg EC/kg	153 ± 177	649 ± 376
mg OC/kg	534 ± 194	1827 ± 700
mg NO_x/kg	280 ± 26	276 ± 100
mg SO_2/kg	1 ± 1	21 ± 18
Emission Factor per Energy Delivery		
Parameters	Gasifier	Three-stone fire
g CO_2/MJ_d	368 ± 38	646 ± 29
g CO/MJ_d	14 ± 3	18 ± 4
mg CH_4/MJ_d	269 ± 102	405 ± 149
mg $NMHC/MJ_d$	642 ± 219	763 ± 377
mg $PM_{2.5}/MJ_d$	1408 ± 461	1555 ± 410
mg EC/MJ_d	165 ± 161	371 ± 203
mg OC/MJ_d	641 ± 224	1016 ± 310
mg NO_x/MJ_d	18 ± 1	20 ± 8
mg SO_2/MJ_d	>1 ± 1	2 ± 1
Emission Rate		
Parameters	Gasifier	Three-stone fire
g CO_2/min	28 ± 4	47 ± 12
g CO/min	1 ± 1	1.3 ± 1
mg CH_4/min	20 ± 5	29 ± 13
mg NMHC/min	47 ± 10	56 ± 34
mg $PM_{2.5}$/min	103 ± 22	107 ± 16
mg EC/min	11 ± 8	27 ± 14
mg OC/min	43 ± 18	70 ± 14
mg NO_x/min	8 ± 1	8 ± 5
mg SO_2/min	>1 ± 1	1 ± 1

Note: The carbon balance in all test was 98 ± 5, min = 90%, max = 104%.

3.3.2. Field

Table 4 shows the energy performances of the Patsari stove with the use of briquettes (Patsari/briquettes) and the "U" type open fire burning fuelwood ("U" type/fuelwood) on a tortilla cooking task. The Patsari stove was designed to use firewood, but this study shows the capability of this device to perform the task of making tortillas with the use of briquettes. The Patsari/briquette showed a cooking time higher than the "U" type/fuelwood (56 ± 6 and 40 ± 3, respectively), but the fuelwood consumption is lower than the "U" type/ fuelwood (1791 ± 94 and 2027 ± 181, respectively). The fuel consumption and cooking time of the "U" type/ fuelwood are similar to the results from previous studies [13].

Likewise, the fuel consumption and cooking time of the Patsari/briquette were similar to the results obtained from field tests where the Patsari used fuelwood. The Patsari cookstove generates more char when using briquettes than when using fuelwood. Figure 4 shows a typical cook during the cooking tests and the combustion chamber of the Patsari stove at the beginning and at the end of the test.

Table 4. Comparative performance parameters of Patsari/Briquette and "U" type/fuelwood for cooking tortillas in a Controlled Cooking Tests.

Energy Performance				
Parameter	**Patsari/Briquette**	**Patsari/Fuelwood**	**"U"/Fuelwood**	**"U"/Fuelwood**
Cooking time (min)	56 ± 6	51 ± 6 [13]	40 ± 3	45 ± 6 [13]
p-value	-	<0.2	<0.01	<0.05
Dry fuel consumption (g)	1791 ± 94	1281 ± 131 [13]	2027 ± 181	1829 ± 117 [13]
p-value	-	<0.01	<0.1	<0.2
Char (g(C)/kg fuel)	193 ± 31	49 ± 10 [33]	172 ± 9	34 ± 21 [33]
p-value	-	<0.01	<0.2	<0.01

Note: Values shown are averages ± standard deviation. Patsari/Briquette values were tested against Patsari/fuelwood, "U"/fuelwood using a t-distribution with *α = 0.1, *α = 0.05 and *α = 0.01 Patsari/fuelwood and "U" type/fuelwood used White oak (*Quercus* bicolor) and the average fuelwood moisture content for all CCT tests was 10 ± 2%, expressed as wet basis with a range of 7% to 15% [13], 8 ± 3% [33] and for this study was 9 ± 1%, expressed as wet basis with a range of (8–10%). The HHV of the char (Patsari/briquette) was 32.37 ± 0.06 MJ/kg, the humidity on a wet basis was 1.7 ± 0.1 %, and the ash content was 4.6 ± 0.1%.

Figure 4. (**a**) Firestarter (weight), (**b**) Briquettes (biofuel), (**c**) Tortilla dough (weight), (**d**) Field cooking in the Patsari cookstove, (**e**) Combustion during the starting of the cooking test, (**f**) Generation of charcoal before finishing the test.

3.4. Scenarios

3.4.1. CO_2e

In San Francisco Pichátaro, Michoacán, Mexico, there are approximately 744 families, of which more than 70% cover their different cooking activities with traditional fuelwood (mixed and exclusive users). As a result of the community diagnosis, it was found that 45% of families cook exclusively with firewood, and 79% of these families use an open fire. Assuming a fNRB of 0.25 [32], the CO_2e per kg of dry fuel in open-fire/fuelwood is 3.9 times greater than in briquette gasification (See Table 5), and EC + OC has the largest contribution (4.8 times more). This paper is a pioneering study in the energy performance of briquettes, since no fuel savings and CO_2e reduction have been reported for Mexico. On the other hand, large emissions were recorded during the combustion of briquettes from hemp straw by Kraszkiewicz et al. [34]. Additionally, in wheat straw, significant emissions of NO_2 and SO_2 were discovered in char briquettes combustion (maize straw, wheat straw, and rice straw) [35]. Finally, the briquettes of cashew nut shells showed the potential for cooking in an acceptable level with low GHG emissions [36].

Table 5. CO_2e /kg dry fuel consumed per pollutant.

	g CO_2e (CO_2)/kg	g CO_2e (CO)/kg	g CO_2e (CH_4)/kg	g CO_2e (HCNM)/kg	g CO_2e (EC)/kg	g CO_2e (OC)/kg	TOTAL g CO_2e/kg
Gasifier/Briquette	77 ± 19	23 ± 9	7 ± 3	7 ± 3	104 ± 120	−42 ± 15	173 ± 145
TSF/Fuelwood	285 ± 31	61 ± 18	20 ± 8	16 ± 8	441 ± 256	−144 ± 55	677 ± 276

There is a relationship between fuels and technologies to achieve optimal performance [15]. In this study, the gasifier that uses forced air contributes to the reduction of GHG that causes climate change. Figure 5 shows a gradual transition scenario for partially replacing the use of fuelwood with *Pinus* spp. briquettes (mix of wood shavings and sawdust, 50–50%). The briquette gasification achieves a 74% reduction of CO_2e emissions in the task of heating water, in comparison with the open fire/fuelwood tested in the laboratory.

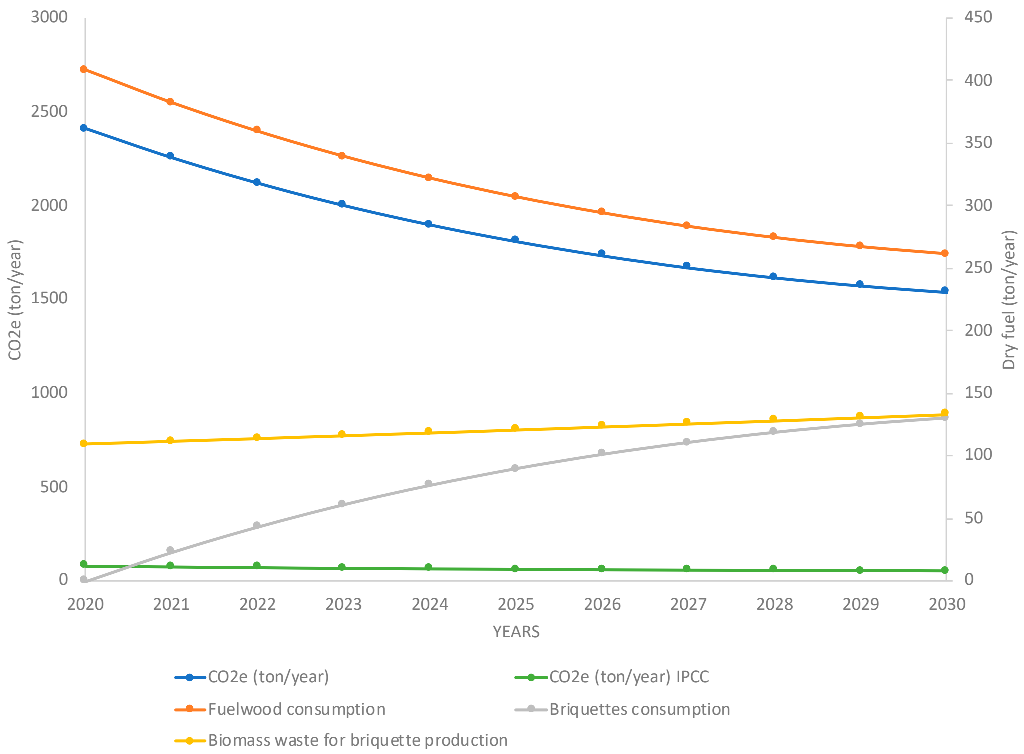

Figure 5. Fuel consumption scenario in San Francisco Pichátaro. Note: The annual population growth was assumed to be 4% [37,38] and the transition of open fire to improved cookstove was estimated to be 10% [20]. The calculation of CO_2e (IPCC) considers CO_2 as carbon-neutral and considers only the contribution of CH_4 and N_2O. N_2O, which is typically associated with high temperature combustion, was not measured in our study and has been demonstrated to be a small fraction of biomass stove global warming commitments in prior studies [39]. The CO_2e and briquettes consumption represent the gasification of briquettes for heating or boiling water. This scenario refers to the implementation of gasifiers.

3.4.2. Energy Savings

There is a fuel saving of 12% for the use of the Patsari/briquettes compared to the open-fire /fuelwood (see Figure 5); however, the produced char was very similar in both devices (193 ± 31 and 172 ± 9, respectively). The char production in the Patsari cookstove using briquettes increases five times compared to using firewood; therefore, the exclusive use of briquettes on this type of stove does not represent the best energy savings. The use of char could be implemented to reduce the fuel consumption. The combined use of briquettes and firewood on the Patsari cookstove should be explored for achieving optimal performances. The average fuelwood consumption was 318 ± 49 t/year, and the briquette consumption was 80 ± 43 t/year for the 2020–2030 scenario (The forestry sector in Mexico generates around 700,000 t/year of forest residues). Obi et al. [32] reported fuel savings of 18.6% using rice husk and 20.4% of sawdust briquettes in comparison with fuelwood burning in a three-stone fire. Carrillo-Parra et al. [40] determined the physical and mechanical properties of sawdust briquettes, Pérez-Pérez et al. [41] reported the physical and mechanical properties of pine briquettes, and similar studies reported the quality evaluation of biomass.

4. Discussion

4.1. Energy Needs and Energy Transition

This study shows the use of a type of biomass residue produced locally. This residue could be a complementary fuel in the residential sector since there is a combined use of technologies and fuels to satisfy energy needs. The addressed approach includes the use of wood residue to mitigate environmental impacts and to generate local markets, producing affordable forms of renewable energy. The biomass residue from the wood industry of the indigenous community currently has no economic value and it is seen as a problem due to the enormous quantities produced, the insufficient storage, and the lack of knowledge to use it as a raw material in other production processes; however, if added value is given, the economy and the local market can be boosted. Approximately 89 ± 3 t/year of sawdust residues and 123 ± 9 t/year of wood shavings are generated. Some workshops could complement their economic activities by elaborating and selling briquettes for residential consumption. The use of briquettes can be explored for wood drying in the manufactured furniture process (It is also necessary to generate more technological innovation). This activity will generate biomass residue for the production of briquettes. In this way, a local circular economy is generated by distributing wealth and benefits among the community and leaving behind centralized energy production models. Even the use of biomass residue could be the input to produce electrical energy locally, as in the case of some success stories in other countries [42]. Challenges for scale production include the development and maintenance of local technology. The briquette machine is a local initiative that can overcome these barriers and define a price based on local incidents and not externalities, as happens with fossil fuels [8]. This machine could be improved for producing cheaper briquettes. Some alternatives are: (a) use of a piston-press hot densification system without binder: this study innovated in the local production of briquettes; the production cost is mainly generated by the binder, and thus the temperature and pressure parameters must be optimized to avoid the use of binders. Another option is to produce a binder locally; (b) modification of the proportion of sawdust and wood shavings to avoid the addition of a binder, hence decreasing the cost of production; and (c) reduction of a mold diameter could improve briquettes' stable density and reduce compaction pressure requirements [43]. Laboratory and on-field briquette evaluations show the energy performance, but do not reflect the biofuel savings on uncontrolled cooking tasks and cooking cycles typical of the region.

There is also a challenge in the efficiency of the briquettes used on an improved stove. In the case of the Patsari cookstove, the generated char is higher than in an open fire. The excess airflow could improve the energy performance of the briquettes on the Patsari cookstove because the char sinks to the bottom of the combustion chamber causing a build-up. With a char reduction, the briquette consumption will decrease. Further evaluations on other cookstove models could show the proper characteristics of a combustion chamber to use briquettes (or a mixture of firewood and briquettes). There is still not enough evidence that this study will replicate in other communities. To achieve this, the first step is to learn about the energy needs and to evaluate the biomass potential available in another locality for thermal purposes.

4.2. Greenhouse Gas Mitigation and Energy Savings

As a first contribution, it has been identified that the generated wood shavings and sawdust in the workshops of the community of San Francisco Pichátaro, Michoacán, Mexico, are suitable raw materials for making briquettes. The production of briquettes was estimated using only 60% of the produced residue. In the future, biomass residue could be used for other purposes. To ensure that open fire exclusive users have a gradual transition towards the use of briquettes, long-term monitoring and follow up activities are needed. The substitution of open fires with new technologies (including fuels and devices) could allow to satisfy the energy needs in rural areas, could help to contribute to accomplish the objectives of sustainable development, and could help to mitigate climate change while also providing clean and affordable energy, and improving the quality of life of local users [15]. The economy of the families in the community could improve if users buy less fuelwood and use cookstoves with higher thermal efficiency and with a longer useful life. On the other hand, the increase in the cost of the LPG in the community may cause some users to adopt the use of improved cookstoves, which reduces CO_2e emissions in the long term. Technological innovation (fuel/device) is crucial in GHG mitigation; however, a supply chain must be implemented to ensure sustained use. CO_2e mitigation does not include GHG mitigation by avoiding uncontrolled burning of produced wood residues in furniture manufacturing workshops, and including this variable would give a more complete scenario. It is expected that by integrating this evaluation, CO_2e mitigation will increase, mainly regarding methane and EC.

As Figure 5 indicates, there is a CO_2e contribution from other GHG that are not currently considered in the total CO_2e (e.g., elemental carbon). In recent years, there are important initiatives to reduce EC emissions globally. Mexico is committed to mitigating 50% of its EC emissions by 2050. The use of forest residues contributes to reducing the consumption of firewood and avoiding the uncontrolled burning of this type of residue. The scenario in Figure 5 shows a 36% mitigation of the CO_2e emissions currently produced by the use of open fires in the Pichátaro area. These results are an opportunity to boost Carbon-Offset projects in the community.

5. Conclusions

The present study helps to better assess the briquettes production from a local view. The use of biomass residue is an energy option in rural communities and contributes to reducing firewood consumption and mitigating GHGs. Several important policy and technical implications can be derived from this study:

- It is necessary to learn about the energy needs of the community to propose a partial solution. A full replacement of fuelwood could lead to misplaced expectations. Note that 45% of users cook with fuelwood exclusively, while 55% cook with fuelwood and LPG.
- With the use of biomass residues, it is possible to produce briquettes at a similar cost to or cheaper than fuelwood. This might generate a local market with local benefits.
- Briquettes examined in this study could be the most effective stacking option in terms of fuelwood savings and GHG mitigation. The use of briquettes on the Patsari stove showed energy savings of 12% compared to the "U" type open fire. Laboratory tests showed that briquettes gasification to heat water reduces 74% of GHG emissions.

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