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Assessment of Pellets from Three Forest Species: From Raw Material to End Use

Miguel Alfonso Quiñones-Reveles [1], Víctor Manuel Ruiz-García [2,*], Sarai Ramos-Vargas [2], Benedicto Vargas-Larreta [1], Omar Masera-Cerutti [2], Maginot Ngangyo-Heya [3] and Artemio Carrillo-Parra [4,*]

[1] Sustainable Forest Development Master of Science Program, Tecnológico Nacional de México/Instituto Tecnológico de El Salto, El Salto, Pueblo Nuevo 34942, Mexico; maqr21@hotmail.com (M.A.Q.-R.); vlbene@gmail.com (B.V.-L.)
[2] Bioenergy Laboratory and Bioenergy Innovation and Assessment Laboratory (LINEB), Ecosystems Research Institute and Sustainability (IIES), Universidad Nacional Autónoma de México (UNAM), Morelia 58190, Mexico; sarv_3@hotmail.com (S.R.-V.); omasera@gmail.com (O.M.-C.)
[3] Faculty of Agronomy (FA), Autonomous University of Nuevo León (UANL), Francisco Villa s/n, Col. Ex-Hacienda "El Canadá", Escobedo 66050, Mexico; nheyamaginot@yahoo.fr
[4] Institute of Silviculture and Wood Industry (ISIMA), Juarez University of the State of Durango (UJED), Boulevard del Guadiana 501, Ciudad Universitaria, Torre de Investigación, Durango 34120, Mexico
* Correspondence: vruiz@cieco.unam.mx (V.M.R.-G.); acarrilloparra@ujed.mx (A.C.-P.)

Abstract: This study aimed to evaluate and compare the relationship between chemical properties, energy efficiency, and emissions of wood and pellets from madroño *Arbutus xalapensis* Kunth, tázcate *Juniperus deppeana* Steud, and encino colorado *Quercus sideroxyla* Humb. & Bonpl. in two gasifiers (top-lit-up-draft (T-LUD) and electricity generation wood camp stove (EGWCS)) in order to determine the reduction of footprint carbon. In accordance with conventional methodologies, we determined the extracts and chemical components (lignin, cellulose, holocellulose), and the immediate analyses were carried out (volatile materials, fixed carbon, ash content and microanalysis of said ash), as well as the evaluation of emission factors (total suspended particulate matter ($PM_{2.5}$), CO, CO_2, CH_4, black carbon (BC), elemental carbon (EC), and organic carbon (OC)). The results were statistically analyzed to compare each variable among species and gasifiers. The raw material analyzed showed how the pH ranged from 5.01 to 5.57, and the ash content ranged between 0.39 and 0.53%. The content values of Cu, Zn, Fe, Mg, and Ca ranged from 0.08 to 0.22, 0.18 to 0.19, 0.38 to 0.84, 1.75 to 1.90, and 3.62 to 3.74 mg kg^{-1}, respectively. The extractive ranges from cyclohexane were 2.48–4.79%, acetone 2.42–4.08%, methanol 3.17–7.99%, and hot water 2.12–4.83%. The range of lignin was 18.08–28.60%. The cellulose content ranged from 43.30 to 53.90%, and holocellulose from 53.50 to 64.02%. The volatile material range was 81.2–87.42%, while fixed carbon was 11.30–17.48%; the higher heating value (HHV) of raw material and pellets presented the ranges 17.68–20.21 and 19.72–21.81 MJ kg^{-1}, respectively. Thermal efficiency showed statistically significant differences ($p < 0.05$) between pellets and gasifiers, with an average of 31% Tier 3 in ISO (International Organization for Standardization) for the T-LUD and 14% (ISO Tier 1) for EGWCS, with *Arbutus xalapensis* being the species with the highest energy yield. The use of improved combustion devices, as well as that of selected raw material species, can reduce the impact of global warming by up to 33% on a cooking task compared to the three-stone burner.

Keywords: wood biomass; wood pellets; GHG; CO_2e; gasification; $PM_{2.5}$; thermal efficiency

1. Introduction

Fossil fuels are the main source of primary energy worldwide. The strong global dependence on this energy source generates high greenhouse gas (GHG) emissions and, accordingly, has adverse effects on the environment and humans [1]. The excessive use of fossil fuels has been related to environmental problems such as climate change, high levels of suspended particles, and environmental pollution [2,3].

Nowadays, renewable energy sources provide about 10% of the final energy demand worldwide, of which bioenergy is the main source with an offer of 55.6 exajoules (EJ) per year, or 47% of total renewable energy [4]. Moreover, the scarcity of fossil fuels, the concern for their depletion, and the energy dependence of countries with scarce conventional energy resources make the development of renewable energies sources such as biomass necessary [5]. The energy produced from wood biomass is as important as all other renewable energy sources together (hydroelectric, geothermal, waste, biogas, solar and liquid biofuels) [6]. In addition to this, the production of wood pellets was driven by European policies starting in 2013, growing to 23.6 million tons, and it is expected that by 2025 the world demand for pellets will increase to 54 million tons [7,8]. Therefore, biomass is considered a viable option in the short, medium, and long term [9]. On another side, in most of the forest areas of Mexico and particularly in the state of Durango, containing forests with a cold temperate climate, there are little-used species such as *Arbutus xalapensis*, *Juniperus deppeana*, and *Quercus sideroxyla* that due to their growth behavior, harvesting methods favoring conifers species, or low level of knowledge regarding their characteristics are not used properly, and thus increasing the research to determine their properties would potentially expand the solid biofuels production, increasing the economic gains and reducing the pressure on the pine forests exploitation.

On the other hand, biofuels are considered an ecological alternative, and through looking between species and through advanced forest management, one finds that the carbon sequestration rate could potentially be six times better due to its low GHG emissions, with it also promoting the development of rural communities and contributing to the bioeconomy through income generation [10–12]. Forest residues are an important source of biomass that are currently underused in many countries. It is estimated that of each tree harvested for timber production, only 20% is used commercially, 40% is left in the forest as waste, and the remaining 40% becomes by-products of the process of splintering, bark, and sawdust [13]. These wastes can be used in energy production. However, given their low density, high moisture content, and heterogeneity, they require pre-treatments to improve energy parameters. In the same way, the impact of climate change, the need to reduce GHG emissions, and the energy generation required to satisfy elementary tasks have increased the demand and use of clean energy [5].

The instability of the market, coupled with new environmental energy policies, are making biomass an essential element of energy policies in both developed and developing countries [14,15].

According to the World Health Organization [16], around 3 billion people cook and heat their homes with solid biofuels [17]. In Mexico, approximately 22.5 million people (80% of the rural population) depend on wood for cooking, heating, and other domestic tasks [18]. However, the biomass combustion produces particulate matter (PM), the main source of air pollution [19], as well as short-lived climate pollutants such as black carbon (BC) and methane (CH_4) [20]. To reduce the GHG into the environment during biomass combustion, micro-gasifiers modify the primary and the secondary airflow so that the combustion is cleaner [21]. Some alternatives to reducing emissions of conventional solid biofuels as such as fuelwood is to use wood-based pellets and briquettes on more efficient end-use devices [1]. They maximize energy performance and allow for the use of biomass waste as fuels.

The demand for wood pellets has markedly increased in the last 10 years; such estimates indicate that the maximum demand for technically available wood pellets could reach up to 150 million tons in 2020 [22]. Worldwide, there is very little information on the combustion and emissions associated with the burning of pellets, and thus it is extremely important to know their use in technologies that minimize the release of pollutants into the environment.

The energy use of wood pellets is neutral in emissions, and therefore it can be guaranteed that they are kept to a minimum, since they are the only form of energy that guarantees

a sustainable supply because they produce CO_2 equivalent to the amount retained in the fabric of the plants. Thus, they are considered less polluting compared to fossil fuels [23].

Rojas [24] mentions that burning pellets is one of the best options to reduce CO_2 emissions by up to 50% compared to other energy sources such as firewood and chips. Therefore, the use of pellets might be an option to reduce the concentrations of CO_2, Sulfur oxides (SOx), and Nitrogen oxides (NOx) that cause the "greenhouse effect" and climate change [25]. It should be noted that the use of pellets could help to meet the goals of reducing greenhouse gas emissions that Mexico has committed to reducing by 22% by 2030 according to the Paris agreement signed in 2015 [26].

The main objective of this research was to evaluate and compare the relationship between chemical properties, energy efficiency, and emissions of wood and pellets from three forest species in two types of gasifiers.

2. Materials and Methods

2.1. Selection and Collection of the Woody Species

Arbutus xalapensis Kunth, *Juniperus deppeana* Steud, and *Quercus sideroxyla* were selected because of their low industrial use on the approximately 1,567,440 ha of temperate forest in Durango, Mexico [27]; in addition, although they are species adapted to the climatic and edaphic conditions of the region, there is little knowledge of their chemical and energetic properties. From each species, five 1.20 m long logs were collected from the main stem. The species were identified and selected during forest harvesting activities in the Chavarría Nuevo forest community located between Universal Transverse Mercator (UTM) coordinates 443657 and 2625546, within the municipality of Pueblo Nuevo, Durango, Mexico.

Sawdust and Pellets Production

One Section 5 cm thick of the upper part of each log was cut and chipped with a circular saw, chisel, and hammer. The chips were dried on laboratory conditions and ground in a micron mill MK-20, according to the standard T 257 om-85 [28]; finally, sawdust was sieved with *Mont inox* sieves and was kept in hermetic bag to avoid moisture absorption. The remaining section of each log was cut into 2 pieces, 1 of them was debarked, and both were chipped and milled; then, 10 kg of sawdust pellets of each species with bark (WB) and without bark (D) were produced through an industrial flat disk machine Small Hammer Mill (TFS) 420 hammer mill manufactured in China with a 3.15-mm screen, with a capacity of 350 kg h^{-1}.

2.2. Chemical and Energetic Properties of Pellets and the Raw Material Used for Their Production

2.2.1. Chemical Characterization of the Raw Material

The pH was taken using an immersion electrode potentiometer from Thermo Fisher Scientific, manufactured in Waltham, MA, USA in 2 g of flour sample of each of the species with and without rind; adding 20 mL of distilled water, the readings were taken at the beginning then at 5 minutes; at 4, 24, and 48 h; and then an average—this was done using the methodology of Sandermann and Rothkamm [29]. Six grams of 40 mesh-sieved sawdust was used to determine the percentage of extracts with the Soxhlet equipment using solvents of increasing polarity, that is, cyclohexane, acetone, methanol, and hot water at reflux for 6 h for each solvent. The solvents were distilled under vacuum on a rotary evaporator and the aqueous extracts were weighed [30]. One gram of extract-free sawdust was used for the analysis of lignin, holocellulose, and cellulose. The lignin content (%) was determined with the Runkel and Wike technique [31]. Holocellulose (%) was measured with the Wise method [32], adding sodium chlorite and acetic acid to the extracts of free wood dust. The cellulose content (%) was obtained following ASTM D 1103-60 [33], treating the dry base holocellulose powder with sodium hydroxide (17.5%) and then with acetic acid (10%). Three repetitions on all the analyzes were carried out.

2.2.2. Proximate Analysis and Sawdust Ash Microanalysis

The ash content (%) analysis was carried out using the gravimetric method by the UNE-EN 14775 standard [34]. The volatile material content was determined following the standard UNE-EN 15148 [35]. The percentage of fixed carbon was calculated according to ASTM D-1762-84 [36]. The microanalysis of the ash obtained was carried out with the help of an Atomic Absorption Spectrometer PinAAcle 900F manufactured by Perkin Elmer in Waltham, MA, USA. For all analyses, 1 g of 40 mesh sieved sawdust was used.

2.2.3. Higher Heating Value Analysis from Raw Material and Pellets

The higher heating value (HHV) of each type of pellet and the raw material (with and without bark) was calculated according to EN-14918 in a LECO AC600 isoperbolic calorimeter manufactured by LECCO Corporation in St. Joseph, USA. The calorific value of the calorimeter was calibrated using benzoic acid as a reference [23].

2.2.4. Pellet Energy Performance

The energy performance of the pellets obtained from the 3 forest species under study was tested in the gasifiers electricity generation wood camp stove (EGWCS) manufactured in New York, USA and top-lit-up-draft (T-LUD) manufactured in Painesville, OH, USA, while the WBT test (water boiling test) [37] was performed using 325 g of pellets per each species, plus 75 g submerged in isopropyl alcohol to serve as the initiator, with the total fuel used being in accordance with the load capacity of the gasifiers. Five replicate tests were performed for each gasifier/fuel combination. The parameters measured were the boiling time of the water, the power, and the thermal efficiency in a high power phase, according to ISO 19867-1 [38].

2.3. Evaluation of Emissions Generated by Pellet Combustion

Simultaneously to energy performance assessment, emissions concentrations were measured. The carbon monoxide (CO), carbon dioxide (CO_2), and total suspended particulate matter ($PM_{2.5}$) were continuously monitored using a Laboratory Emission Monitoring System (LEMS) modified from the Aprovecho Research Center (ARC). The concentration was measured in real time by an electrochemical cell for CO, a sensor that uses non-dispersive infrared (NDIR) for CO_2, and a scattering photometer for $PM_{2.5}$. The CO and CO_2 sensors were calibrated using gas standard at 500 and 5000 ppm, respectively. Pure nitrogen was used to establish the zero point [39,40].

The $PM_{2.5}$ mass was gravimetrically measured using filter-based sampling, which consists of a vacuum pump that draws a sample through a sample line and a critical orifice at a steady flow of 16.7 L/min [41]. The $PM_{2.5}$ was collected on hydrophilic, binderless glass fiber filter paper (FPAE-102) positioned downstream of a cyclone particle separator (URG, 2.5 μm). Filters were equilibrated at $35 \pm 5\%$ relative humidity and 23 ± 2 °C before measuring pre- and post-weights on a microbalance (model EX225D, OHAUS, Parsippany, NJ, USA) [39,40].

A second gravimetric system was used for measuring elemental carbon (EC) and organic carbon (OC). Samples were collected on quartz fiber filters with a sample flow of 3 L/min. The particles collected during the test were analyzed for EC and OC concentration with a thermal-optical carbon analyzer (Total Inorganic Carbon analysis, CM150, UIC Inc., Joliet, IL, USA). The sample was oxidized in a furnace (CM5300) at a constant temperature (700 °C to quantify total carbon and 500 °C for OC). The CO_2 produced in the furnace was carried to a coulometric titration unit (CM5017, UIC Inc., Joliet, IL, USA) to measure the concentration of EC and OC [42]. Black carbon (BC) was analyzed with an Optical Transmissometer (by the SootScan, model OT21, Ljubljana, Slovenia), which is a nondestructive method [39,43,44]. Organic matter (OM) was estimated by multiplying the organic carbon by a factor that accounts for oxygen, hydrogen, and some other atoms present in the organic material (OM = $1.9 \times$ OC) [45,46].

The methane (CH_4) and nonmethane hydrocarbons (NMHC) were analyzed using a Young Ling gas chromatograph model 6500 (GC YL6500, Anyangcheondong-ro, Korea) with a flame ionization detector (FID from YL6500 chromatograph, Anyangcheondong-ro, Korea) that works with dry air and nitrogen. An injection valve was used to sample 2 mL, using a split mode 1:20. Calibrations curves were built to determine the concentration of every gas using 3 different gases patterns: 15, 100, and 200 ppm for methane [39].

Total Global Warming Impact

To determine the total warming impact from the gasifier emissions, we applied the GWP for each pollutant to all the emissions, including particulate matters onto the same scale as carbon dioxide equivalent (CO_2e) per kilogram of firewood. The GWP factors (Table 1) were obtained from Intergovernmental Panel on Climate Change (IPCC) over a 100-year time horizon [47,48]. A three-stone stove fed with *Q. sideroxyla* pellets was used as a control to compare it with the T-LUD and EGWCS gasifiers.

Table 1. Global warming potential values for a 100-year time horizon.

Pollutant	CO_2	CO	CH_4	TNMHC	EC/BC	OC	OM
GWP	1	1.9	28	12	680	−79	−50
Reference	[47]	[48]	[47]	[49]	[50]	[50]	[46]

2.4. Statistical Analysis

To analyze differences in the variables evaluated, we carried out an analysis of variance considering the species and the presence and absence of bark as factors. When significant statistical differences were found ($p \leq 0.05$), multiple means comparison tests were performed using the Tukey method ($p \leq 0.05$). Likewise, a multiple correlation analysis was performed by the "Pearson relationship" between the analytical methods, which was established using the coefficient of determination (R^2) to compare regression lines from 2 types of aerosols using the method. Both analyses were carried out using the InfoStat statistical package. The relationship between the analytical methods was established using the coefficient of determination (R^2) to compare regression lines from 2 types of aerosols [51].

3. Results

3.1. Characteriztics of Biomass Raw Material

3.1.1. pH

The pH values ranged between 5.01 and 5.57 (Table 2). The species with lower pH value was *Q. sideroxyla* without bark, and the higher value was *J. deppeana* without bark.

Table 2. Average percentage of extracts and wood components of the species evaluated.

Species	pH	Ashes (%)	Concentration (mg kg^{-1})				
			Cu	Zn	Fe	Mg	Ca
Arbutus xalapensis D	5.25(0.11)	0.40(0.02) [a]	0.08(0.01) [a]	0.18(0.0007) [a]	0.47(0.007) [b,c]	1.83(0.002) [c]	3.62(0.59) [a]
Juniperus deppeana D	5.01(0.07)	0.39(0.04) [a]	0.13(0.05) [c]	0.18(0.0004) [a]	0.38(0.06) [a]	1.75(0.008) [a]	3.69(0.13) [a]
Quercus sideroxyla D	5.57(0.39)	0.52(0.13) [a]	0.09(0.005) [b]	0.19(0.0007) [a]	0.38(0.14) [a]	1.89(0.002) [e]	3.63(0.17) [a]
Arbutus xalapensis WB	5.08(0.09)	0.46(0.02) [a]	0.14(0.06) [d]	0.19(0.0007) [a]	0.47(0.02) [c]	1.87(0.003) [d]	3.67(0.41) [a]
Juniperus deppeana WB	5.27(0.28)	0.40(0.07) [a]	0.22(0.07) [e]	0.18(0.0003) [a]	0.43(0.08) [b]	1.79(0.002) [b]	3.74(0.36) [a]
Quercus sideroxyla WB	5.32(0.24)	0.53(0.07) [a]	0.13(0.05) [c]	0.19(0.0004) [a]	0.84(0.03) [d]	1.90(0.002) [f]	3.65(0.12) [a]

In brackets is the standard deviation. Similar letters in the column's direction indicate statistical equality ($p \leq 0.05$). D = without bark, WB = with bark.

3.1.2. Ash Content and Microanalysis

The percentage of the ashes obtained from the analysis did not present significant statistical differences ($p \geq 0.05$) among the three wood species (Table 2). *Q. sideroxyla* with bark presented the highest percentage of ash (0.53%), while the species that presented the

lowest percentage was *J. deppeana* without bark (0.39%), which met the standards for making pellets. The Cu content was higher ($p \leq 0.05$) in *J. deppeana* with bark (0.22 mg kg^{-1}), whereas *A. xalapensis* showed the lowest value (0.08 mg kg^{-1}). Range values of ash content varied from 0.39 to 0.53%. In this study, the content of zinc (Zn) was not significantly different ($p > 0.05$) among species. *Q. sideroxyla* with bark showed the highest Fe value (0.84 mg kg^{-1}), while *J. deppeana* and *Q. sideroxyla* with bark were the species that showed the lowest Fe value (0.38 mg kg^{-1}) without statistically significant differences ($p > 0.05$). The content of magnesium and calcium were the elements that were shown in the highest proportion (1.75–1.90 and 3.62–3.74 mg kg^{-1}, respectively), showing no statistically significant differences in calcium content (Table 2).

3.1.3. Extractives Substances of the Raw Material

The highest solubility (7.99%) was shown with methanol. *A. xalapensis* (with bark and without bark) presented 7.99% and 10.64%, respectively, followed by *J. deppeana* without bark with 6.45% showing significant statistical differences ($p \leq 0.05$) (Table 3). The hot water extracts of *A. xalapensis* (with bark) was 5.5%, while for cyclohexane the values for *Q. sideroxyla* with bark and *J. deppeana* without bark were 4.49% and 2.48%, respectively. Acetone presented values from 2.42 to 4.08% for *J. deppeana* with bark and *A. xalapensis* without bark, respectively.

Table 3. Contents (%) of extracts and chemical components of three forest species from the State of Durango, Mexico.

Species	Cyclohexane	Acetone	Methanol	Water	Lignin	Cellulose	Holocellulose
A. xalapensis D	4.71(1.45) [a]	2.42(1.19) [a]	7.31(1.4) [b]	4.83(0.59) [b,c]	18.80(0.8) [a]	45.92(0.9) [b]	57.30(1.1) [b]
J. deppeana D	2.48(0.45) [a]	3.72(0.84) [a]	3.83(0.2) [a]	2.12(1) [a]	27.60(3.6) [b]	43.30(0.3) [a]	53.50(0.4) [a]
Q. sideroxyla D	4.16(1.37) [a]	3.47(0.62) [a]	3.17(0.7) [a]	3.1(0.93) [a,b]	20.63(0.9) [a]	51.81(1.1) [c]	62.80(0.9) [c]
A. xalapensis WB	4.74(1.67) [a]	2.82(0.83) [a]	7.99(1.7) [b]	5.5(1.40) [c]	19.14(1.2) [b]	47.71(1.2) [b]	58.20(0.9) [b]
J. deppeana WB	3.29(0.40) [a]	4.08(0.48) [a]	6.45(1.6) [a,b]	3.55(0.11) [a,b,c]	28.60(1) [b]	45.6(0.6) [a,b]	54.52(0.5) [a]
Q. sideroxyla WB	4.79(2.05) [a]	3.71(0.83) [a]	3.24(0.08) [a]	4(0.51) [a,b,c]	21.11(3.1) [a]	53.90(1) [c]	64.02(1) [c]

In brackets is the standard deviation. The same letters in the direction of the columns indicate statistical equality ($p \leq 0.05$). D = without bark, WB = with bark.

3.1.4. Structural Composition of the Raw Material

The range of lignin content was 18.80–28.60%, where *J. deppeana* with bark presented the highest value (28.60%) and *A. xalapensis* without bark, the lowest value (18.80%) (Table 3). *Q. sideroxyla* with bark registered the highest percentage of cellulose (53.90%), while *J. deppeana* without bark presented the lowest value (43.30%). Regarding holocellulose, a percentage from 53.50% to 64.02% was registered, with *Q. sideroxyla* with bark presenting the highest percentage (64.02%), followed by *A. xalapensis* with bark (58.20%), whereas *J. deppeana* without bark showed the lowest value (53.50%).

3.1.5. Volatile Material

The volatile material values ranged from 82.12 to 87.42% for *J. deppeana* with bark and without bark, and from 87.32 and 87.34% for *A. xalapensis*. *Q. sideroxyla* presented values from 81.20 and 87.42% (Table 4). Statistical differences were observed ($p < 0.05$) between *A. xalapensis*, *J. deppeana*, and *Q. sideroxyla* without bark.

Table 4. Higher heating value and immediate analysis of the three species studied.

Species	HHV of Raw Material (MJ kg^{-1})	HHV of Pellets (MJ kg^{-1})	Volatile Material of Raw Material (%)	Fixed Carbon of Raw Material (%)
A. xalapensis (D)	18.93 [d]	20.41 [a,b]	87.32 [a,b]	12.28 [a,b]
J. deppeana (D)	20.21 [e]	21.81 [b,c]	87.42 [b]	11.30 [a]
Q. sideroxyla (D)	18.68 [c,d]	20.12 [a]	81.20 [a]	18.28 [b]
A. xalapensis (WB)	18.32 [b,c]	20.40 [a,b]	87.34 [a,b]	12.20 [a,b]
J. deppeana (WB)	17.68 [a]	20.51 [b,c]	82.12 [a,b]	17.48 [a,b]
Q. sideroxyla (WB)	18.09 [b]	19.72 [a]	87.08 [a,b]	12.39 [a,b]

The same letters in the direction of the columns indicate statistical equality ($p \leq 0.05$). D = without bark, WB = with bark.

3.1.6. Fixed Carbon

The raw material of *Q. sideroxyla* without bark and *J. deppeana* with bark had the highest values (18.28% and 17.48%, respectively), followed by *Q. sideroxyla* with bark (12.39%) and *A. xalapensis* without bark (12.28%) (Table 4). The lowest percentage of fixed carbon was obtained for *A. xalapensis* with bark and *J. deppeana* without bark, with 12.20% and 11.30%, respectively.

3.1.7. Higher Heating Values (HHV) of Raw Material and Pellets

The raw material of *Juniperus deppeana* without bark presented a high calorific value (20.21 MJ kg^{-1}), exceeding the values of the other species studied and with significant statistical differences ($p \leq 0.05$) (Table 4). The bark component was associated to the lowest HHV in all cases. The pellets of *J. deppeana* with bark and without bark had the highest HHV values (20.51 and 21.81 MJ kg^{-1}, respectively); this could be the result of differences in the chemical compounds present in both the bark and wood. According to the results, bark component reduced HHV in the pellets of all species.

3.2. Pellets Energy Performance

Table 5 shows the results of the energy performance obtained in the evaluation of the three species of pellets from the water boiling tests in gasifiers. The performed Tukey test indicated that the values obtained for burning time, burning rate, power, and thermal efficiency between samples with bark and without bark and among species were statistically similar, except for *Q. sideroxyla*, with significantly different powers between samples without bark and with bark of 2.7 and 2.4 kW, respectively. It can be seen that for the energy performance tests that there were statistically significant differences ($p \leq 0.05$) between the gasifiers except for the boiling time.

Table 5. Average energy performance of different types of pellets according to the standard ISO test.

Energy Performance Test	Comparation between Gasifiers	A. xalapensis (D)	J. deppeana (D)	Q. sideroxyla (D)	A. xalapensis (WB)	J. deppeana (WB)	Q. sideroxyla (WB)
Boiling time (min)	A	10(1.4) [a,**]	13(2.2) [a,b]	12(1.4) [a,b]	11(1.0) [a,b]	14(2.3) [b]	14(1.5) [b]
	A	11(0.9) [a,b]	14(1.2) [b]	13(8.4) [a,b]	11(2.2) [a,b]	12(1.9) [a,b]	12(2.1) [a,b]
Boiling time + prolonged boiling (min)	A	33(3.2) [a]	39(5.8) [a,b,c]	36(1.5) [a,b]	34(2.1) [a,b]	36(4.9) [a,b]	37(1.1) [a,b,c]
	B	43(4.4) [a,b,c]	47(5.6) [c]	41(9.2) [a,b,c]	41(5.1) [a,b,c]	43(3.3) [a,b,c]	44(6.9) [b,c]
Burning rate (g min^{-1})	A	11(1.2) [a]	9(1.7) [b,c]	10(0.4) [a,b,c]	11(0.6) [a]	10(1.6) [a,b,c]	10(0.5) [a,b,c]
	B	9(0.9) [b,c]	8(0.9) [c]	9(2.2) [b,c]	8(0.5) [c]	8(0.6) [c]	8(1.3) [c]
Power (KW)	A	3.6(0.4) [a]	3.2(0.6) [a,b]	3.1(0.1) [a,b]	3.4(0.2) [a,b]	3.3(0.6) [a,b]	2.9(0.1) [a,b]
	B	2.7(0.3) [a,b]	2.7(0.3) [b]	2.7(0.7) [b]	2.6(0.1) [b]	2.8(0.2) [b]	2.4(0.4) [c]
Thermal efficiency (%)	A	31(1) [a,b]	30(2) [a,b]	34(1) [b]	31(3) [a,b]	29(3) [a]	31(1) [a,b]
	B	12(12) [c]	14(13) [c,d]	11(11) [c]	12(12) [c]	16(15) [d]	14(13) [c,d]

Standard deviation in parentheses. ** Equal letters in the direction of the columns ([a], [b], [c], and [d]) indicate statistical equality between species ($p \leq 0.05$), and the letters in the direction of the rows (A, B) indicate statistical equality between gasifiers ($p \leq 0.05$). D = without bark, WB = with bark. Rows in gray = Top-lit-up-draft (T-LUD), rows in white = electricity generation wood camp stove (EGWCS).

In the device–fuel combinations evaluated, we found that pellets from *A. xalapensis*, both with and without bark in the T-LUD gasifier, showed the highest thermal efficiency (31% and ISO Tier 3). The species that presented higher values was *A. xalapensis* with and without bark, with a burning rate of 11 g min^{-1}, which was reflected in a greater amount of energy delivered to the task per unit time, and less time of boiling water (10 min).

3.3. Emissions Generated by the Combustion of Pellets

The mass of pollutant emitted from the energy released by the dry fuel quantity consumed in the gasification is shown in Table 6. The lowest CO_2 values were obtained for *J. deppeana* with bark and without bark (63 g CO_2 MJ^{-1}) in the T-LUD gasifier, which shows a statistically significant difference ($p < 0.05$) concerning the EGWCS gasifier (Table 6). Emissions of CO for *A. xalapensis* with bark using EGWCS were significantly influenced by the bark, registering values of 1 973 mg CO MJ^{-1}, while debarked *A. xalapensis* presented

values lower than 1274 mg CO MJ^{-1}. Only in the EC content did we find that there were no significant differences between species; however, there were between gasifiers ($p \leq 0.05$).

Table 6. Average emission factors per energy source.

Mass of Gas Emitted mg MJ^{-1}	Comparison between Gasifiers	*A. xalapensis* (D)	*J. deppeana* (D)	*Q. sideroxyla* (D)	*A. xalapensis* (WB)	*J. deppeana* (WB)	*Q. sideroxyla* (WB)
g CO$_2$ MJ^{-1}	A	74(2.9) [a]	63(4.1) [c]	78(1) [d,c]	73(0.9) [b]	63(1.6) [c]	74(0.5) [c]
	B	93(3) [a]	88(5) [a]	97(9) [c]	94(2) [a]	82(7) [a,b]	95(7) [a,c]
CO	A	425(201) [a,b]	230(53) [a]	477(66) [a,b]	514(24) [a,b]	254(50) [a,b]	468(47) [a,b]
	B	1274(105) [c]	341(54) [a,b]	1135(251) [c]	1973(275) [d]	664(210) [b]	1412(466) [c]
CH$_4$	A	6.3(1.1) [a,b]	5.8(0.7) [a,b]	6.2(0.5) [a,b]	6.2(0.7) [a,b]	5.2(0.6) [a,b]	7.2(0.7) [b]
	A	1.3(0.2) [a]	8.2(6.9) [c]	3.7(2.2) [a,b]	5.5(4.9) [a,b]	3.6(1) [a,b]	4.2(4.8) [a,b]
PM$_{2.5}$	A	17(5.9) [b,c]	5(1.2) [a]	11(2) [a,b]	18(7.3) [c]	6(1) [a]	12(3.9) [a,b,c]
	B	8(2.1) [a]	8(2.8) [a]	6(2.8) [a]	8(2.2) [a]	12(3.0) [a,b,c]	7(1.4) [a]
EC	A	6(4) [a]	4(1) [b]	4(6) [b]	8(6) [a,c]	3(2) [b]	7(4) [a]
	B	2(1) [c]	4(2) [c]	2(3) [c]	3(1) [c]	3(1) [c]	2(1) [c]
OC	A	6(1) [d]	1(0) [a]	4(1) [a,b]	6(1) [c,d]	1(1) [a]	3(3) [a,b,c]
	A	3(2) [a,b,c]	2(0) [a,b]	2(1) [a]	2(1) [a,b]	5(1) [b,c,d]	3(1) [a,b,c]

Standard deviation in parentheses. The letters in the direction of the columns ([a], [b], [c], and [d]) indicate statistical equality between species ($p \leq 0.05$), and the letters in the direction of the rows (A, B) indicate statistical equality between gasifiers ($p \leq 0.05$). D = without bark, WB = with bark. Rows in gray = T-LUD, rows in white = EGWCS.

Table 7 shows the emission factors per mass of fuel (kg) consumed in the combustion of gasifiers. On average, using *A. xalapensis* pellets with bark in the T-LUD gasifier produced a higher emission rate of 1290 g CO$_2$ kg^{-1} released to the environment, followed by *Q. sideroxyla* without bark with 1262 g CO$_2$ kg^{-1}, while *J. deppeana* obtained the lowest emission rate, with and without bark, with values ranging from 1104 to 1140 g CO$_2$ Kg^{-1}. T-LUD gasifier showed a statistically significant difference ($p \leq 0.05$) compared with the EGWCS gasifier. On the other hand, in comparison with the T-LUD gasifier, the EGWCS gasifier presented the highest values in terms of the emission rate. *Arbutus xalapensis* with and without bark presented the highest emission factor with values ranging from 1606 to 1629 g CO$_2$ kg^{-1}, followed by *J. deppeana* with bark (1588 g CO$_2$ kg^{-1}) and *Q. sideroxyla* without bark (1573 g CO$_2$ kg^{-1}), without showing significant differences ($p > 0.05$).

Table 7. Average emission factors per mass of fuel consumed.

Mass of Gas Emitted mg Kg^{-1}	Comparison between Gasifiers	*A. xalapensis* (D)	*J. deppeana* (D)	*Q. sideroxyla* (D)	*A. xalapensis* (WB)	*J. deppeana* (WB)	*Q. sideroxyla* (WB)
g CO$_2$/ Kg	A	1290(50) [b,c]	1104(29) [a,b]	1262(17) [a,b]	1247(15) [a,b]	1140(74) [a]	1171(7) [a,b]
	B	1629(59) [e]	1588(99) [d,e]	1573(143) [d,e]	1606(37) [d,e]	1444(118) [c,d]	1506(117) [d,e]
CO	A	7 (3.5) [a,b]	4(0.9) [a]	8(1.1) [a,b]	9 (0.4) [a,b]	4(1.0) [a]	7(0.7) [a,b]
	B	22(1.8) [d]	6(1) [a,b]	18(4) [c,d]	34(4.7) [e]	12(3.7) [b,c]	22(7.4) [d]
CH$_4$	A	111 (20) [a,b]	91(10) [a,b]	101(9) [a,b]	105 (11) [a,b]	105(13) [a,b]	114(10) [b]
	A	24(4) [a]	148(126) [c]	60(35) [a,b]	94(84) [a,b]	33(18) [a,b]	63(76) [a,b]
PM$_{2.5}$	A	303 (102) [c,d]	100(18) [a,b]	170(33) [a,b]	315 (1025) [d]	91(22) [a,b]	186(62) [a,b,c]
	A	141(37) [a,b]	146(52) [a,b]	91(46) [a,b]	128(110) [a,b]	206(53) [b,c,d]	104(23) [a,b]
EC	A	112(69) [a,b,c]	48(33) [a,b,c]	62(8) [a,b,c]	133(97) [c]	73(17) [a,b,c]	117(71) [b,c]
	B	39(25) [a,b,c]	79(41) [a,b,c]	37(47) [a,b,c]	51(20) [a,b,c]	44(18) [a,b,c]	30(13) [a,b]
OC	A	106(21) [d]	24(14) [a]	60(19) [b,c,d]	101(18) [c,d]	15(3) [a]	52(41) [a,b]
	A	56(15) [a,b,c]	37(11) [a]	30(11) [a]	43(21) [a]	89(23) [b,c,d]	41(17) [a]

Standard deviation in parentheses. The letters in the direction of the columns ([a], [b], [c], [d] and [e]) indicate statistical equality between species ($p \leq 0.05$), and the letters in the direction of the rows (A, B) indicate statistical equality between gasifiers ($p \leq 0.05$). D = without bark, WB = with bark. Rows in gray = T-LUD, rows in white = EGWCS.

The organic carbon (OC) and particulate material (PM$_{2.5}$) emitted were compared. The aim was to assess the performance of this lower cost method [43]. Organic carbon (OC) of dry fuel consumed showed a positive correlation with the amount of emitted particulate material (PM$_{2.5}$) in both gasifiers (Figure 1). The best correlation ($R^2 = 0.93$ and $p < 0.05$) was observed when using the T-LUD gasifier, while the use of the EGWCS gasifier presented

a weaker positive relationship ($R^2 = 0.81$ and $p < 0.05$). Regarding to total OC and $PM_{2.5}$ emissions, we observed that the lower the formation of organic matter (organic carbon), the lower the emissions of $PM_{2.5}$. The results in Figure 1 show a clearly low dispersion of the data points, indicating a high accuracy in the estimation of OC using $PM_{2.5}$. Similar to previous studies, de la Sota et al. [43] showed a correlation between black carbon and elemental carbon ($R^2 = 0.84$). On other hand, Thompson et al. [52] showed a significant correlation between composition (OM + EC) and $PM_{2.5}$ ($R^2 = 0.94$), and no correlation between composition EC/total carbon (TC) and $PM_{2.5}$ emission factors ($R^2 = 0.07$).
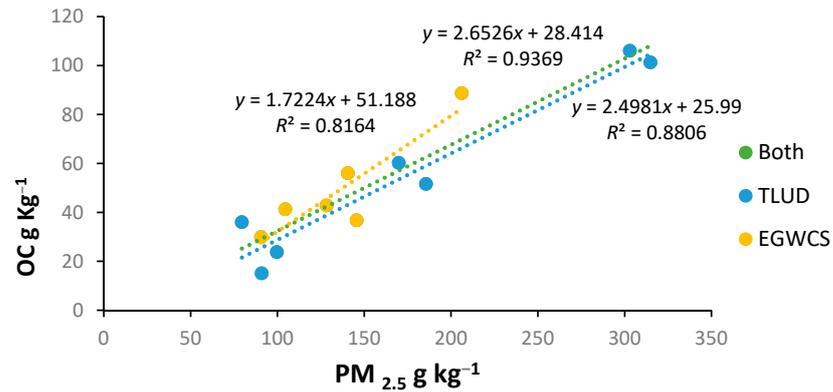

Figure 1. Relationships between total suspended particulate matter ($PM_{2.5}$) and organic carbon (OC) of each gasifier.

Impact on Global Warming

Figure 2 shows the impact on average global warming or radioactive forcing of pollutants from incomplete combustion. The emission of CO_2e was higher for pellets produced from *A. xalapensis* (with bark and without bark) burned in the gasifier T-LUD, while *J. deppeana* with bark showed the lowest production of grams of CO_2e. On the other hand, the EGWCS gasifier had the highest contribution of CO_2e. Concerning the T-LUD gasifier, *A. xalapensis* with bark and without bark presented the highest emission, followed by *Q. sideroxyla*. *J. deppeana* with bark emitted 412.56 g CO_2e kg^{-1}, which showed the lowest contribution for this gasifier.

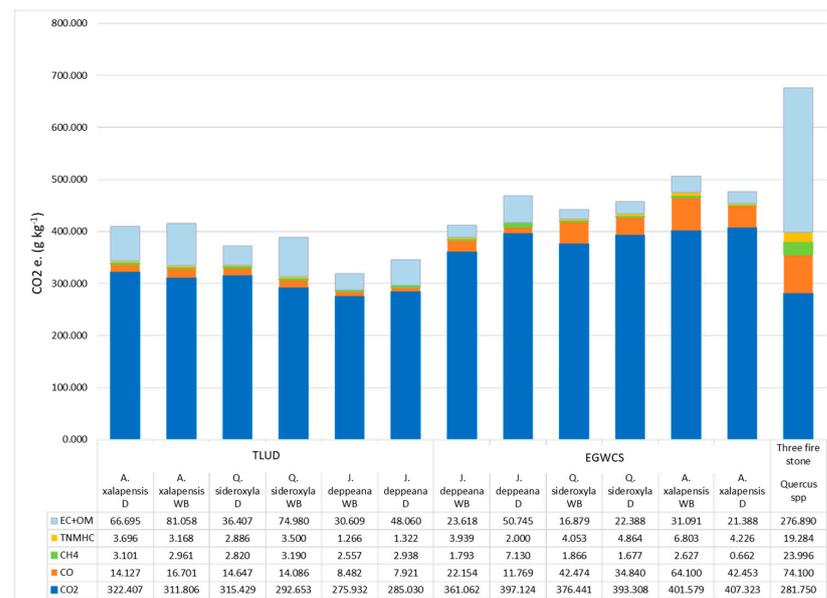| | TLUD | | | | | | EGWCS | | | | | | Three fire stone |
	A. xalapensis D	A. xalapensis WB	Q. sideroxyla D	Q. sideroxyla WB	J. deppeana WB	J. deppeana D	J. deppeana WB	J. deppeana D	Q. sideroxyla WB	Q. sideroxyla D	A. xalapensis WB	A. xalapensis D	Quercus spp
EC+OM	66.695	81.058	36.407	74.980	30.609	48.060	23.618	50.745	16.879	22.388	31.091	21.388	276.890
TNMHC	3.696	3.168	2.886	3.500	1.266	1.322	3.939	2.000	4.053	4.864	6.803	4.226	19.284
CH4	3.101	2.961	2.820	3.190	2.557	2.938	1.793	7.130	1.866	1.677	2.627	0.662	23.996
CO	14.127	16.701	14.647	14.086	8.482	7.921	22.154	11.769	42.474	34.840	64.100	42.453	74.100
CO2	322.407	311.806	315.429	292.653	275.932	285.030	361.062	397.124	376.441	393.308	401.579	407.323	281.750

Figure 2. Carbon dioxide equivalent (CO_2e) (g kg^{-1}) of dry pellets consumed (considering elemental carbon and organic matter).

4. Discussion

4.1. Chemical and Energetic Properties of Pellets and the Raw Material Used for Their Production

The pH is influenced by the amount and type of extractable substances from the wood, mainly by the presence of resinous acids; in this study, the material was considered slightly acidic, coinciding with that reported for species from temperate or Nordic climates [53,54]. According to López-Albarrán and Martínez-Sotres [55], the pH values are an indicator of water content in fibrils of lignocellulosic tissue; acid values indicate little water content, while slightly basic values (between 7 and 7.9) indicate high water content. According to this, it is feasible to relate the calorific power of the wood with its pH values, as shown by the results of this study, with *J. deppeana* without bark, being the species that presented the most acidic pH and the highest calorific value. In another way, during increasing combustion temperature, the pH increases, since some carboxyl group and the water molecules divide forming other chemical bonds changing the acidity of the wood up to incineration [56].

The results of this study show a low ash content, which makes this type of biomass a better raw material, since an optimal ash content is one that does not exceed 0.7%, and high ash values require constant cleaning of combustion equipment [57,58]. The results in this research show a higher ash content in wood with bark that can be attributed to the method of extraction from the raw material because trunks are dragged through the ground during harvest and some sand can be added, which is undesirable during pelletizing since it decreases compaction of the particles affecting the bonding among particles, constituting impurities on pellets that also increase the ash percentage during burning [59].

Saito et al. [60] mentioned that iron (Fe) acts as a smelting agent in contact with molten chlorides (responsible for corrosion in incinerators), which causes attrition on the equipment. The accumulation of Zn and Cu in biomass incineration might cause problems when recycling ashes for fertilization purposes, due to the formation of aerosols and particles, as well as corrosion due to the formation of chloride deposits in combustion equipment [61,62].

Juniperus deppeana (with bark) presented the highest value of calcium (Ca) content (3.74 mg kg^{-1}), while for magnesium (Mg), *Q. sideroxyla* (with bark) showed the highest content (1.90 mg kg^{-1}). The content of Ca, Mg, and Zn varies among species and parts of the tree; this explains the variation of the total content of the elements [63]. Some elements such as Ca and Mg in biofuels influence combustion residues since high Ca content increases the melting point of the ash, and in addition minimizes the amount of ash accumulated in the combustion equipment [57]. In this study, the contents of Ca and Mg were the highest proportion, which indicates that the wood of *A. xalapensis*, *Q. sideroxyla*, and *J. deppeana* is suitable for the production of pellets [64–66].

The content of extracts for *A. xalapensis* with bark and without bark is slightly higher than the values reported by Andrade et al. [67], who found values from 10.04 to 20.57% for *Arbutus unedo* L. In this study, slightly low values were obtained for *J. deppeana*, with bark and without bark, ranging from 12.15 to 17.37%, compared to those obtained by Orhan [68], who used *Juniperus oxycedrus* subsp. *oxycedru, Juniperus communis* subsp. *nana, Juniperus sabina, Juniperus foetidissima*, and *Juniperus excels,* with values from 16.3 to 22.2% using water as solvent. In the same study, methanol was used as solvent obtaining values ranging from 27.6 to 35.2%, slightly higher values compared with this study. As regards the extractions of *Q. sideroxyla* with bark and without bark, extraction values ranging from 13.9 to 15.74% were found using solvents of increasing polarity, being slightly higher than the reported by Bárcenas-Pazos et al. [69], who studied the species *Quercus tinkhami* and *Quercus sebifera* from Sierra de Álvarez in Mexico, obtaining extract contents with the mixture of ethanol-benzene and hot water, resulting in values ranging from 7.67 to 9.16% when using hot water, and from 4.50 to 6.13% when using the ethanol-benzene mixture. On the basis of the high variability of the results, we believe it is important to consider the report by Fonseca [70], who mentions that the amount and composition of the extractive depends on species, tree section, growth conditions, and method of extraction,

since the metabolism of plants can vary to contain various compounds such as fats, waxes, phenols, and sugars. On the other hand, the content of extractables affects the physical and technological properties. In some species, they can increase dimensional stability and mechanical strength; moreover, they can reduce the saturation point of fiber and the equilibrium moisture content and affect other technological properties [71].

Honorato [72] reported percentages values from 51.94 to 56.43% for cellulose, and from 19.84 to 22.57% for lignin for Mexican *Quercus* woods. These results are comparable with the present study, in which values from 51.81 to 53.90% of cellulose and from 20.63 to 21.11% of lignin were obtained for *Q. sideroxyla* with and without bark, respectively.

The obtained cellulose and lignin values are similar to the reported by Bland [73,74] and Fernández [75]. The lignin contents of the species under study are within the Klason lignin interval published for Mexican pine woods (23.6%–31.2%) [76,77]. The lignin content of pine is similar to those of the species in this study, even if pine wood is more remunerated in other uses [78]. The biomass with bark showed the highest amount of cellulose. This could be due to the fact that tree bark shows a higher percentage of extracts that may contain higher amounts of phenolic compounds, which provide support and protection against microorganism attacks [79]. Pereira et al. [80] report that energy efficiency is related to the chemical composition of the wood, since this influences its performance and quality. On the other hand, Jara [81] points out that the chemical composition of wood is mainly influenced by lignin and extractables. This is in line with Cunha et al. [82], who state that the calorific value is higher the higher the percentage of lignin and extractables.

Villalvazo and Faix [83] carried out a study for *Quercus candicans*, *Quercus laurina*, *Quercus obtusata*, and *Quercus resinosa*, finding a variation in the main components of these woods that ranged from 53.9% to 56.3% for cellulose, from 18 to 21% for pentose, and from 15% to 22% for lignin. These results are similar to those obtained in this study for *Q. sideroxyla*, which obtained values for cellulose between 51.81% and 53.90%. The results regarding the holocellulose content (53.50–64.02%) were higher than the values reported for the *Fagus* species (34.40%) [84].

The thermal properties are directly influenced by the amount of volatile material, since a high content of this increases reactivity but in turn helps to convert to dust more quickly [85,86]. The volatile content determined in this study for pellets is consistent with the range mentioned by Ragland et al. [87], who indicated that, depending on the species, volatile materials can vary between 70 and 90%. Likewise, it is in line with the range reported by Koppejan and Van Loo [88] for fuels obtained from biomass (76–86%).

The results for fixed carbon obtained in this study are similar to those reported by Forero-Núñez et al. [89], who reported a value of 11.71% for sawdust and 16.8% for the cocoa husk; in addition, they mention that fixed carbon is one of the most important parameters in terms of energy potential. A low fixed carbon content increases friability and fragility and decreases resistance to compression and cohesion [90].

The HHV of raw material is similar to that presented by Lima-Rojas [78], who reported values between 17.83 and 18.81 MJ kg^{-1} in four species of conifers. FAO [91] mentions that HHV strongly depends on the part of the tree and on the species, and thus it can conclude that for the species analyzed in this study and in the Lima-Rojas study, the characteristics of the biomass are similar.

The HHV of a material is influenced by its chemical composition, with lignin and extractables content (gums, resins, waxes, fats, and oils) having the most influence [92,93]. This is because both lignin and extractives contain less oxygen than polysaccharides present in holocellulose (cellulose and hemicellulose). The HHV value obtained for pellets of *J. deppeana* (21.81 MJ kg^{-1}) shows the relationship between lignin and calorific power, since this species showed the highest value of this compound and also the highest calorific value, which is in line with different reports showing that HHV of biomass is proportional to the lignin content [94,95].

4.2. Pellet Energy Performance

The burning time, the burning rate, the power, and the thermal efficiency between wood with bark and without bark, as well as between species, have a directly proportional relationship with the calorific value of this type of pellet, where the HHV in the biofuel can represent more power in a given device.

The cooking energy supplied is determined by the sensible heat that increases the temperature of the water in the pot and the latent heat that produces steam. The amount of lost energy is depreciated, but the average thermal efficiency is measured accurately [41]. According to the statistical analysis, the energy performance is significantly influenced by the device (gasifier)/biofuels (pellet) ratio (Table 6). The T-LUD gasifier has lower boiling time and an increase of the useful energy delivered per unit of time since it increases the thermal efficiency with respect to the EGWCS gasifier. The use of the T-LUD gasifier in normal conditions could benefit to the user by reducing fuel consumption and the time in which the cooking tasks are carried out.

Diez-Martínez [96] have focused on the operation of several types of gasifier, but their results could not be understood without understanding the type of fuel that is being used. The choice of fuel will basically depend on the ease of being acquired in the environment in which the user is within. Therefore, the handling of this, as well as the moisture content, will have a positive or negative influence on the energy performance of the gasifiers.

In this same context, the results of this research suggest that the chemical properties of the biomass and pellets with bark and without bark of the three species studied are suitable to produce pellets. Furthermore, the difference in emission values between pellets from different sources may be due to the chemical composition of the material, such as the content of extracts, as this can increase the amount of emissions due to resinous acids in wood. The chemical composition is very important within the energy performance since the disposition of the extractables implies an energy difference between the woods. For instance, the use of raw materials with bark to produce pellets generates greater HHV; however, this does not guarantee the best thermal efficiencies in its final use, as was observed with the pellets of *J. deppeana*, which presented the highest HHV, but low thermal efficiencies. Therefore, the joint evaluation of technologies and fuels is essential to know the real energy savings. For example, in the case of pellets of *Q. sideroxyla* without bark, a difference of 0.4 kW in operating power was obtained, resulting in a threefold difference in thermal efficiency (2.7 kW to obtain a thermal efficiency of 11%, and 3.1 kW to obtain a thermal efficiency of 34%).

Understanding energy needs will help achieve technological innovation and energy transition, and thus it should be noted that local production of pellets and innovation in green technology would accelerate the energy transition.

4.3. Emissions Generated by the Combustion of Pellets

The total mass associated with carbonaceous aerosols, defined as organic matter plus EC, is estimated from OM and organic carbon plus associated elements, which are usually estimated from OC measurements [50]. These results are directly related to combustion efficiency, which suggests that the use of species without bark allows more complete combustion. *Juniperus deppeana* with bark and without bark presented a significant difference ($p \leq 0.05$) in CH_4 emissions, obtaining values of 3.6 ± 1 and 8.2 ± 6.9 mg CH_4 MJ^{-1}, respectively. This could have been due to an increase in the temperature in the combustion because wood without bark has a higher calorific value, promoting in consequence the formation of methane in a greater proportion. *Juniperus deppeana* with bark and without bark presented the lowest averages of pollutant mass emitted (CO_2, CO, CH_4, $PM_{2.5}$, OC, and EC) by energy delivered in the T-LUD gasifier. This was because the pellets of this species have a higher calorific value, lignin and extractable, and a lower pH value (see Tables 3 and 5), to which an independent thermal degradation can be attributed, and can vary according to the heating rate and temperature type of the biomass under study [97].

Emissions produced during combustion are influenced by the gasifier/biofuel ratio. The T-LUD gasifier versus the EGWCS gasifier had significantly lower emissions of CO_2, CO, and EC per energy unit (MJ). For the emissions of CH_4 and OC, no statistically significant differences ($p > 0.05$) between gasifiers were observed. On the other hand, the evaluation of particulate material is very important because it is directly related to damage to health [96,98]. The emissions of particulate matter ($PM_{2.5}$) for the case of T-LUD were significantly higher and can be directly related to the energy performance of the gasifier, i.e., having a higher power and an increase in the burning rate (Table 7), the air/fuel ratio decreases, resulting in lower oxygenation and higher soot production during combustion. The same effect was observed when comparing *A. xalapensis* and *J. deppeana*, which showed the highest and lowest emission factors for $PM_{2.5}$ material with values of 17 and 6 mg $PM_{2.5}$ MJ^{-1}, respectively. Authors such as MacCarty et al. [50] considered that $PM_{2.5}$ emissions depend on different factors, such as size, physical characteristics of the fuel, and design of the gasifier. The values obtained for emissions of $PM_{2.5}$ per kilogram of fuel ranged from 91 to 315 mg $PM_{2.5}$ kg^{-1}, which were lower than the average presented by efficient stoves (1 to 2.8 g $PM_{2.5}$ kg^{-1}) [46,50].

The difference of CO_2, CO, and $PM_{2.5}$ emissions by energy released among species in the pellets may have been due to the chemical composition of the material. The content of extracts in the pellets can be an element that increases the emissions, as observed for *A. xalapensis,* for which a greater amount of extractable and a higher content of EC and OC emissions was obtained.

Elemental carbon (EC), or black particles, comprise the soot generated during combustion. The organic carbon (OC) are white particles produced during slow combustion, with a cooling effect in the atmosphere. These elements come from incomplete combustion, and their formation is closely related to the chemical composition of the fuel, the temperature of combustion, and the amount of oxygen [99]. The type of device, user habits, chemical characteristics, type of biofuel, and moisture content also have a significant effect on the type of particles produced during combustion. The T-LUD gasifier produced fewer emissions for each fuel load, unlike the EGWCS gasifier, which had slightly higher emission values ($p < 0.05$); only OC emissions were statistically equal between gasifiers.

The difference in gaseous emissions between pellets can be related to the formation of agglomerated ash on the stove's grills, creating an irregular combustion airflow through the fuel bed, which affect the oxidation of gaseous compounds [100]. The three-stone fire chamber has a net contribution of 676.02 g CO_2e kg^{-1} (Figure 2), with high emissions of CO, CH_4, and EC. On this device, the increment of temperature and primary air decreases CO_2 but increases CO, CH_4, and EC values present in volatile compounds and aerosols [101].

To compare GHG, we determined the global warming potential (GWP) using CO_2 as a reference gas [96]. The GWP was applied to each of the pollutants emitted, including the particulate material contribution in the same scale to grams CO_2e kg^{-1} of fuel. The use of improved combustion devices such as gasifiers can reduce the impact of global warming up to 33% on a cooking task with respect to the three-stone fire. The heating potential of black carbon particles has a significantly stronger effect (680/50 = 14 times stronger) than organic carbon particles (cooling). Due to the large difference, it is almost impossible for the cooling particles to dominate the heating particles, even in devices considered to be clean combustion [50]. According to Smith et al. [102], most of the products of incomplete combustion are oxidized to CO_2, but in the meantime, they have greater global warming potential (GWP) than CO_2. Indeed, if one is going to put carbon gases into the atmosphere, the least damaging form from a global warming standpoint is CO_2. Carbon dioxide equivalent (CO_2e) is a term for describing different greenhouse gases in a common unit. For any quantity and type of GHG, CO_2e indicates the amount of CO_2 that would have the equivalent global warming impact. A quantity of GHG is expressed as CO_2e by multiplying the amount of the GHG by its GWP.

A CO_2 non-renewable factor (fNRB) of 25% (estimated percentage in subnational units as a result of direct collection of firewood) was considered for Mexico [103]. The difference in gaseous emissions between pellets and three-stone fire can be related to the formation of agglomerated ash in the grills, producing an irregular combustion air flow through the fuel bed, which has a negative effect on the oxidation of the gaseous compounds. There was a strong linear correlation between $PM_{2.5}$ and OC emitted by fuel (kg). The construction of reliable correlation curves by fuel device will allow for more comprehensive evaluations regarding the measurement of organic carbon. On the other hand, the use of gasifiers and types of pellets evaluated showed a reduction of CO_2e compared to open fire. Therefore, technological innovation showed an important role in the reduction of elemental carbon and methane that are short-lived pollutants (SLCP) of interest worldwide to face climate change. In this investigation, reductions between 70 and 97% of methane were obtained and 70–94% of organic matter (containing black carbon) for an open fire. Even in devices considered as clean combustion, the difference in gaseous emissions between pellets and wood can be related to the formation of agglomerated ashes in the grills.

5. Conclusions

The evaluation of pellets from raw material of three forest species to end use helps to better understand the relationship of energy and emissions performance of the different types of pellets. Technical implications can be derived from this study:

(a) The chemical properties of the biomass of *Arbutus xalapensis*, *Juniperus deppeana*, and *Quercus sideroxyla* influence the efficiency of energy and emissions, as well as the concentration values of cellulose and lignin, and favored the pellet production and quality. Pellets made from forest residues can be an important source for energy production.

(b) The CO_2e emissions were mitigated using the gasifier efficient technologies; the same was the case when using sawdust pellets, both allowing for reaching the optimal performance, which can lead to reducing the use of low-quality biofuels and cooking time.

(c) The use of innovative of end-use technologies, as well as high quality fuels such as pellets, contributes to the mitigation of greenhouse gases and improves energy efficiency. Gasification processes are an alternative to reduce particulate matter (specialty values of elemental carbon) in the combustion of solid biofuels. It is important to mention that this research only included the water boiling test, but it is also necessary to evaluate if gasifiers allow for cooking typical dishes of Mexico and Latin America.

The results provided information with direct applications in the use of biomass to make pellets as well as the relationship of chemical properties that are directly related to the total emissions to the environment, highlighting that the use of gasifiers improves performance and reduces emissions.

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