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Integrated Life Cycle Assessment Modelling of Densified Fuel Production from Various Biomass Species

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Abstract: This work presents new data on the life cycle impact assessment of various lignocellulosic biomass types in Mexico. A comparative life cycle assessment model of biomass densification systems was conducted. An integrated approach that incorporated various process variables, such as technology and variations in feed properties, within the analysis was employed to evaluate the environmental impact of producing 1 MJ of energy-containing densified fuel. The results show that the densification unit and curing (fuel drying) have the highest impact on the life cycle's operational energy and the total life cycle energy, respectively. Of all the 33 biomass types from the 17 species sources considered in this study, sweet sorghum and sandbur grass have the highest global warming potential, 0.26 and 0.24 (kg CO_2-eq), and human toxicity 0.58 and 0.53 (kg 1,4-dichlorobenzene-eq), respectively, while coffee pulp and cooperi pine wood have the least impact in both categories, with values of 0.08 and 0.09 (kg CO_2-eq), and 0.17 and 0.16 (kg 1,4-dichlorobenzene-eq), respectively. Chichicaxtla sawmill slabs also have a low environmental impact, and cooperi pine and Ceiba wood have the lowest ozone depletion and ecotoxicity potential. A sensitivity analysis indicated the effects of the transportation system and energy source on the life cycle's environmental impact. Adequate feed preparation, the blending of multiple feeds in the optimum ratio, and the careful selection of densification technology could improve the environmental performance of densifying some of the low-bulk-density feed biomass types.

Keywords: integrated modelling; LCA; densification; biomass; energy; environmental impact

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1. Introduction

Lignocellulosic biomass is one of the world's primary renewable and environmentally friendly energy sources, and could be used to create a circular bioeconomy, displacing the fossil-based linear economy. In developing countries such as Mexico, lignocellulosic biomass, such as forest and agricultural residues, provide a significant portion (e.g., 56.9%) of renewable energy sources, which are estimated at about 4% and, more recently, 7% of the total energy supply at both local and industrial scales [1–3], with potential for more advanced energy and biofuel production via thermochemical and biochemical processes [4]. The efficient utilisation of these biomass resources is essential to the success of the bioenergy sector. It is important to produce biofuels of the highest possible quality, even from lower-quality raw material, and avoid the production of low-quality biofuels from high-quality raw materials [5]. The quality of the final biofuel is influenced by different properties of the solid biomass, and bulk density and moisture are regarded as established properties with significant influence on efficiency across the biofuel production value chain [5]. It is therefore important to ensure consistency and quality control of solid biofuels across the supply chain. Agricultural and some forest residues, such as loose straws, husks, and sawdust, are available in large quantities but are associated with low bulk density, which presents a significant limitation on their utilisation in advanced fuel production [6,7]. Low bulk density increases the energy cost of transportation, storage, and processing of these materials, affecting the environmental and economic sustainability of processing lignocellulosic biomass. One way of tackling the low bulk density of loose biomass is via densification into briquettes or pellets, allowing the efficient transportation, storage, and processing of the biomass [8–11]. Interest in biomass densification has grown consistently over the years because of its associated benefits and the convenience it creates in the biofuel production process [7,12]. However, in recent years, the additional energy required in the densification process has been a subject of concern over the sustainability of densifying loose biomass prior to advanced conversion. Various stakeholders, such as manufacturers, distributors and consumers (e.g., energy generators) are willing to optimise and streamline key processes in order to develop more sustainable logistical environments [12]. Sustainability assessments are required to guide stakeholders as to the best methods to adopt in tackling the current challenges related to the biomass densification process. Several research studies have been carried out to evaluate the sustainability of biomass densification using the life cycle assessment (LCA) and other sustainability assessment tools [13–16]. Often missing in most of the research on the LCA of biomass densification is an understanding of the relevance of process variables to the environmental effects of the life cycle. For example, biomass properties, such as density and moisture content, and densification technology, can affect the energy requirements for densification [17]. It is therefore vital to explore the suitability of various biomass resources for potential utilisation as bioenergy sources via sustainability assessments, to ensure the sustainable utilisation of these resources.

This study conducts a comprehensive LCA of densified fuel production from a whole range of biomass species in Mexico [2,4] to provide insights into the potential sustainability profile of densifying these renewable carbon resources, an essential step towards creating a circular bioeconomy.

2. Materials and Methods

The current study employs a comparative LCA model of biomass densification system [17] to simulate the process and feed parameters associated with various Mexican biomass types. The specific biomass range used and composition are from published studies [2,4,18]. A range of forestry and agricultural biomass from different sources and species were used, as shown in Table 1; additional data on biomass, including loose and compacted densities, were sourced from the literature (Table 1). For simplicity, and since the authors did not carry out the actual densification of these biomass resources, some key assumptions were employed. For example, a percentage relaxation of 10% was applied where data for relaxed densities were not available for specific biomass [11,19]. Due to similarities in composition (e.g., moisture content) across each of the different biomass categories, as shown in Table 1, and limited data for some of these biomass resources, one or more specific biomass was used to represent the specific category associated with it or them. For example, Apapaxco sawdust represents other sawdust biomass forms originating from the *Pinus spp*. species source.

A functional unit of 1 MJ densified biomass energy content at the plant gate was defined for the LCA modelling. A system boundary of gate-to-gate was utilised, as established in the parent model (Figure 1) [17]. The case study focuses on identifying variations in the environmental impact of densifying different biomass resources, and the feed biomass used was assumed to have suitable moisture and particle sizes for densification. Critical differences in moisture among biomass species shown in Table 1 were accounted for in the modelling. It is also established in the parent model that biomass densification is carried out at 25 ± 2 °C, with a mass loss of 7% during packaging, i.e., average shattering and abrasion resistance of densified fuel [19], and only moisture loss in the curing unit. The shattering and abrasion resistance value excludes losses during transport but includes losses during packaging of the densified fuel within the production plant).

Table 1. Mexican biomass data used in integrated LCA modelling for densified fuel production.

Species Source	Biomass	Moisture (%)	Moisture for Densification (%)	Density (kg/m^3)	Heating Value (MJ/kg)	Type	Green Density by Compaction (kg/m^3)	Relaxed Density (kg/m^3)	REF
Pinus spp.	Apapaxco Sawdust	25	12	257	16.91	Woody Biomass	1100	990	[20–23]
	Chichicaxtla Sawdust	25	12	257	16.91	Woody Biomass	1100	990	
	El Brillante Sawdust	25	12	257	16.91	Woody Biomass	1100	990	
	INAFO Sawdust	25	12	257	16.91	Woody Biomass	1100	990	
	Ixtlán Sawdust	25	12	257	16.91	Woody Biomass	1100	990	
	La Victoria Sawdust	25	12	257	16.91	Woody Biomass	1100	990	
Pinus cooperi	Cooperi pine wood	25	12	500	20.3	Woody Biomass	920	828	[23]
Pinus duranguensis	Duranguensis pine	25	12	500	20.3	Woody Biomass	920	828	
Pinus teocote	Teocote pine wood	25	12	500	20.3	Woody Biomass	920	828	
Pinus spp.	Sawmill slabs Apapaxco	25	12	177	18.3	Woody Biomass	980	882	[6,21,24,25]
	Sawmill slabs Chichicaxtla	25	12	177	18.3	Woody Biomass	980	882	
	Sawmill slabs El Brillante	25	12	177	18.3	Woody Biomass	980	882	
	Sawmill slabs INAFO	25	12	177	18.3	Woody Biomass	980	882	
	Sawmill slabs Ixtlán	25	12	177	18.3	Woody Biomass	980	882	
	Sawmill slabs La Victoria	25	12	177	18.3	Woody Biomass	980	882	
Alnus spp.	Alder wood	25	12	450	18.9	Woody Biomass	886	797.4	[26,27]
Ochroma pyramidale	Balsa wood	25	12	130	16	Woody Biomass	900	810	[26]
Ceiba pentandra	Ceiba wood	25	12	230	17.78	Woody Biomass	800	716	[28]
Hevea brasiliensies	Rubberwood	25	12	560	19.4	Woody Biomass	1089	980.1	[29]
Agave salmiana	Agave bagasse	50	17	160	16.8	Agro-Residue	950	855	[30–32]
Saccharum officinarum	Sugarcane bagasse	50	17	173	19	Agro-Residue	1022	919.8	[19]
Malus domestica	Apple bagasse	50	17	150	17.9	Agro-Residue	950	855	[31,32]
Oryza sativa	Rice husks	15	8	354	16	Agro-Residue	796	696	[19]
Hordeum vulgare	Barley husks	15	8	350	15.6	Agro-Residue	705	687	[20]
Triticum aestivum	Wheat straw	15	8	62.75	17.2	Agro-Residue	699	629.1	[33]
Cenchurs echinatus	Sandbur grass	50	17	100	16.9	Grasses	850	765	[34,35]
Rottboellia cochinchinensis	Itchgrass	50	17	100	16.9	Grasses	850	765	
Panicum maximum	Guinea grass	50	17	100	16.9	Grasses	850	765	
Pennisetum purpureum	Elephant grass	50	17	100	16.3	Grasses	850	765	
Coffea arabica	Coffee pulp	50	17	740.35	18.2	Agro-Residue	1110	999	[36,37]
Zea mays	Corn stover	15	8	80.24	18	Agro-Residue	842	757.8	[33]
Sorghum bicolor	Sweet sorghum stalks	15	8	59.3	18	Agro-Residue	559.9	503.91	[38,39]

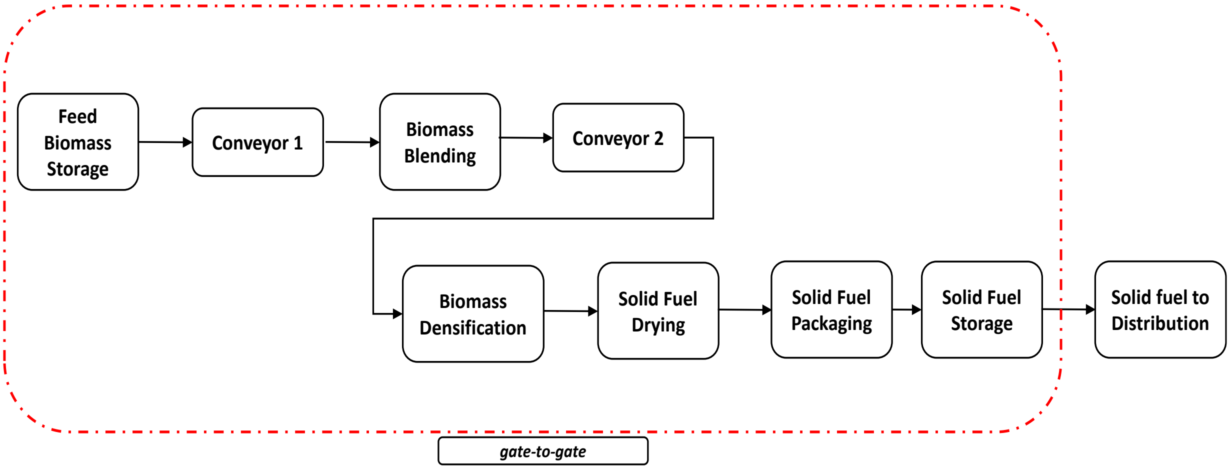


Figure 1. Process flow for a gate-to-gate biomass densification system (adapted from Muazu et al. [15]).

Since 95–99% of the results of LCA modelling are data-dependent [17,40], a sensitivity analysis was undertaken to check the effect of some of the input variables used in the assessment. Considering the comparative nature of the LCA model, the sensitivity analysis was carried out within the model and various input variables, such as transport means, energy source, and densification equipment, were tested.

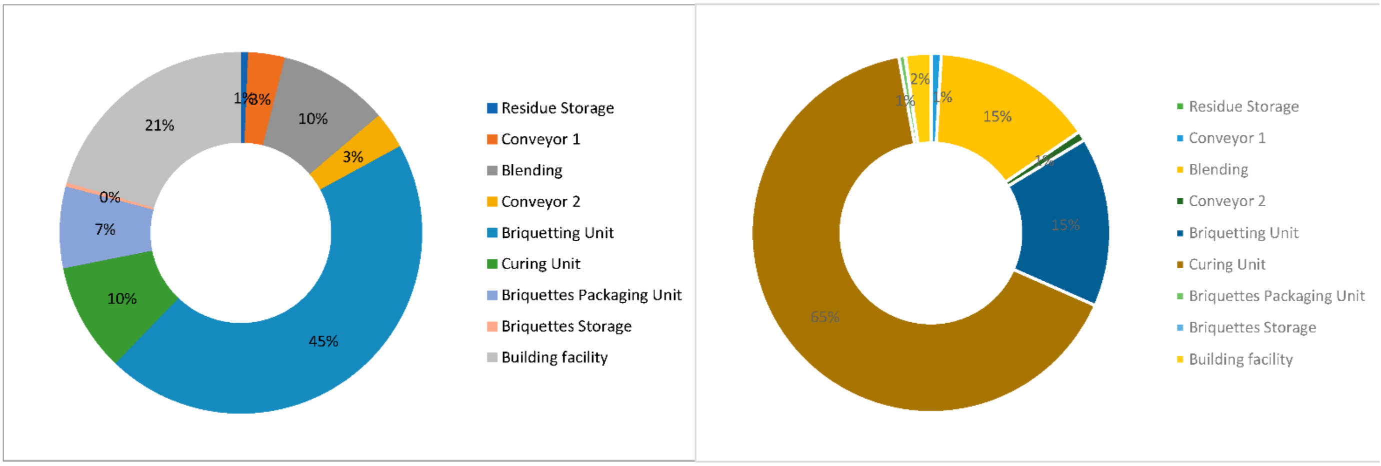
3. Results and Discussion

The output of the integrated LCA modelling of densified fuel production from various Mexican biomass is described in the following sections.

3.1. Life Cycle Energy and Carbon Emissions from Densification of Various Biomass Species

Among the several biomass species used in the current study, the Apapaxco sawdust from *Pinus spp.* was used as a representative feed to evaluate the life cycle contribution of the different units in the densification process. Figure 2 shows the percentage of each densification process unit in the life cycle operational energy (MJ) and total life cycle energy (including embodied) used to produce 1 MJ of solid fuel from Apapaxco sawdust. A value of 0.04 MJ and 1.1 MJ per 1 MJ of densified fuel energy was obtained for the life cycle operational and total life cycle energy, respectively. A total life cycle energy value of 0.08 MJ was also obtained by removing the standby allowance for the equipment of each unit integrated into the model; this reduced the embodied burden.

The densification and blending units have the highest operational energy share contributions, of 45% and 21%, respectively, within the gate-to-gate densification system, while the curing unit (solid fuel drying) makes a significant contribution, of over 60%, to the total life cycle energy. Biomass and briquette storage units have the lowest energy requirements over the life cycle of solid fuel production. The findings by Muazu et al. [17] also show a similar percentage share contribution, of 40%, from densification (briquetting) units to the operational life cycle energy of rice husks and corn-cob briquettes; this is also in line with the findings by Shie et al. for rice straw pellets [41]. Work by Rosenbaum and Bergman [42] also shows that the densification unit makes the highest contribution to energy consumption after torrefaction units for torrefied briquette production from forest residues. However, varying results for the total life cycle energy are observed. The significant contribution of the curing unit to the total life cycle energy may be attributed to embodied energy impact. For example, the net weight of the equipment used for curing is higher than that of other units, such as the densification unit. Furthermore, the number of equipment items required seems higher due to the long drying cycle for the chosen dryer. An increased dryer capacity would increase the material energy requirement, as well as the embodied transport burden, over the life cycle of the equipment.



(**a**) (**b**)

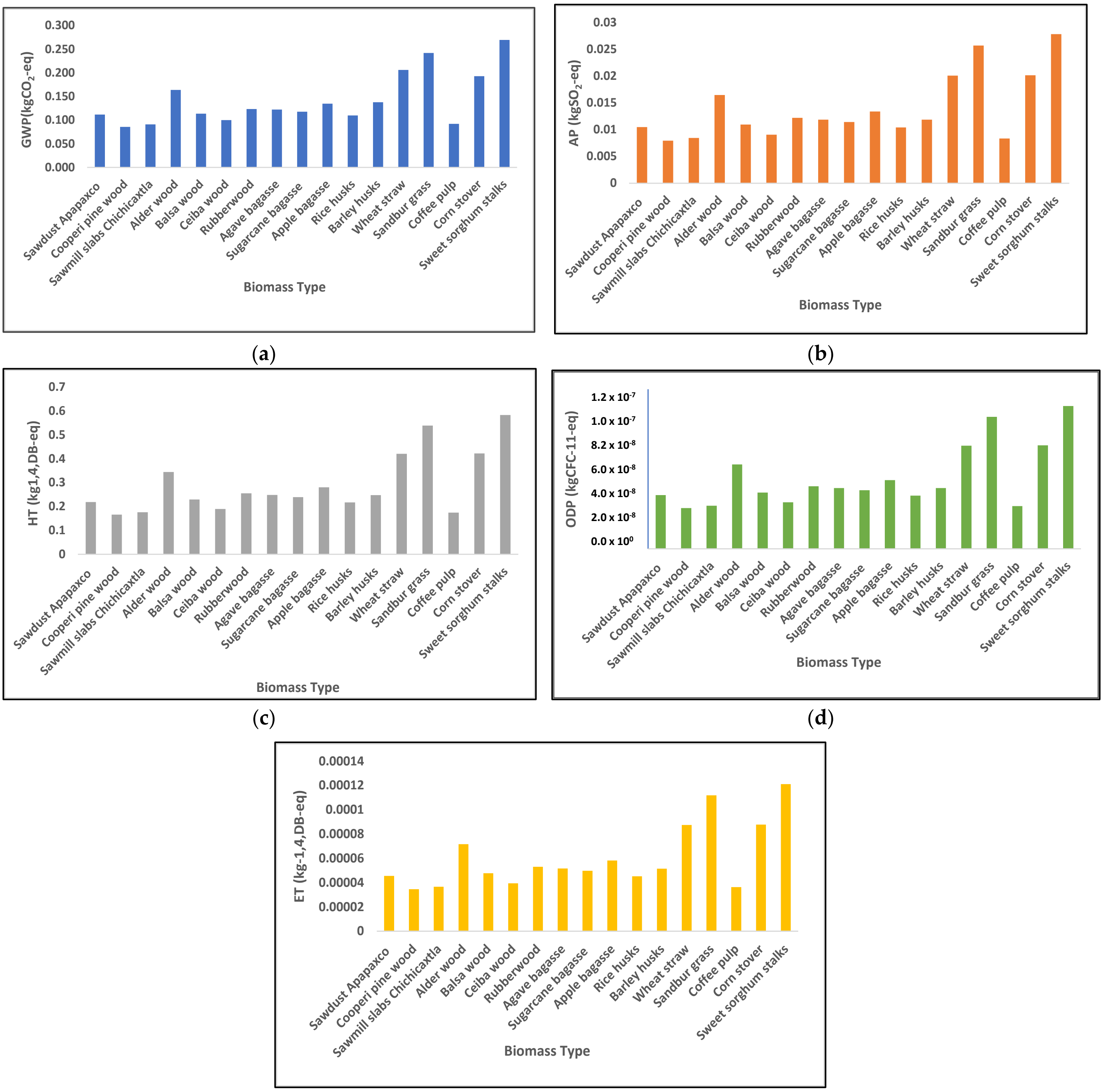
Figure 2. Percentage contribution of different units to (**a**) life cycle operational energy and (**b**) total life cycle energy.

For the various biomass species (Table 1), an energy (MJ) requirement range of 0.4 to 1.1 per MJ of densified fuel energy was observed, while a net energy production ratio (NER) of 13 to 30 and an energy return on investment (EROI) 14 to 33 were obtained. The NER indicates how much energy is produced as saleable products concerning the external, non-feed, and energy input, while the ratio of useful energy gained defines the EROI; the higher the EROI, the more renewable the fuel [41].

3.1.1. Life Cycle Environmental Impact Assessment

The potential environmental impact of producing 1 MJ of densified fuel from the range of biomass species considered in this study is shown in Figure 3a–e. The impact categories considered include the global warming potential (GWP), in Figure 3a, the acidification potential (AP), in Figure 3b, the human toxicity potential (HT), in Figure 3c, the ozone-layer depletion potential (ODP), in Figure 3d, and the ecotoxicity potential (ET), in Figure 3e. Among the impact categories considered, densification's most significant environmental impact is on GWP and HT, and its most negligible impact is on ODP. The results agree with Bergman et al.'s findings for briquette production from logging residues and lumber manufacturing coproducts [43], and those of Wang et al. for corn-stalk briquette production [44]. The large impact of densification on GWP and HT is linked to the high embodied impact of plant facilities and the effects of the operational and transport stages, respectively [17].

Of all the biomass species in Table 1, sweet sorghum and sandbur grass have the highest GWP and HT, respectively. Coffee pulp and cooperi pine wood have the least impact in both categories; Chichicaxtla sawmill slabs also have a low environmental impact. Cooperi pine and Ceiba wood have the least ODP and ET. The high environmental impact of sweet sorghum compared to the rest of the biomass may be associated with its very low loose biomass bulk density and the low density of the produced solid fuel; similarly, Sandbur grass has a low loose biomass density. This implies the increased energy costs of feed preparation, including blending, storage, transport, and biomass compaction. The work by Muazu and Stegemann [19] demonstrated the feasibility of improving the performance of biomass with unsuitable properties for densification by blending multiple feeds in the optimum ratio and carefully selecting the densification technology. Meanwhile, improving the properties of the biomass or processing variables may impact the existing sustainability profile of producing densified fuel from the specific biomass. Therefore, continuous evaluation is required through an integrative approach, as used in this study.



(**a**) (**b**)

(**c**) (**d**)

(**e**)

Figure 3. Environmental impact of solid fuel production from various biomass forms on (**a**) global warming potential ($kgCO_2$-eq), (**b**) acidification potential ($kgSO_2$-eq), (**c**) human toxicity (1,4-dichlorobenzene-eq) [45], (**d**) ozone depletion potential (kg chlorofluorocarbon-eq) and (**e**) ecotoxicity (1,4-dichlorobenzene-eq) [45].

3.1.2. Sensitivity Analysis

The sensitivity analysis results obtained for the densification of the different biomass species are shown in Figures 4–6. The modelling platform employed in this study integrates the effects of the densification process variables on the LCA, which provides a robust and transparent way of understanding the underlying causes of the variations in the LCA outcomes. According to Figure 4, changes in the transport means are only apparent in GWP, and transoceanic shipping appears as the most environmentally intensive means of transporting densification equipment, compared with inland waterway barges and freight trains. The results also indicate that HT and GWP are the most sensitive to the changes, and the effect of changing energy sources is further shown for these two categories. A GWP of 0.06 kg CO_2-eq to 0.1 kg CO_2-eq per MJ of densified biomass fuel was obtained for the *Pinus spp.* species. Furthermore, applying the 70% energy efficiency of the *Pinus spp.* combined heat and power system, as shown in Martinez-Hernandez et al. [46], a GWP of 0.09–0.14 kg CO_2-eq per MJ of output energy (heat and electricity) was obtained in this study. Martinez-Hernandez et al. [46] report 1.4% of a GWP of 1.526 kg CO_2-eq per kWh of electricity from the chipping, machinery, harvesting, forwarding, and infrastructure of *Pinus spp.* They also report an 11% electricity generation efficiency. The contribution of the GWP of the *Pinus spp.* upstream processing to the combined heat and power system in their work is thus 1.526 $\frac{\mathrm{kgCO_2eq}}{\mathrm{kWh}} \times \frac{1}{0.11} \times 0.014 \times \frac{\mathrm{1kWh}}{\mathrm{3.6MJ}}$ or 0.05 kg CO_2-eq per MJ of output energy (heat and electricity). The difference in the GWP reported in the two studies, 0.09–0.14 kg CO_2-eq per MJ of output energy (heat and electricity) in this study and 0.05 kg CO_2-eq per MJ of output energy (heat and electricity) in [46], is due to the different unit operations or system boundaries considered in the densified biomass fuel production system. Other methodological choices may also be responsible for the small difference, which is not uncommon among LCA studies [16].

For the energy sources, gas (medium-voltage electricity) appears to have the lowest GWP and HT, while energy from oil had the highest impact on GWP, followed by the country mix. This may be attributed to the greenhouse gas emissions associated with fossil fuel production and use. Solar energy also had a high effect on HT, below that of the country mix. The extraction of resources during solar energy system production leads to emissions that affect human health, including carcinogens and respiratory inorganics. Moreover, the processes involved in the panel production phase can significantly affect air quality as hazardous substances are emitted into the atmosphere and biosphere [47]. The embodied energy and carbon of materials for equipment and buildings had a coefficient of variations in the range of 0.3 to 27.3. The errors associated with the LCA model employed in this study (including the operational input parameters and emissions data) were between 8 and 15%, for changes in biomass variability, and up to 95% for building and densification technology [17].

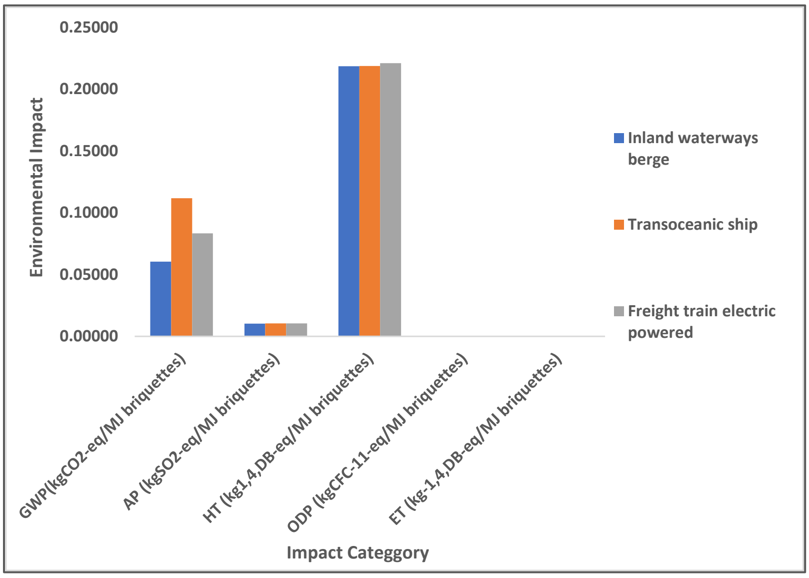


Figure 4. Effect of embodied transport means on LCA outcome of 1 MJ of densified biomass.

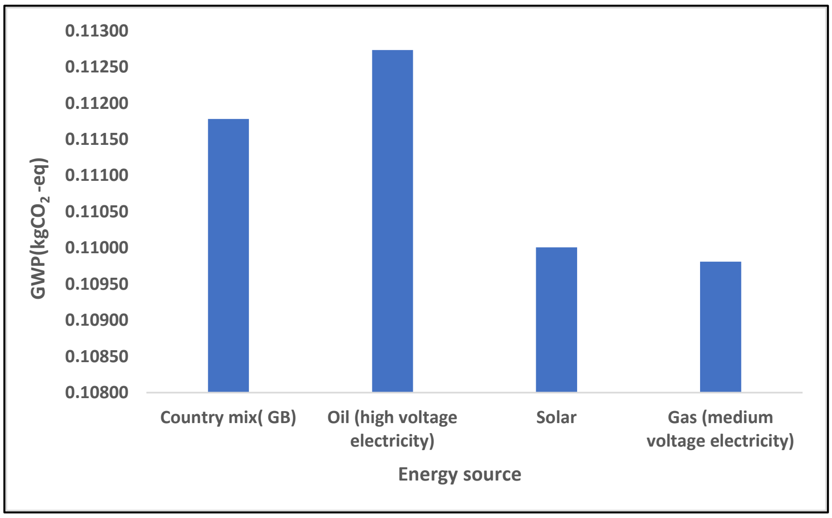


Figure 5. Effect of energy source on LCA outcome (GWP) of 1 MJ of densified biomass.

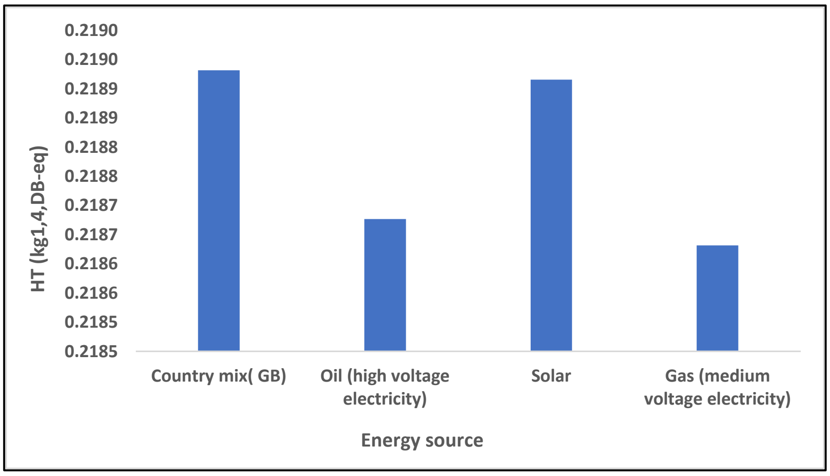


Figure 6. Effect of energy source on LCA outcome (HT) of 1 MJ of densified biomass.

4. Conclusions

Robust LCA modelling of the solid fuel production from various biomass species found in Mexico was conducted in this study. A total of 33 different lignocellulosic biomass types from 17 different species sources was assessed for potential densification into solid fuels to guide existing and future projects related to utilising these biomass resources for energy production. The new data presented in this study are also expected to guide practitioners in developing better understanding of the effects of the specific components of densification process on the environmental sustainability profiles of the various biomass species. We established the influence of the feed biomass variability associated with the different lignocellulosic biomass types considered in this study, as well as that of the processing variables on the environmental performance of the densification of these biomass resources. The approach used in this study incorporates various elements across the gate-to-gate life cycle of the densification process to provide a more robust and transparent output of the assessment. The densification and curing (fuel drying) units affect the life cycle's operational energy and the total life cycle energy, respectively. Of all the biomass types considered in this study, sweet sorghum stalks and sandbur grass have the highest global warming potential, 0.26 and 0.24 (kg CO_2-eq), and human toxicity, 0.58 and 0.53 (kg 1,4-dichlorobenzene-eq), respectively, while coffee pulp and cooperi pine wood have the lowest impact in both categories, with values of 0.08 and 0.09 (kg CO_2-eq), and 0.17 and 0.16 (kg 1,4-dichlorobenzene-eq), respectively. Cooperi pine and Ceiba wood have the lowest ozone depletion (kg chlorofluorocarbon-11-eq) and ecotoxicity (kg 1,4-dichlorobenzene-eq) effects. Further work on practical densification would provide more details to incorporate into the integrated modelling platform.

Author Contributions: R.I.M.: conceptualization, methodology, software, resources, validation, formal analysis, investigation, data curation, writing—original draft preparation. J.S.: conceptualization, resources, writing, review and editing, visualization, supervision, project administration, funding acquisition. S.G.: writing—review and editing, supervision. All authors have read and agreed to the published version of the manuscript.

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