Life cycle assessment of electricity generation from combustion and gasification of biomass in Mexico

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Greenhouse gases – GHG

Life cycle assessment – LCA

non-renewable energy use - NRE

Global warming potential – GWP

Functional unit – FU

Intergovernmental Panel on Climate Change - IPCC

Environmental Protection Agency - EPA

Ozone depletion potential – ODP

Photochemical oxidation formation potential - humans – HOFP

Photochemical oxidation formation potential - ecosystems – EOFP

Terrestrial acidification potential – TAP

Freshwater eutrophication potential – FEP

Human toxicity potential - cancer – HTPc

Human toxicity potential - non-cancer -HTPnc

Fossil fuel potential – FFP

Water consumption potential -WCP

Abstract

One measure to mitigate some of the nowadays environmental problems is the generation of products from renewable resources. In this context, this study's objective is to evaluate the environmental impacts associated with the use of sugarcane and agave bagasse from Mexico as a raw material for the generation of bioenergy, applying a life cycle assessment approach. Four scenarios were compared to determine the optimal feedstock (sugarcane or agave) and processing routes (combustion or gasification) from an environmental perspective. Life cycle assessment is performed according to the cradle-to-gate approach. In the case of the two-feedstocks studied, it was observed that the feedstock processing stage has high impact values in almost all impact categories. In this sense, it was observed that the combustion scenarios have high impact values in terms of ozone depletion potential ($4.73x10^{-6}$ and $7.59x10^{-7}$ kg CFC11 eq), terrestrial acidification potential ($1.41x10^{-2}$ and $7.82x10^{-3}$ kg SO_2 eq), and fossil fuel potential ($9.30x10^{-2}$ and 0.12 kg oil eq) for sugar extraction and bacanora production, respectively). For the gasification scenarios, the highest impact values were observed for the terrestrial acidification potential ($1.27x10^{-2}$ kg SO_2 eq) and fossil fuel potential ($8.41x10^{-2}$ kg oil eq) for sugar production and the ozone depletion potential ($6.85x10^{-7}$ kg CFC11 eq), human toxicity potential - non-cancer ($2.05x10^{-2}$ kg1,4-DCB) and fossil fuel potential (0.11kg oil eq) for bacanora production. Furthermore, it was observed that the sugarcane cultivation stage generates between 2 and 6 times more impact than the agave cultivation stage for almost all impact categories. Regarding the stages related to thermochemical processes, the impact values were relatively low, except for the following categories global warming potential, photochemical oxidation formation potential - humans, photochemical oxidation formation potential - ecosystems, terrestrial acidification potential, and water consumption potential, between 21 % and 88 % for the combustion process and between 32 % and 63 % for the gasification process. The main results of the comparisons between the four scenarios showed that the best scenario from an environmental perspective is agave bagasse combustion, followed by agave bagasse gasification, sugarcane bagasse gasification, and sugarcane bagasse combustion.

Keywords: Life cycle assessment; sugarcane bagasse; agave bagasse; combustion; gasification.

1. Introduction

In recent years, it was observed that population growth and the significant development of technologies (e.g., technologies that use fossil fuels) harm the earth's non-renewable natural resources without being able to cover all the needs of the population (Destek and Sinha, 2020). Although many industrial processes are already improved and modernized – e.g., reducing the use of raw materials – it is recommended to reduce the consumption of non-renewable energy further. Anthropogenic activities like industrial processes, transportation, agriculture, deforestation, or organic waste generate large quantities of greenhouse gases (GHG) that contribute to global warming (IPCC, 2014; Soreanu, 2014). To reduce GHG emissions and the consumption of non-renewable resources, it is essential to use renewable energy sources.

Biomass is a renewable energy source produced in large quantities and is available all over the world. In 2018, Mexico produced a total of 57.1 and 1.77 million t of sugarcane and agave biomass, respectively (SAGARPA, 2018b), with a large amount of bagasse being produced. Bagasse represents the fibrous fraction of sugarcane and agave, which can be used for energy or non-energy applications (e.g., energy, cellulose, batteries, adsorbent, animal feed, bioethanol, methane) (Candido and Gonçalves, 2019; Gongora and Villafranco, 2018; Gschaedler Mathis et al., 2017; Oliveira et al., 2019; Wang et al., 2018).

The composition of the biomass, its degree of humidity and the type of desired final product have a considerable influence on selecting the conversion technology. Among the thermochemical processes, the most widely discussed options are combustion, gasification, and pyrolysis. Combustion is the most commonly used thermochemical process to convert biomass into energy (heat or subsequently electricity) and ash, at high temperatures (> 550 °C) and under an atmosphere containing oxygen (e.g., air) (López-González et al., 2013). Gasification occurs at high temperatures in the presence of a gasifying agent (steam, air, oxygen, or a mixture), transforming biomass into gaseous fuels (Shayan et al., 2018). The generated gas (syngas) can be used to provide energy (heat or electricity), transport fuel, or chemicals (Ahmad et al., 2016).

Recently, producers, consumers, decision-makers, and society are paying more attention to the environmental performance of goods and services production. In this context, it is necessary to identify the environmental impacts occurring along the entire life cycle of a product, using the life cycle assessment approach (LCA) (ISO14000, 2009).

Several studies on the LCA applied to the thermochemical conversion of different biomass types have been recently reported (Gemechu et al., 2019; Ruiz et al., 2018; Ubando et al., 2019). Several studies related to the LCA of the valorization of sugarcane bagasse to produce energy have been published. In this sense, Renouf et al. (2013) investigated environmental impact generated by the production of energy from sugarcane bagasse, ethanol from molasses, bagasse and cane juice, and polylactide plastic from cane juice. The LCA results showed that ethanol and polylactide production from cane juice further reduces the impact of non-renewable energy use (NRE) and global warming potential GWP than the production of electricity and the production of ethanol from molasses and bagasse. Lopes Silva et al. (2014) analyzed the environmental performance of sugarcane bagasse combustion to obtain energy. The authors have identified that the categories most affected were photochemical ozone and human toxicity due to sugarcane harvesting and chemical application processes. Besides, Silalertruksa et al. (2017) carried out the LCA of a sugarcane biorefinery, obtaining electricity and steam from bagasse, ethanol from molasses and fertilizers from vinasse. The results revealed that mechanized agriculture and the integration of waste valorization reduces environmental impacts. Amezcua-Allieri et al. (2019) carried out a techno-economic-environmental study to determine the cost and environmental impact of supplying heat and electricity in the sugar production process by comparing the use of fuel oil and bagasse. The study shows that bagasse as a solid fuel is better from an economic and environmental point of view due to replacing fossil fuel and the electricity, based mainly on fossil fuels in Mexico. Meza-Palacios et al. (2019) analyzed the environmental damage generated by sugar production from sugar cane. The results show that the sugarcane cultivation and harvesting stage generate the most damaging environmental impacts, followed by electrical cogeneration, sugarcane transportation and sugar milling. Recently, Mohammadi et al. (2020) evaluated the environmental impacts of energy production from sugarcane bagasse through combustion, gasification, and anaerobic digestion processes. The results showed that replacing natural gas with bagasse to produce energy in the sugar mills reduces GHG emissions. Furthermore, they observed that the burning of bagasse generates more electricity compared to gasification and anaerobic digestion.

However, no study compared the environmental performance of electricity production by sugarcane and agave bagasse combustion or gasification. Since both crops have a substantial revenue in the Mexican market, a comparison is pertinent to determine which crop has environmental and economic benefits. Therefore, the main novelty and aim of this paper is to compare the environmental performance associated with the production of electrical energy from sugarcane and agave bagasse combustion and gasification processes.

2. Methodology

2.1. Goal and scope

In this study, the LCA approach was applied to evaluate the environmental impacts associated with sugarcane and agave bagasse valorization through combustion and gasification to obtain electricity as the main product. The LCA was performed by the cradle-to-gate approach, considering the following stages: sugarcane and agave cultivation; sugar extraction and bacanora production; sugarcane and agave bagasse combustion process; sugarcane and agave bagasse gasification process. The functional function (FU) considered is 1 MJ of electricity produced. The system boundary is shown in Figure 1.

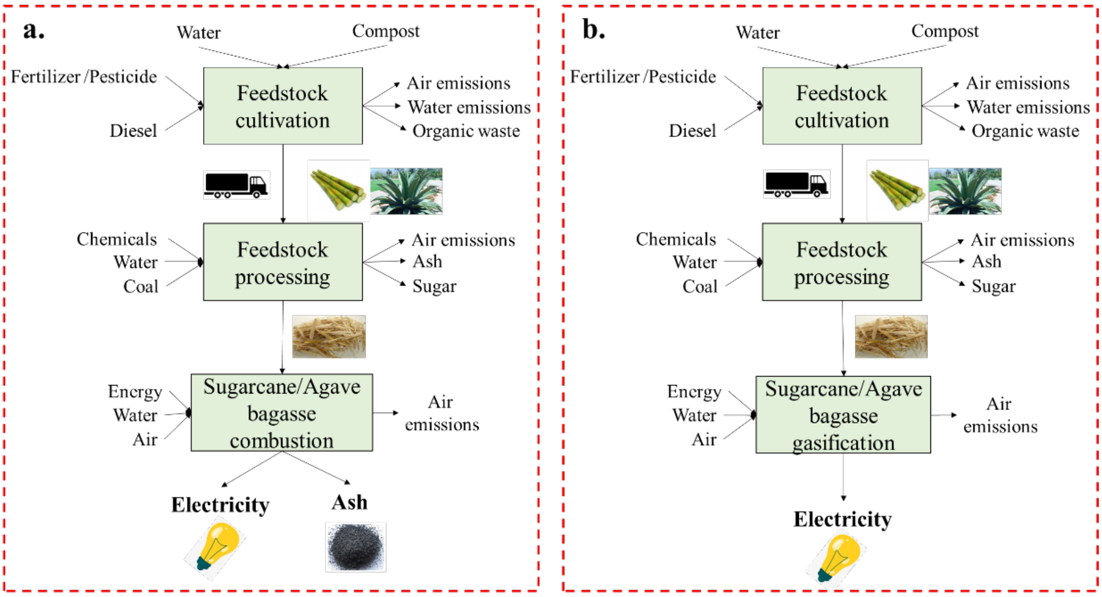

Figure 11: System boundaries of the electricity production from sugarcane and agave through: a. combustion process and b. gasification process.

An important aspect to be considered for LCA is the identification of the system boundaries. In the present study infrastructure, machinery, and equipment for the different stages were excluded. The system boundary also excludes the use and end of life of electricity products, sugar, bacanora, and ash. In this work, data on fertilizers, chemicals, water, diesel, fuel oil and electricity production were extracted from Ecoinvent database (Ecoinvent, 2019). Also, the transport of fertilizers, sugarcane, and agave was taken into account. It was assumed that the sugarcane and agave processing plant and the combustion and gasification facilities were located in the same place. Besides, it was considered that before reaching the conversion plant, the sugarcane and agave bagasse are dried naturally in "bagaceras" (by sun exposing). However, the emissions generated during this process were not considered in this investigation.

2.2. Life cycle inventory analysis

According to Lee and Inaba (2004), the processes' input and output data, depending on the data quality requirements, can be obtained from various sources, such as on-site data, literature data, or even from databases. In this study, the primary input and output data for the sugarcane and agave cultivation stage was obtained from a real plant in Mexico (Veracruz). Only air and water emissions were calculated according to Intergovernmental Panel on Climate Change (IPCC), Environmental Protection Agency (EPA), and Ecoinvent (EPA, 2016, 2017; Klein et al., 2006; Nemecek and Kägi, 2007). The inventory data for sugar and bacanora production were extracted from literature (CONADESUCA, 2020; Consorcio, 2012; Lauzurique Guerra et al., 2017; Livier, 2004; Mandavgane et al., 2018). Finally, the combustion and gasification plants were simulated using Aspen Plus® v8.8 software to estimate the mass and energy balances that constitute the processes' inventory data.

The main inputs and outputs of the sugarcane and agave cultivation stage, sugar and bacanora production stage are shown in Tables 1 and 2.

Table 1: Inventory data for sugarcane and agave production stages, considering 1 MJ of electricity produced as FU.

		Combustion		**Gasification**	
		Sugarcane	Agave	Sugarcane	Agave
Input*					
Urea	kg	1.38 x10^{-2}	-	1.25 x10^{-2}	-
River water	m^3	6.76 x10^{-2}	-	6.12x10^{-2}	-
Compost	kg	0.34	0.15	0.31	0.14
Pyrethroid	kg	5.17 x10^{-7}	4.65 x10^{-3}	4.68 x10^{-6}	4.22 x10^{-3}
Nitrogen fertilizer	kg	3.18x10^{-3}	-	8.32x10^{-3}	-
Phosphate fertilizer	kg	3.18 x10^{-3}	-	8.32 x10^{-3}	-
Potassium fertilizer	kg	3.18 x10^{-3}	-	8.32 x10^{-3}	-
Diesel	kg	6.42 x10^{-3}	6.20 x10^{-3}	5.82 x10^{-3}	5.63 x10^{-3}
Tap water	kg	3.21 x10^{-4}	3.10 x10^{-4}	2.94 x10^{-4}	2.81 x10^{-4}
Glyphosate	kg	-	5.58 x10^{-4}	-	5.07 x10^{-4}
Copper sulfate	kg	-	5.58 x10^{-4}	-	5.07 x10^{-4}
Transport	kg*km	58.8	38.7	53.3	35.2
Output*					
Sugarcane	kg	2.35	-	2.13	-
Agave	kg	-	1.55	-	1.41
Organic waste	kg	0.17	0.16	0.15	0.14
Air emissions**					
N_2O	kg	1.62 x10^{-4}	5.31 x10^{-5}	1.47 x10^{-4}	4.82 x10^{-5}
NH_3	kg	6.51 x10^{-4}	7.15 x10^{-6}	5.90 x10^{-4}	6.49 x10^{-6}
NO_x	kg	3.40 x10^{-5}	1.12 x10^{-5}	3.08 x10^{-5}	1.01 x10^{-5}
CO_2	kg	2.72 x10^{-2}	3.04 x10^{-2}	2.47 x10^{-2}	2.76 x10^{-2}
CH_4	kg	7.06 x10^{-7}	1.02 x10^{-6}	6.40 x10^{-7}	9.27 x10^{-7}
Water emissions**					
NO_3	kg	2.36 x10^{-3}	1.22 x10^{-3}	2.14 x10^{-3}	1.10 x10^{-3}
P_2O_5	kg	1.22 x10^{-5}	1.68 x10^{-5}	1.11 x10^{-5}	1.53 x10^{-5}

*from Mexico (real plant); **(EPA, 2016, 2017; Klein et al., 2006; Nemecek and Kägi, 2007)

Table 2: Inventory data for sugar and bacanora production stages, considering 1 MJ of electricity produced as FU.

		Combustion		**Gasification**		**Ref.**
		Sugarcane	Agave	Sugarcane	Agave	
Input						
Sugarcane	kg	2.35	-	2.13	-	(CONADESUCA, 2020)
Agave	kg	-	1.55	-	1.40	(Livier, 2004)
Flocculating agents	kg	2.35 x10^{-5}	-	2.13 x10^{-5}	-	(Consorcio, 2012)
SO_2	kg	2.32 x10^{-4}	-	2.13 x10^{-4}	-	(Consorcio, 2012)
NaOH	kg	4.71 x10^{-4}	-	4.26 x10^{-4}	-	(Consorcio, 2012)
Water	kg	1.64	4.20	1.49	38.1	(Gamboa, 2006; Livier, 2004)
Quicklime	kg	1.88 x10^{-3}	-	1.71 x10^{-3}	-	(Consorcio,
Fuel oil	kg	9.41 x10^{-3}	7.75 x10^{-2}	8.53 x10^{-3}	7.04 x10^{-2}	(Ecoinvent, 2019)
Output						

Bagasse	kg	0.33	0.40	0.30	0.37	(CONADESUCA, 2020; Livier, 2004)
Sugar	kg	0.27	-	0.25	-	(CONADESUCA, 2020)
Bacanora	kg	-	0.11	-	0.10	(Livier, 2004)
Ash	kg	7.77 x10^{-3}	7.97 x10^{-3}	7.07 x10^{-3}	1.65 x10^{-2}	(Lauzurique Guerra et al., 2017; Mandavgane et al., 2018)
Organic waste	kg	-	2.67	-	2.43	(Livier, 2004)
Air emissions						
H_2O	kg	-	2.02	-	1.83	(Livier, 2004)
SO_2	kg	1.08 x10^{-2}	7.12 x10^{-3}	9.80 x10^{-3}	6.47 x10^{-3}	(Lauzurique Guerra et al., 2017; Mandavgane et al., 2018)
CO_2	kg	0.25	0.16	0.22	0.15	
PM2.5	kg	9.99 x10^{-4}	6.58 x10^{-4}	9.05 x10^{-4}	5.97 x10^{-4}	
NO_x	kg	2.61 x10^{-4}	1.72 x10^{-4}	2.37 x10^{-4}	1.56 x10^{-4}	
CO	kg	1.42 x10^{-3}	9.35 x10^{-4}	1.29 x10^{-3}	8.49 x10^{-4}	
Hydrocarbons	kg	1.41 x10^{-6}	9.30 x10^{-7}	1.28 x10^{-6}	8.44 x10^{-7}	
Avoid products						
Molasses	kg	7.95 x10^{-2}	-	7.20 x10^{-2}	-	(CONADESUCA, 2020)
Cachaza	kg	4.13 x10^{-3}	-	3.74 x10^{-3}	-	(CONADESUCA, 2020)
Vinasse	kg	-	0.18	-	0.16	(Livier, 2004)

2.2.1. Feedstock cultivation

a. Saccharum officinarum

For the cultivation of sugarcane (*Saccharum officinarum*), a lifetime of five years is considered. Being in the first year, soil preparation (harrowing, plowing, and raking) is carried out. 20,000 kg compost is applied per hectare for soil conditioning. The compost is transported from the sugar plant "La Gloria" located 25 km away. Along with compost, fertilizer application is a critical productivity factor for sugarcane. In this case, the following amounts of fertilizers and pesticides are applied annually: Triple17 (300 kg/ha), urea (150 kg/ha), Allectus 300sc (12 kg/ha), and Engeo (12 kg/ha). These are transported 7 km in a truck of 3 t of capacity.

On the other hand, gravity irrigation is carried out using water from a natural river located 2 km from the plot. The harvested sugarcane is transported by a truck to the mill, 25 km away from the field. Each year's total yields are the following: 1st year 140 t/ha, 2nd year 120 t/ha, 3rd year 100 t/ha, 4th year 90 t/ha, and 5th year 85 t/ha.

b. Agave salmiana

In the case of agaves, the considered useful life is six years. For plantation establishment, plants of approximately six months are used, which are distributed in rectangular form (3 x 3 m distance between the plants), obtaining an average of around 1,200 plants/ha.

This plant's main advantage is that it can be grown on very degraded soils, poor in nutrients and water (LaFevor et al., 2018). Pruning is done every two years, removing the outer leaves, which are already adult and dry. For a higher yield, approximately 4 t/ha of compost, 3 kg/ha glyphosate, 20 to 30 kg/ha bifenthrin, and 3 kg/ha copper sulfate are applied annually. During the entire cultivation period, the crop is irrigated only by rainwater. The agave yield is 1,200 plants/ha with a weight of around 250 kg/plant.

2.2.2. Feedstock processing

a. Sugar extraction

After transporting the sugarcane to the sugar extraction plant, it is weighed and stored. Subsequently, it is fed into the processing equipment. The sugarcane is transported to the choppers using a conveyor belt system. The choppers break the sugarcane to facilitate the extraction of the juice. Broken sugarcane is crushed using six mills to extract the juice. For crushing, water is added to the unsaturated juices to extract the sucrose contained in the fibrous material (bagasse). In the last mill, the bagasse is separated (Consorcio, 2012). A part of the remaining bagasse from the sugar extraction process is burned to obtain electricity, which is used again in the same process. It is assumed that fuel oil is added to bagasse in the combustion process to increase the electricity yield (Ecoinvent, 2019). The rest of the bagasse is used as a raw material in the thermochemical processes (combustion and gasification).

Since the extracted juice contains large amounts of sucrose, it is sent to the sugar production process. The juice is weighed to define the proportion of calcium oxide needed to be added. After adding the calcium oxide to the juice, it is heated up to 102 to 105 °C and passed to the clarifier to separate the juice's impurities, forming insoluble calcium salts (Consorcio, 2012). The solid impurities are subjected to a sucrose recovery process using filtration. The solids obtained (cachazas) in the rotary filter can be used as compost. The clarified and filtered juice (12 to 16 wt.% of solids-sugar) is passed to four evaporators to concentrate it up to 60 wt.% of solids (syrup) (Consorcio, 2012). After the evaporation stage, crystallization takes place, using three tanks that operate under vacuum pressure. In this sense, the liquid with crystals obtained in the first tank is mixed in a mixer and centrifuged to separate the liquid's solids, receiving commercial sugar. After three successive crystallizations, exhausted honey (molasses) is produced. (Consorcio, 2012).

b. Bacanora production

Bacanora is an alcoholic beverage originating from the state of Sonora, Mexico, received from agave fermentation and distillation. Generally, it is a colorless drink with high alcohol content (38 vol% and 55 vol% alcohol).

The bacanora production process begins in the field by selecting agave plants according to their size, preventing them from starting to bloom. This measure is carried out to increase the reserve of sugars. After 1 or 2 years, the plants are harvested, the leaves are removed, and the plants' center is transported to the bacanora production plant.

Once the agaves have arrived at the bacanora production plant, the plants' cooking stage begins using an autoclave with saturated steam under pressure (Livier, 2004).

During this stage, cooked agave and condensed honey are generated. The cooked agave is cut, leaving organic waste. The cut agave goes through three grinding stages using water to facilitate the agave juice extraction process. After three grinds, juice and bagasse are obtained (Livier, 2004). As in the sugar extraction process, one part of the bagasse obtained is burned in an existing boiler to receive electricity used as input for the bacanora production process. It is also here assumed that fuel oil is added along with the bagasse in the burning process to increase electricity yield (Consorcio, 2012; Ecoinvent, 2019). The other part of bagasse is used as a raw material in the thermochemical processes.

All honey obtained during the cooking and milling process is stored in a conditioning tank and sent to an anaerobic fermenter, getting the fermented juice. To control the fermenter temperature, water-cooled streamers are used. After the fermentation stage, the juice is inserted into the shredder, which uses saturated steam to remove the heavier compounds called "Flemas" and to obtain three vapor fractions (Livier, 2004). The main vapor fraction is sent to the rectifying column, where the second distillation took place in the presence of saturated steam, bacanora is obtaining. Further, vinasse and organic waste are also generated. The received bacanora is sent to a sterilization tank. By adding water, the final bacanora is produced (Livier, 2004).

2.2.3. Thermochemical processes

The combustion and gasification processes are simulated using the Aspen Plus® software. Since the Aspen Plus® database does not include biomass as components, it was necessary to characterize sugarcane and agave bagasse to integrate them into the simulation. Table 3 shows the composition of these biomasses. Before carrying out the characterization analysis, bagasse was dried in the open air for 48 hours to lower its humidity. In this sense, non-conventional biomass is converted into conventional components in Aspen Plus ®. The enthalpy was calculated using the HCOALGEN model, and for the processing of data and the determination of the thermodynamic properties, the Peng-Robinson method was used for the combustion process. The Ideal Property method was selected for the gasification process.

Table 3: Characterization of the sugarcane and agave bagasse.

	Ultimate analysis (wt%)				
	C	**H**	**N**	**S**	**O***
Sugarcane bagasse* **	44.86	5.87	0.24	0.06	45.87
Agave Bagasse	39.81	5.08	1.79	0.30	41.61
	Proximate analysis (wt%)				**HHV (MJ/kg)**
	Moisture	**Ash**	**Volatile matter**	**Fixed carbon****	
Sugarcane bagasse* **	5.40	3.10	80.20	11.30	18.00
Agave Bagasse	2.68	11.41	71.00	14.91	15.43

*: obtained by the difference of C, H, N, S, and ash; **: calculated from the difference of moisture, ash, and volatile matter, higher heating value (HHV); ***(Varma and Mondal, 2016)

a. Combustion process

The flowsheet diagram for the combustion process is shown in Figure 2.

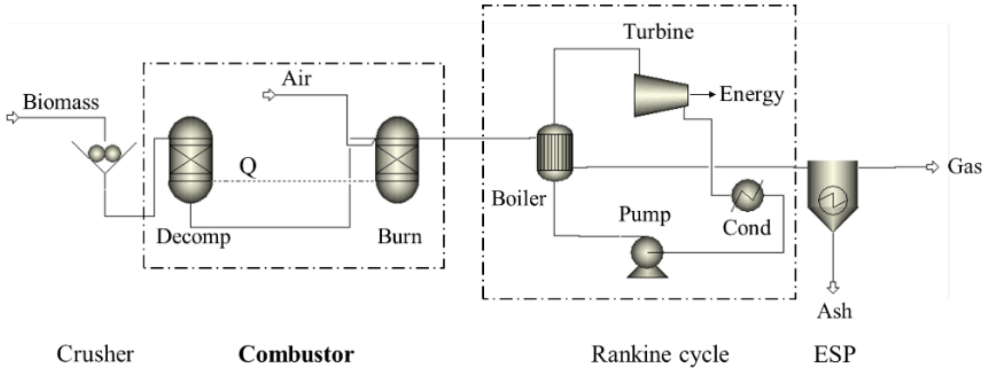

Figure 2: Aspen Plus® flowsheet simulation for the combustion process.

Bagasse must undergo a drying process before being used in thermochemical plants. The most used way to dry this type of biomass, due to its low cost, is naturally in "bagaceras" under solar heat between 20 and 50 days (Bernal, 2019). After drying, the bagasse is fed to the crushing stage in the “crusher” to reduce the biomass's size to 5 mm. The "Combuster" was simulated using two different reactors (López, 2017). The first reactor, ("decomp" - RYield), was used to simulate the decomposition of biomass (non-conventional component) into volatile matter (conventional components). The second reactor ("burn" - RGibbs) was considered to simulate stoichiometric combustion reactions, with the combustion of the formed carbon taking place (López, 2017). The two reactors' names were thought to specify in an easy way in which reaction takes place in each reactor. The RGibbs reaction temperature was 1550 °C. Finally, the electricity was obtained by simulating a “Rankine cycle”. Thus, the gas obtained after the combustion of the bagasse was fed to the “boiler” (Heat X), obtaining steam at 20 bar and 500 °C that was fed to the “turbine” (Compr) to reduce the gas pressure to 1 bar (Srinophakun et al., 2001). The difference between inlet enthalpy and outlet enthalpy was transformed into the turbine's outlet electricity (Srinophakun et al., 2001). Subsequently, the “condenser” (heater) was used to convert the resulting steam into saturated liquid. Then, a “pump” at 20 bars was used to feed the liquid to the boiler. The isentropic efficiencies for the turbine and pump were 85 % and 65 %, respectively (Liu et al., 2014; Saleh et al., 2007). The exhausted gas obtained from the “boiler” heating was sent to an electrostatic precipitator (“ESP”) at 175 °C and 1 bar to separate the gas and the ashes (Rastegarfar et al., 2018). It was assumed that all the ash obtained (8.90 $\mathbf{x}10^{-3}$ for sugarcane bagasse and 4.06 $\mathbf{x}10^{-2}$ for agave bagasse) in this reactor was 100 % carbon.

b. Gasification process

The flowsheet diagram for the gasification process is shown in Figure 3.

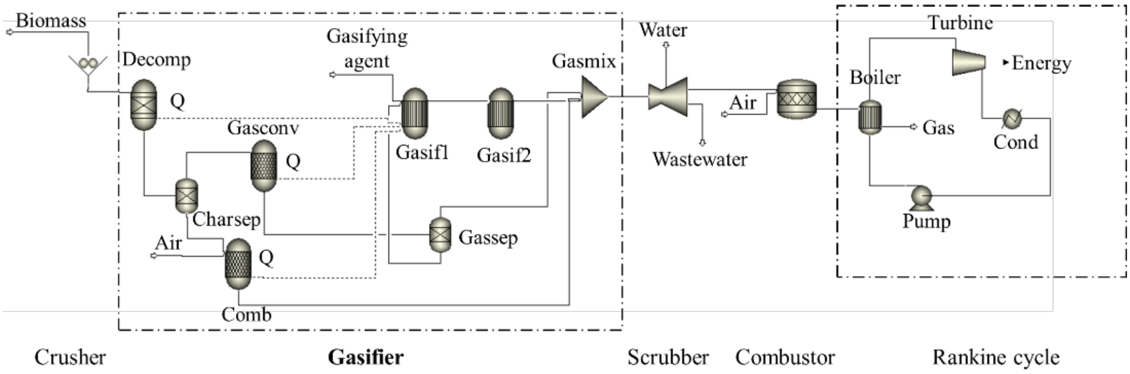

Figure 3: Aspen Plus® flowsheet simulation for the gasification process.

The first stage considered in the gasification process is pyrolysis (volatiles released and char formation). On the other hand, the dual fluidized bed gasifier has two zones: combustion and gasification. Combustion is carried out to increase the bed particles' temperature and offers optimal conditions to carry out gasification. These conditions are provided by burning a part of the char. To simulate the dual fluidized bed gasifier, pyrolysis and combustion processes and the gasification reactor are integrated.

Due to the complexity of the process, some assumptions have to be made related to the simulation of the gasification (Burra et al., 2016; López, 2017; Prabowo et al., 2014): the gases generated during the gasification were H_2, CH_4, CO, CO_2, H_2O, NH_3, H_2S, and HCl; char is only composed of carbon and ash; ash is considered inert and does not participate in the reactions; 100% of the char conversion during gasification; all the reactions involved in the gasification process reach equilibrium.

The simulation was carried out using an equilibrium model based on a Gibbs free energy minimization to simulate a dual fluidized bed gasifier (Shabbar and Janajreh, 2013). As mentioned above, there are two separate chambers in this type of gasifier: the combustion chamber (char combustion) and the gasification chamber.

Gasification begins with the crushing of biomass (”Crusher”) to reduce the particle size (5 mm). Several different types of equipment simulated the gasifier. The first reactor was the “Decomp” reactor (RYield) that was used to convert non-conventional biomass (bagasse) into conventional components (volatile matter) by pyrolysis. The char obtained, considered to be 100 % carbon, was separated from the gas using a separator (“Charsep” - Sep2) (Fernandez-Lopez et al., 2017). The “Comb” reactor (RStoic) was used to burn the char to reach the appropriate temperature of the bed particles, providing the necessary heat for the gasification reaction. The combustion reactor temperature was 1000 °C and it was used an air excess of 1.12 (Doherty et al., 2013). The gas obtained in the “Charsep” was fed to the “Gasconv” reactor (RStoic) to simulate the conversion of nitrogen, chlorine, and sulfur contained in the biomass into NH_3, HCl, and H_2S, respectively. The “Gassep” separator (Sep 2) was used to remove NH_3, H_2S, and HCl from the mainstream (Fernandez-Lopez et al., 2017). The remaining gas was introduced into the “Gasif1” and “Gasif2” reactors (RGibbs) to simulate de gasification itself. It was assumed that all reactions involved in the gasification process reached equilibrium (Formica et al., 2016; Pala et al., 2017). The objective of the first gasification reactor is to simulate the reaction between the biomass char and the gasifying agent. The gasifying agent (steam) was fed into the gasifying reactor at 1 bar and 150 °C. The energy obtained in the combustion chamber was supposed to be transferred to the gasification chamber. Furthermore, the "Decomp" and "Gasconv" blocks were energetically integrated with "Gasif1" through the generated heat flows (Fernandez-Lopez et al., 2017). Thermodynamic equilibrium models underestimate the formation of CO_2 and CH_4 and overestimate those of H_2 and CO (Formica et al., 2016). The resulting gas from the first reactor passed to the second reactor to eliminate these discrepancies and to adjust the gas composition (Formica et al., 2016). Selected chemical reactions were analyzed in the RGibbs reactor module in Aspen Plus®, which uses the minimization of Gibbs free energy for each compound as a thermodynamic principle to find equilibrium compositions (Becerra et al., 2017). The gasification temperature was 950 °C and 1 bar. The "Gasmix" (mixer) was used to mix the three gases obtained, which were then fed to the "Scrubber" (VScrub) to separate the ash from the synthesis gas, using water (Marco et al., 2017; Mohammadi et al., 2020). To increase electricity yield, the combustion of the obtained gas was carried out at 900 °C and 1 bar ("Combustor" - RStoic). Finally, the electricity was obtained through the "Rankine cycle", which was the same as explained in the previous simulation.

The gasification reactor was simulated using the existing dual fluidized bed gasifier of a real plant in Güssing (Austria) as a reference (Kirnbauer and Hofbauer, 2011; Kirnbauer et al., 2012; Kraft et al., 2017). In Parascanu et al. (2019), more information was reported about the gasification reactor simulation validation.

2.3.Impact assessment methodology

To carry out the LCA, it is necessary to consider the standards of the ISO 14000 family for Environmental Management Systems (ESM), especially the standards from ISO 14040 to 14049 (ISO14000, 2009). In this investigation, LCA was carried out using the SimaPro 8 software and selecting the Midpoint ReCiPe 2016 as a methodology to calculate impact indicator values. The environmental performance associated with electricity production is calculated for ten categories:

1. global warming potential (GWP),
2. ozone depletion potential (ODP),
3. photochemical oxidation formation potential - humans (HOFP),
4. photochemical oxidation formation potential - ecosystems (EOFP),
5. terrestrial acidification potential (TAP),
6. freshwater eutrophication potential (FEP),
7. human toxicity potential - cancer (HTPc),
8. human toxicity potential - non-cancer (HTPnc),
9. fossil fuel potential (FFP)
10. water consumption potential (WCP).

During all feedstock-to-electricity chains studied, more than one product was obtained, and, for this reason, multifunctionality has to be handled in some way. According to PCR (2019), the sugar production stage from sugarcane has been identified as a multifunctional process. If it is not possible to avoid allocation, an allocation between sugar and co-products is realized. Here, in all stages, an economic allocation was considered related to the final product (Mandegari et al., 2018; PCR, 2014; Silalertruksa et al., 2017). Thus, for the second stage (sugar extraction and bacanora production) the economic allocation factors were: 96.8 % (0.58 €/kg) for sugar, 3.2 % (0.014 €/kg) for sugarcane bagasse, 95.9 % (5.52 €/kg) for bacanora and 4.1 % (0.035 €/kg) for agave bagasse (Barrera et al., 2016; SAGARPA, 2018a). For the bagasse combustion, the price for electricity and ash was 0.23 €/MJ and 0.07 €/kg, respectively. Considering these prices, the economic allocation factors for the combustion stage were 99.7 % for electricity and 0.3 % ash in the case of sugarcane, and 98.5 % for electricity and 1.5 % for ash in the case of agave (Song et al., 2019; Xu et al., 2019).

3. Results

3.1. Combustion process using sugarcane and agave bagasse

The Aspen Plus® simulations carried out to analyze electricity production from sugarcane bagasse and agave bagasse provide important data about the processes' mass and energy balance. Thus, in Table 4, the inventory data for electricity production through combustion process are presented.

Table 4: Inventory data for sugarcane and agave bagasse valorization through combustion and gasification processes., considering 1 MJ of electricity produced as FU.

		Combustion*	
		Sugarcane	Agave
Input			
Bagasse	kg	0.33	0.40
Electricity	kWh	1.85 x10^{-2}	1.85 x10^{-2}
Air	kg	2.42	2.65
Cooling water	m^3	7.74 x10^{-2}	8.20 x10^{-2}
Output			
Electricity	MJ	1.00	1.00
Ash	kg	8.90 x10^{-3}	4.06 x10^{-2}
Air emissions			
N_2	kg	1.86	2.04
H_2O	kg	0.18	0.19
O_2	kg	0.19	0.20
NO_2	kg	1.32 x10^{-5}	1.36 x10^{-5}
NO	kg	6.59 x10^{-3}	6.65 x10^{-3}
S	kg	5.11 x10^{-13}	1.99 x10^{-12}
SO_2	kg	3.72 x10^{-4}	2.34 x10^{-3}
SO_3	kg	1.19 x10^{-6}	4.86 x10^{-6}
H_2	kg	4.61 x10^{-6}	3.86 x10^{-6}
CO	kg	2.83 x10^{-4}	2.49 x10^{-4}
CO_2	kg	0.51	0.57
Particulates	kg	8.67 x10^{-4}	4.02 x10^{-3}
Water emissions			
H_2O	m^3	7.74 x10^{-2}	8.20 x10^{-2}

*from Aspen Plus® software

Figures 4a and 4b show the comparison of relative LCA results for the electricity production from sugarcane and agave bagasse through combustion, considering sugarcane and agave cultivation, sugar extraction/bacanora production, and bagasse combustion. In detail, Figure 4a shows the impact values for combustion of sugarcane bagasse, while Figure 4b illustrates the environmental results for agave bagasse combustion. The absolute characterized results for the environmental impacts of the sugarcane combustion and agave combustion scenarios are summarized in Tables 5 and 6, respectively.

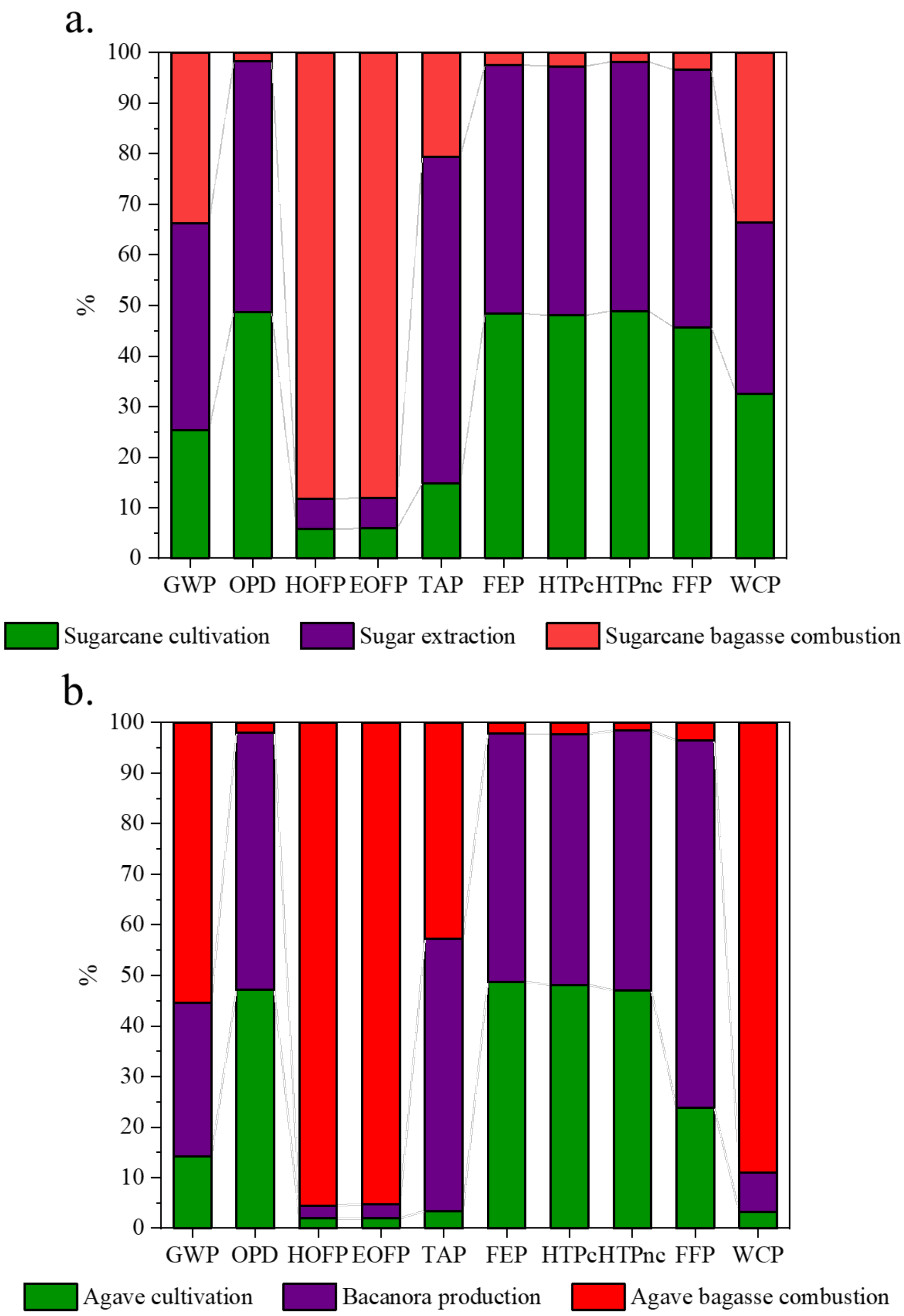

Figure 4: Environmental impact generated by the electricity production through combustion process: (a) sugarcane scenario and (b) agave scenario

Table 5: Characterized results for the sugarcane combustion scenario (FU: 1 MJ of electricity).

Impact category	**Unit**	**Sugarcane cultivation**	**Sugar extraction**	**Sugarcane bagasse combustion**
GWP	kg CO$_2$ eq	0.40	0.65	0.54
ODP	kg CFC$_{11}$ eq	$4.65\ x10^{-6}$	$4.73\ x10^{-6}$	$1.62\ x10^{-7}$
HOFP	kg NO$_x$ eq	$6.64\ x10^{-4}$	$6.75\ x10^{-4}$	$1.01\ x10^{-2}$
EOFP	kg NO$_x$ eq	$6.81\ x10^{-4}$	$6.93\ x10^{-4}$	$1.01\ x10^{-2}$
TAP	kg SO$_2$ eq	$3.23\ x10^{-3}$	$1.41\ x10^{-2}$	$4.49\ x10^{-3}$
FEP	kg P eq	$2.54\ x10^{-5}$	$2.58\ x10^{-5}$	$1.30\ x10^{-6}$
HTPc	kg 1,4-DCB	$8.69\ x10^{-4}$	$8.91\ x10^{-4}$	$4.84\ x10^{-5}$
HTPnc	kg 1,4-DCB	$4.51\ x10^{-2}$	$4.54\ x10^{-2}$	$1.65\ x10^{-3}$
FFP	kg oil eq	$8.35\ x10^{-2}$	$9.30\ x10^{-2}$	$6.20\ x10^{-3}$
WCP	m^3	$7.71\ x10^{-2}$	$8.05\ x10^{-2}$	$7.95\ x10^{-2}$

Table 6: Characterized results for agave combustion scenario (FU: 1 MJ of electricity).

Impact category	**Unit**	**Agave cultivation**	**Bacanora production**	**Agave bagasse combustion**
GWP	kg CO$_2$ eq	0.15	0.32	0.59
ODP	kg CFC$_{11}$ eq	$7.05\ x10^{-7}$	$7.59\ x10^{-7}$	$3.06\ x10^{-8}$
HOFP	kg NO$_x$ eq	$2.04\ x10^{-4}$	$2.78\ x10^{-4}$	$1.02\ x10^{-2}$
EOFP	kg NO$_x$ eq	$2.12\ x10^{-4}$	$2.91\ x10^{-4}$	$1.02\ x10^{-2}$
TAP	kg SO$_2$ eq	$4.98\ x10^{-4}$	$7.82\ x10^{-3}$	$6.22\ x10^{-3}$
FEP	kg P eq	$2.13\ x10^{-5}$	$2.15\ x10^{-5}$	$9.50\ x10^{-7}$
HTPc	kg 1,4-DCB	$8.38\ x10^{-4}$	$8.63\ x10^{-4}$	$3.89\ x10^{-5}$
HTPnc	kg 1,4-DCB	$2.08\ x10^{-2}$	$2.27\ x10^{-2}$	$7.17\ x10^{-4}$
FFP	kg oil eq	$3.93\ x10^{-2}$	0.12	$5.82\ x10^{-3}$
WCP	m^3	$2.97\ x10^{-3}$	$7.24\ x10^{-3}$	$8.22\ x10^{-2}$

According to Figure 4a, considering the global environmental damage, it was observed that the stage that most negatively affects the environment in terms of electricity production from sugarcane was the sugar extraction, followed by the sugarcane cultivation and bagasse combustion. In agave bagasse valorization through combustion, the environment's most damaging stage was the bacanora production, followed by the combustion of agave bagasse and agave cultivation (Figure 4b). These conclusions were drawn considering the average of all the impact values. However, the impact category values of each stage will be detailed below.

The sugar extraction process has high impact values in almost all categories, showing the highest values for GWP (41 %), FEP (50 %), TAP (65 %). FEP (49 %), HTPc (49%), HTPnc (49%), FFP (51 %) and WCP (35 %) (Figure 4a). The significant amount of emissions released during sugar production and fuel oil consumption for electricity generation are mainly responsible for these results (Table 2). The sugarcane cultivation stage has a higher contribution to ODP (49 %), FEP (48 %) HTPc (48 %). HTPnc (48%) and FFP (46 %) (Figure 4a), mainly due to the use of fertilizers and the air and water emissions generation (Table 1). Finally, conversion of sugarcane bagasse into electricity had the highest contribution in GWP (34 %), HOFP (88 %), EOFP (88 %), TAP (21 %), and WCP (34 %) (Figure 4a), due to released emissions and electricity and water consumption (Table 4).

However, Figure 4 shows a different trend for electricity production from agave bagasse. Thus, it was observed that the bacanora production stage was found to be the stage with the highest values for ODP (51 %), TAP (54 %), FEP (49 %), HTPc (50 %), HTPnc (51 %) and FFP (73 %) (Figure 4b), due to the emissions produced and the fuel oil used (Table 2). Regarding the combustion of agave bagasse, this stage is responsible for the high impact values in terms of GWP (55 %), HOFP (95 %), EOFP (95 %), TAP (43 %), and WCP (89 %) (Figure 4b). The contributing factors in these impact categories were the emissions released and electricity and water consumption during the conversion process (Table 3). Agave cultivation shows high impact values for ODP (47 %), FEP (49 %), HTPc (48 %), HTPnc (47 %) and FFP (24 %) categories (Figure 4b). These impact categories are affected by the air and water emissions and the use of fertilizers and compost (Table 1).

Furthermore, analyzing Tables 5 and 6, the sugarcane combustion scenario has higher impact values than the agave combustion scenario. Therefore, the sugar production stage affects the environment more than bacanora production. In this case, a significant difference for WCP, ODP, HOFP, EOFP, GWP, and HPTnc is highlighted. In this sense, it is observed that sugar production has higher impact values than bacanora production with 7.32 $\mathbf{x}10^{-2}$ m^3 (WCP), 3.97 $\mathbf{x}10^{-6}$ kg CFC_{11} eq (ODP), 3.98 $\mathbf{x}10^{-4}$ kg NO_x eq (HOFP) and 4.02 $\mathbf{x}10^{-4}$ kg NO_x eq (EOFP), 0.33 kg CO_2 eq (GWP) and 2.27 $\mathbf{x}10^{-2}$ kg 1.2-DCB (HTPnc), respectively (Tables 5 and 6). These differences are associated with using chemicals needed to extract sugar from sugarcane (flocculating agents, SO_2, NaOH, and quicklime) and the generation of ashes (Table 2). However, it is observed that the production of bacanora exhibits a higher impact than the production of sugar in terms of FFP (Tables 5 and 6) due to the higher amount of fuel oil used to obtain electricity for the process (Table 2).

For the cultivation stages, great differences can be highlighted when referring to WCP, ODP, TAP, HOFP, and EOFP, for which it was observed that the sugarcane had more impact values than agave cultivation, i.e., by 7.42 $\mathbf{x}10^{-2}$ m^3, 3.95 $\mathbf{x}10^{-6}$ kg CFC_{11} eq, 2.73 $\mathbf{x}10^{-3}$ kg SO_2 eq, 4.60 $\mathbf{x}10^{-4}$ kg NO_x eq and 4.69 $\mathbf{x}10^{-4}$ kg NO_x eq, respectively (Tables 5 and 6). These differences appeared due to the different ways the two plants are cultivated, using more compost and fertilizers and generating more water and air emissions to cultivate sugarcane than agave (Table 1). The remarkable difference observed for WCP was associated with the irrigation carried out only to cultivate sugarcane (Table 1).

However, a different trend can be observed for the combustion of sugarcane and agave bagasse. In this sense, agave bagasse combustion has higher impact values than the combustion of sugarcane bagasse for GWP, HOFP, EOFP, TAP, and WCP categories. This result could be caused by the emissions produced during the conversion of bagasse. The amounts are relatively higher in the agave case due to the higher amount of bagasse used in this scenario. For the ODP and HTPnc, the sugarcane scenario had values 5.3 and 2.3 times higher than the agave scenario (Tables 5 and 6). These two impact categories could be directly affected by sugarcane cultivation and sugar extraction stages.

3.2. Gasification process using sugarcane and agave bagasse

The Aspen Plus® simulations carried out to analyze electricity production through the combustion and gasification processes using sugarcane bagasse and agave bagasse as raw material provide important data related to the mass and energy balance of the processes. Thus, in Table 4, the inventory data of the two thermochemical processes analyzed were presented.

Table 7: Inventory data for sugarcane and agave bagasse valorization through combustion and gasification processes., considering 1 MJ of electricity produced as FU.

		Gasification*	
		Sugarcane	Agave
	Input		
Bagasse	kg	0.30	0.37
Electricity	kWh	$1.67\ \mathbf{x}10^{-2}$	$1.67\ \mathbf{x}10^{-2}$
Air	kg	2.76	2.86
Water	kg	3.30	4.01E
Cooling water	m^3	$6.32\ \mathbf{x}10^{-2}$	$7.03\ \mathbf{x}10^{-2}$
	Output		
Electricity	MJ	1.00	1.00
Air emissions			
N_2	kg	2.11	2.20
H_2O	kg	0.95	1.09
O_2	kg	0.30	0.29
NO	kg	$1.31\ \mathbf{x}10^{-3}$	$1.31\ \mathbf{x}10^{-2}$
SO_2	kg	$3.28\ \mathbf{x}10^{-4}$	$2.19\ \mathbf{x}10^{-3}$
CO_2	kg	0.46	0.52
Particulates	kg	$1.49\ \mathbf{x}10^{-4}$	$1.75\ \mathbf{x}10^{-4}$
Water emissions			
H_2O	m^3	$6.58\ \mathbf{x}10^{-2}$	$7.34\ \mathbf{x}10^{-2}$

*from Aspen Plus® software

The environmental impact categories for electricity production from sugarcane bagasse and agave bagasse through the gasification process are shown in Figures 5a and 5b, respectively. The results of the environmental impact categories selected for 1 MJ of electricity produced from sugarcane bagasse and agave bagasse are shown in Tables 7 and 8, respectively.

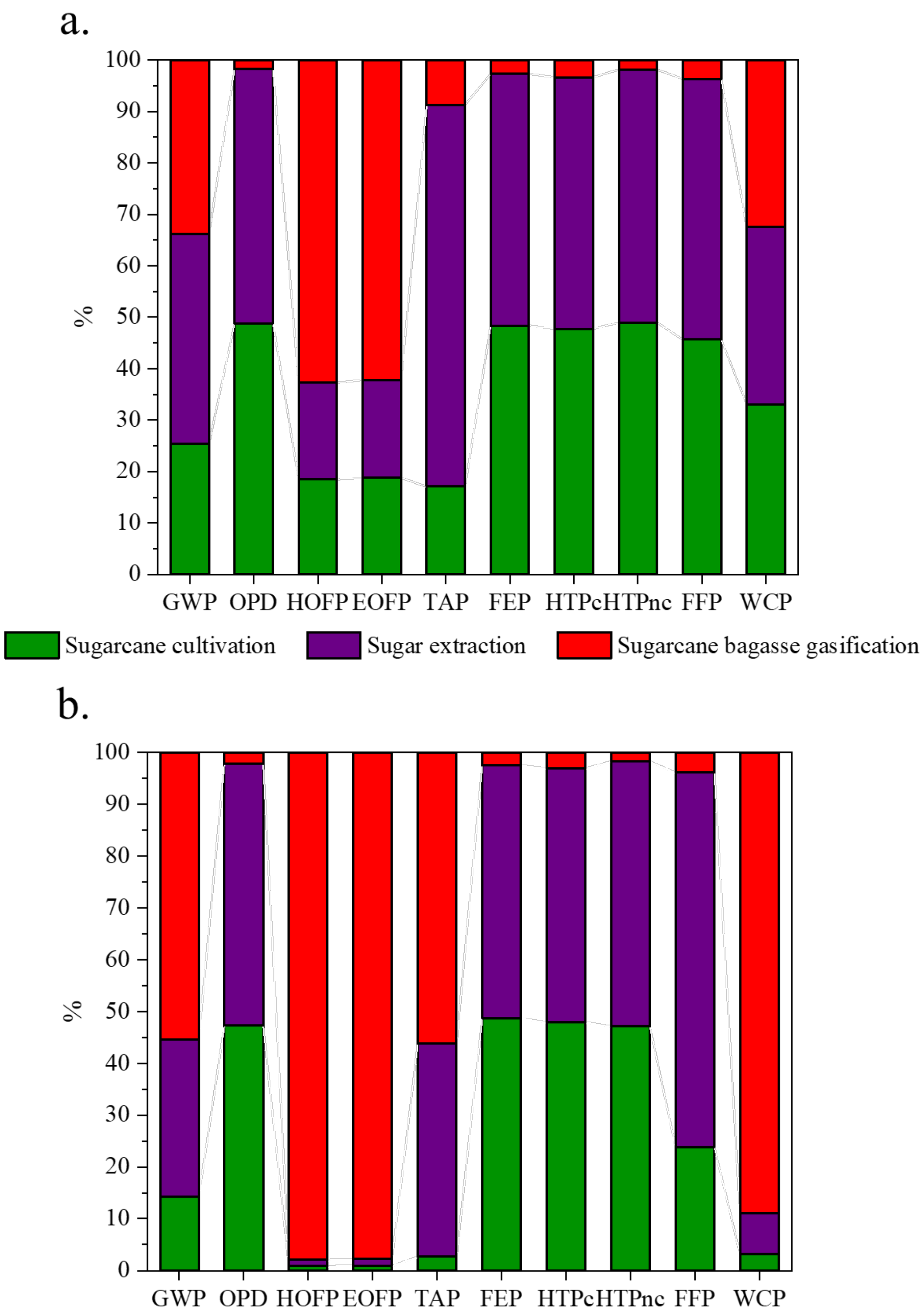

Figure 5: Environmental impact generated by electricity production through the gasification process: (a) sugarcane scenario and (b) agave scenario.

Table 8: Characterized sugarcane bagasse gasification results, considering all the three stages (FU: 1 MJ of electricity).

Impact category	Unit	Sugarcane cultivation	Sugar extraction	Sugarcane bagasse gasification
GWP	kg CO$_2$ eq	0.37	0.59	0.49
ODP	kg CFC11 eq	4.22 x10^{-6}	4.28 x10^{-6}	1.48 x10^{-7}
HOFP	kg NO$_x$ eq	6.02 x10^{-4}	6.11 x10^{-4}	2.04 x10^{-3}
EOFP	kg NO$_x$ eq	6.17 x10^{-4}	6.27 x10^{-4}	2.04 x10^{-3}
TAP	kg SO$_2$ eq	2.93 x10^{-3}	1.27 x10^{-2}	1.49 x10^{-3}
FEP	kg P eq	2.30 x10^{-5}	2.33 x10^{-5}	1.28 x10^{-6}
HTPc	kg 1,4-DCB	7.87 x10^{-4}	8.06 x10^{-4}	5.49 x10^{-5}
HTPnc	kg 1,4-DCB	4.09 x10^{-2}	4.11 x10^{-2}	1.54 x10^{-3}
FFP	kg oil eq	7.57 x10^{-2}	8.41 x10^{-2}	6.05 x10^{-3}
WCP	m^3	6.99 x10^{-2}	7.28 x10^{-2}	6.86 x10^{-2}

Table 9: Characterized agave bagasse gasification results, considering all the three stages (FU: 1 MJ of electricity).

Impact category	Unit	Agave cultivation	Bacanora production	Agave bagasse gasification
GWP	kg CO$_2$ eq	0.14	0.29	0.53
ODP	kg CFC11 eq	6.41 x10^{-7}	6.85 x10^{-7}	2.92 x10^{-8}
HOFP	kg NO$_x$ eq	1.86 x10^{-4}	2.51 x10^{-4}	2.01 x10^{-2}
EOFP	kg NO$_x$ eq	1.93 x10^{-4}	2.63 x10^{-4}	2.01 x10^{-2}
TAP	kg SO$_2$ eq	4.53 x10^{-4}	7.06 x10^{-3}	9.61 x10^{-3}
FEP	kg P eq	1.93 x10^{-5}	1.94 x10^{-5}	9.84 x10^{-7}
HTPc	kg 1,4-DCB	7.62 x10^{-4}	7.79 x10^{-4}	4.88 x10^{-5}
HTPnc	kg 1,4-DCB	1.89 x10^{-2}	2.05 x10^{-2}	7.06 x10^{-4}
FFP	kg oil eq	3.57 x10^{-2}	0.11	5.84 x10^{-3}
WCP	m^3	2.70 x10^{-3}	6.54 x10^{-3}	7.42 x10^{-2}

Overall, the cradle-to-gate analysis of electricity production from sugarcane bagasse (Figure 5a) showed that sugar production is the stage with the highest impact values for many impact categories, followed by the cultivation of sugar cane and the gasification of bagasse. However, within the electricity production chain from agave, the stage that most affects the environment, in almost all impact categories, is the production of bacanora, followed by the gasification process of bagasse and agave cultivation (Figure 5b). In the following paragraphs, the two scenarios will be analyzed and it will be identified which impact categories are most affected by each stage.

Analyzing Figure 5a, it is observed that for the sugarcane bagasse gasification scenario, the sugar extraction stage contributed mostly in GWP (41 %), ODP (49 %), TAP (74 %), FEP (49 %), HTPc (49 %), HTPnc (49 %), FFP (51 %) and WCP (34 %). These values are associated with the emissions released and the fuel oil and chemicals used during the sugar production process (Table 2). Regarding the sugarcane cultivation stage, relatively high impacts were obtained for ODP (49 %), FEP (48 %), HTPc (48 %), HTPnc (49 %), FFP (46 %) and WCP (34 %) (Figure 5a). Responsible for these results is the use of fertilizers, the transport of fertilizers and sugarcane and the emissions generated during the whole stage (Table 1). The sugarcane bagasse conversion into electricity has the lowest values compared to the other two previous stages for almost all impact categories, except for GWP (34 %), HOFP (63 %), EOFP (63 %), and WCP (32 %) (Figure 5a). The impacts of electricity production are caused by released emissions and electricity and water consumption (Table 7).

Comparing the three stages of electricity production from agave bagasse through gasification, bacanora production stage shows the highest impact values in terms of GWP (30 %), ODP (51 %), FEP (49 %), HTPc (49 %) and HTPnc (51 %) and FFP (72 %) (Figure 5b). These results are related to fuel oil use and released emissions during the process stage (Table 2). According to Figure 5b, the agave bagasse gasification showed the highest values for GWP (55 %), HOFP (98 %), EOFP (98 %), TAP (56 %), and WCP (89 %) (Figure 5b), due to emissions emitted and electricity and water consumption (Table 7). Finally, the agave cultivation contributed to the ODP (47 %), FEP (49 %), HTPc (48 %) and HTPnc (47 %) (Figure 5b). Emissions emitted to air and water and fertilizer and compost application are the main factors to affect these impact categories (Table 1).

Tables 8 and 9 show that the agave gasification scenario has lower impact values than the sugarcane gasification scenario for almost all the selected impact categories. Significant differences between the two scenarios were observed in the cultivation and processing stages. Furthermore, the categories that showed important differences were WCP, ODP, TAP, HOFP, EOFP, and WCP. The sugarcane cultivation had values of 6.72 **x**10^{-2} m^3 (WCP), 3.58 **x**10^{-5} kg CFC11 eq (ODP), 2.48 **x**10^{-3} kg SO_2 eq (TAP), 4.16 **x**10^{-4} kg NO_x eq (HOFP) and 4.25 **x**10^{-4} kg NO_x eq (EOFP) higher than the agave (Tables 8 and 9). These differences were obtained because more compost, fertilizers, and water were used for sugarcane crops, and more emissions were generated (Table 1). The sugar extraction stage had higher values than the bacanora production stage i.e. by 6.63 **x**10^{-2} m^3 (WCP), 3.59 **x**10^{-6} kg CFC11 eq (ODP), 2.06 **x**10^{-2} kg 1.4-DCB eq (HTPnc), 3.60 **x**10^{-4} kg NO_x eq (HOFP) and 3.64 **x**10^{-4} kg NO_x eq (EOFP) (Tables 8 and 9). The factors influencing these results were the chemicals used for sugar extraction and ash generation (Table 2). However, analyzing the obtained data, it was observed that, in some categories (HOFP, EOFP, TAP, GWP, and WCP), the agave bagasse conversion stage damaged more the environment than the sugarcane bagasse (Tables 8 and 9) due to the higher amount of emissions released and water consumed in the agave scenario (Table 7). However, it is observed that the production of bacanora exhibits a higher impact than the production of sugar in terms of FFP (Tables 5 and 6) due to the higher amount of fuel oil used to obtain electricity for the process (Table 2).

3.3. Comparison between the four scenarios

The comparative results of electricity production's environmental performance through combustion and gasification processes using sugarcane bagasse and agave bagasse are shown in Figure 6. The characterized results for each scenario are summarized in Table 9.

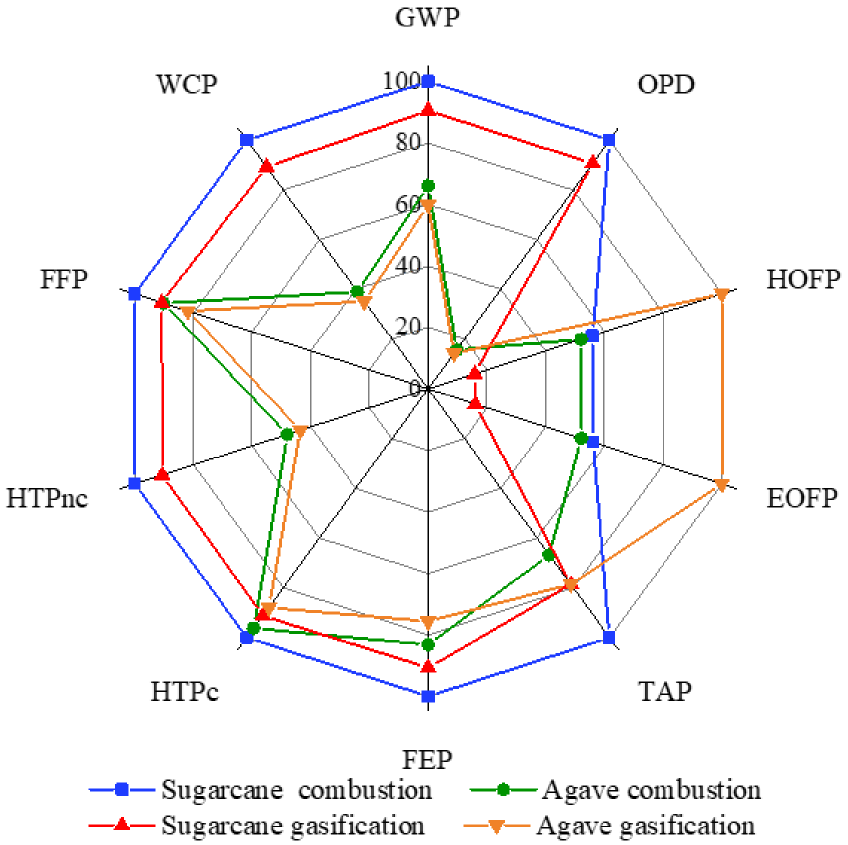

Figure 6: Environmental performance comparing combustion and gasification of sugarcane bagasse and agave bagasse.

Table 10: Environmental impact results for the four alternatives to produce 1 MJ of electricity from sugarcane and agave bagasse through combustion and gasification

Impact category	**Unit**	**Sugarcane bagasse combustion**	**Agave bagasse combustion**	**Sugarcane bagasse gasification**	**Agave bagasse gasification**
GWP	kg CO$_2$ eq	1.60	1.06	1.45	0.96
ODP	kg CFC11 eq	9.54 x10^{-6}	1.49 x10^{-6}	8.64 x10^{-6}	1.36 x10^{-6}
HOFP	kg NO$_x$ eq	1.15 x10^{-2}	1.07 x10^{-2}	3.26 x10^{-3}	2.05 x10^{-2}
EOFP	kg NOx eq	1.15 x10^{-2}	1.07 x10^{-2}	3.29 x10^{-3}	2.05 x10^{-2}
TAP	kg SO$_2$ eq	2.18 x10^{-2}	1.45 x10^{-2}	1.72 x10^{-2}	1.71 x10^{-2}
FEP	kg P eq	5.25 x10^{-5}	4.37 x10^{-5}	4.77 x10^{-5}	3.97 x10^{-5}
HTPc	kg 1,4-DCB	1.81 x10^{-3}	1.74 x10^{-3}	1.65 x10^{-3}	1.59 x10^{-3}
HTPnc	kg 1,4-DCB	9.22 x10^{-2}	4.42 x10^{-2}	8.35 x10^{-2}	4.01 x10^{-2}
FFP	kg oil eq	0.18	0.17	0.17	0.15
WCP	m^3	0.24	9.24 x10^{-2}	0.21	8.34 x10^{-2}

The production stages (feedstock cultivation, feedstock processing, and bagasse conversion) were incorporated into four unitary systems to compare the following scenarios: sugarcane bagasse combustion, agave bagasse combustion, sugarcane bagasse gasification, and agave bagasse gasification. In this sense, an exhaustive discussion is presented of each scenario, identifying the materials or processes that contribute significantly to the selected impact categories.

According to Farahani and Asoodar (2017) and Meza-Palacios et al. (2019), the sugarcane cultivation stage was the one with the highest negative impact on the environment in almost all impact categories, while in the current case study, it was observed that the stage that most damages the environment is the production of sugar. These differences can be related to the different limitations and assumptions that were considered in each of the papers. In the case of the works carried out by Farahani and Asoodar (2017) and Meza-Palacios et al. (2019), it was noted that in the sugar production stage, the necessary chemicals, such as flocculants, SO_2, and NaOH, have not been considered. These chemicals can be responsible for the greatest environmental impact generated in the sugar production stage. However, Farahani and Asoodar (2017) obtained that sugar processing has a higher environmental impact on global warming than sugar cultivation, as observed in this work. On the other hand, it was observed that in the case of the study from Meza-Palacios et al. (2019), the assumed amounts of fertilizers, pesticides, and diesel are higher than in the current paper. This suggests that the values reported by Meza-Palacios et al. (2019) are higher for the cultivation stage compared to sugar production.

Figure 6 shows the environmental impacts of all production stages (feedstock cultivation, feedstock processing, and bagasse conversion) of the following scenarios: sugarcane bagasse combustion, agave bagasse combustion, sugarcane bagasse gasification, and agave bagasse gasification. The results reflect the different methods of cultivating and processing sugarcane and agave. Furthermore, the amount of bagasse used to produce 1 MJ of electricity influences the results, which was greater in combustion. In Tables 4 and 7, it can be seen that, according to the results obtained with the Aspen Plus® software, 0.33 kg of sugarcane bagasse and 0.40 kg of agave bagasse are required to obtain 1 MJ of electrical energy for the combustion process. In contrast, for the gasification process, 0.30 kg of sugarcane bagasse and 0.37 kg of agave bagasse are required. These differences generally affect all the amounts of inputs and outputs considered for each stage because the higher the amount of bagasse needed to obtain 1 MJ of electrical energy, the higher the amounts of inputs and outputs (Tables 1, 2, 4, and 7). Furthermore, it was observed that more bagasse was needed for the agave scenarios compared to the sugarcane scenarios. Finally, to obtain 1 MJ of electrical energy, it was observed that 1.85E-2 kWh of electricity is needed for the combustion process and 1.67 kWh of electricity for the gasification process (Tables 4 and 7), indicating that these processes are viable from an energy point of view.

The GWP values for combustion of sugarcane and agave bagasse were 1.60 and 1.06 kg CO_2 eq, respectively, while for gasification scenarios, the values were 1.45 (sugarcane bagasse) and 0.96 kg CO_2 eq (agave bagasse) (Table 10). These differences between the two studied processes can be attributed to diesel, fuel oil, and electricity consumption during the whole systems performing (Tables 1, 2, 4, and 7). Also, the high amounts of CO_2, N_2O, CH_4, CO, and NO_x emissions released for the combustion scenarios supported the environmental viability of the gasification scenarios (Tables 1, 2, and 4). The generation of greenhouse gases in the scenarios studied was highly related to the burning of fuel oil and bagasse for electricity production in the processing stages and the use of diesel for transportation (Brizmohun et al., 2015; Ghani and Gheewala, 2018; Lauzurique

Guerra et al., 2017; Mandavgane et al., 2018). The differences observed between the two biomasses were related to the N_2O and NO_x release during the cultivation and feedstock processing stages, which were lower for agave culture (Table 1). The N_2O emissions are generated due to compost and N-fertilizer application (Ghani and Gheewala, 2018; Papong et al., 2017). NOx emissions generated during the processing stage are due to burning bagasse and fuel oil to produce the electricity needed (Lauzurique Guerra et al., 2017; Mandavgane et al., 2018).

Furthermore, comparing the four scenarios, ODP values were estimated between 1.36 $\mathbf{x}10^{-6}$ and 9.54 $\mathbf{x}10^{-6}$ kg CFC_{11} eq/ 1 MJ of electricity (Table 10). The highest value was found for the sugarcane bagasse combustion and the lowest for the agave bagasse gasification. Mainly responsible for these results are emissions of N_2O generated due to the consumption of diesel for sugarcane and agave transport (cultivation stage) and the burning of fuel oil and bagasse to obtain electricity (processing stage) (Tables 1 and 2) (Lauzurique Guerra et al., 2017; Mandavgane et al., 2018)(Costa et al., 2018). Apart from the N_2O emissions, the ODP was also affected by hydrocarbons, bromochlorodifluoro- (Halon 1211), bromotrifluoro- (halon 1301), dichlorodifluoro- (CFC-12), and tetrachlo- (CFC-10) (Brizmohun et al., 2015). The background processes (production of compost, chemicals, and diesel) and the burning of bagasse and fuel oil (processing stage) were the main processes contributing significantly to ODP.

Photochemical oxidation is the process of ozone formation in the troposphere that can damage human health and the ecosystem. Figure 6 and Table 10 show that, in this case, agave bagasse gasification was the scenario with the highest impact values, followed by the two combustion scenarios. HOPF and EOPF were associated with NO_x, SO_2, CH_4, and CO emissions (Brizmohun et al., 2015; Michailos, 2018). These emissions were released along the electricity production chain due to fertilizers and pesticide use, transportation, and fuel oil and bagasse burning (Tables 1, 2, 4, and 7) (Costa et al., 2018; Ruiz et al., 2018).

Terrestrial acidification potential (TAP) is generated by the presence of pollutants such as NH_3, NO_x, and SO_2 that react with steam, forming acids that negatively affect soil, water, fauna, and flora. This study highlights that sugarcane bagasse combustion causes the highest impact value in TAP (2.18 $\mathbf{x}10^{-2}$ kg SO_2 eq). This scenario produces a higher quantity of acidifying substances than the other scenarios (Tables 1, 2, 4, and 7). The processes that impacted the TAP were burning fuel oil and bagasse, the use of fertilizers, and the consumption of diesel (Ghani and Gheewala, 2018; Ruiz et al., 2018). Moreover, it was observed that the stage that most negatively affected the environment in three of the four scenarios was the electricity production from bagasse through combustion and gasification processes, impact associated with the high amounts of NO_x and SO_2 emissions and the electricity consumed (Table 4 and 7) (Han et al., 2019; Ruiz et al., 2018).

Eutrophication is generated by nitrogen (N) and phosphorus (P) containing macronutrients that increase plants' growth and change aquatic ecosystems. Figure 6 shows that sugarcane bagasse combustion has the highest impact on freshwater eutrophication potential (FEP), followed by sugarcane bagasse gasification, agave bagasse combustion, and agave bagasse gasification. The main contributing factors to this impact category are the use of compost, fertilizers and pesticides, irrigation, electricity consumption, the generation of wastewater, ash, and P_2O_5 (Tables 1,2, 4, and 7) (Costa et al., 2018; Ghani and Gheewala, 2018; Michailos, 2018; Papong et al., 2017; Ruiz et al., 2018).

Substances that have harmful effects on human health, e.g., causing cancer, are covered by the impact category of human toxicity (HTPc). In this study, it was observed that the values for HTPc are between 1.59 $\mathbf{x}10^{-3}$ and 1.81 $\mathbf{x}10^{-3}$ kg 1.4-DCB eq and between 4.01 $\mathbf{x}10^{-2}$ and 9.22 $\mathbf{x}10^{-2}$ kg 1.4-DCB eq for HTPnc (Table 10). NO_x, SO_2, and particulate emissions were considered responsible for the impact of HTP (Tables 1, 2, 4, and 7). Furthermore, the use of fertilizers, pesticides, electricity, and diesel, the generation of ash and organic waste also affect these impact categories (Tables 1, 2, 4 and 7) (Ghani and Gheewala, 2018; Han et al., 2019; Ruiz et al., 2018). Background processes, such as the production of electricity, fertilizers, or chemicals, generate emissions of heavy metals, aromatic hydrocarbons, and hydrocarbons, contributed significantly to HTPc (Brizmohun et al., 2015).

Finally, it was found that the fossil fuel potential (FFP) and water consumption potential (WCP) are influenced by the application of fertilizers, irrigation, and the use of diesel, chemical products, and electricity during all the analyzed stages (Tables 1, 2, 4 and 7). Direct burning of fuel oil during the processing stages has a great influence on FFP. Coal, natural gas, and oil, required throughout the feedstock-to-electricity chain mainly affected this impact category (Brizmohun et al., 2015; Ghani and Gheewala, 2018). WCP was associated with sugarcane irrigation, the preparation of fertilizers and pesticides, the water used during the feedstock processing stage, and the bagasse combustion/gasification stages (Tables 1, 2, 4, and 7) (Papong et al., 2017).

4. Conclusions

In this study, life cycle impacts from converting sugarcane and agave bagasse into bioenergy have been assessed. The following three production stages were considered: cultivation of sugarcane and agave, production of sugar and bacanora, and the combustion or gasification process of bagasse.

In the cultivation stage, the most important factors for environmental damage are the use of fertilizers, the consumption of diesel for transport, and emissions to air and water. Furthermore, it was observed that the sugarcane cultivation stage generates between 2 and 6 times more impact than the agave cultivation stage for almost all impact categories (except for FEP and HTPc). However, in the case of WCP, the difference was approximately 25 times higher for the sugarcane crop than for the agave crop, related to irrigation of the first crop.

The stage that most negatively affects the environment was the feedstock processing stage (sugar extraction and bacanora production). In the case of the two-feedstock studied, it was observed that the feedstock processing stage has high impact values in almost all the impact categories. In this sense, it was observed that for the combustion scenarios, impact values of 50% (ODP), 65% (TAP), and 51% (FFP) were obtained for sugar production. In the case of the bacanora production stage (combustion scenario), the highest impact values were observed for ODP (51%), TAP (54%), and FFP (73%). On the other hand, for the gasification scenarios, the highest impact values were observed for the TAP and FFP categories (74% and 51%, respectively) for sugar production and the ODP, HTPnc, and FFP categories (51%, 51%, and 73%, respectively) for bacanora production. This stage's high impact values are mainly due to the significant amount of emissions released and fuel oil consumption for electricity generation.

Furthermore, it was observed that the scenario with the highest environmental impact in almost all the selected categories is the combustion of sugarcane bagasse, followed by the combustion of agave bagasse, the gasification of sugarcane bagasse and the gasification of agave bagasse. These results are associated with the different ways in which sugar cane and agave are cultivated and processed, and also because less biomass is needed to produce 1 MJ of electricity in the case of the gasification process, generating lower amounts of emissions.

According to these results, several recommendations can be considered to improve electricity production's environmental performance from sugarcane bagasse and agave bagasse. As explained above, the cultivation stage has a significantly high negative environmental impact on many impact categories. The ideal at this stage is to try to increase crop productivity without damaging the ecosystem. Thus, one of the things to consider is to reduce air and soil contamination. The use of chemical fertilizers is one of the most worrying factors from an environmental point of view. Fertilizers negatively affect many of the impact categories considered (GWP, ODP, TAP, FEP, HTPc, and HTPnc) through their emissions and the background processes (production of fertilizers and pesticides). In this sense, a good option is to replace chemical fertilizers with organic fertilizers or animal waste (Osei et al., 2003; Silalertruksa and Gheewala, 2009; Steiner et al., 2007).

The factor that caused the most severe environmental damage was the burning of fuel oil to produce electricity. Although the use of fuel oil was considered to increase the production of electrical energy needed during this stage, it would be wise to find other energy sources. In this sense, the best improvement could be to choose another type of energy, such as biomass-based or hydropower energy (CEMAD, 2016). Besides, implementing another energy system, such as hydropower energy, would considerably reduce this stage's impact because the emissions released during the combustion of bagasse and carbon would be minimized.

As previously specified, the stages related to thermochemical processes have relatively low environmental impacts. However, it was observed that the combustion process significantly affects the HOFP, EOFP, TAP, and WCP categories, while the gasification process significantly affects the GWP, TAP, and WCP categories. Although the bagasse conversion stages have relatively low impact, it is indicated to reduce the generation of pollutants (as a priority measure to prevent contamination) and to treat the remaining emissions (Soreanu, 2014). For NOx and SOx emission reduction, the most efficient treatment techniques are selective non-catalytic reduction (SNCR), selective catalytic reduction (SCR), and co-utilization of biomass with other fuels (Roy and Dias, 2017). Also, techniques for the absorption of GHG in specific liquids can be considered, e.g., capturing CO_2 by the monoethanolamine system (MEA) (Al-Gailani, 2015). Moreover, in the gasification process, catalysts, absorbers, and high-temperature filtration media can be used to improve the process and integrate biomass gasification and gases cleaning/conditioning in one reactor (Roy and Dias, 2017; Van Oers and Guinée, 2016).

As future work, the production of bioethanol from sugarcane bagasse and agave or from agave juice and molasses could also be analyzed, thus completing the investigation.

Acknowledgment

The authors acknowledge the financial support from the University of Castilla-La Mancha of Spain (UCLM "Plan Propio de I+D+i. (2016 / 14100)" Grant) and Deutscher Akademischer Austauschdienst (DAAD) for the Short-Term Grant. The authors acknowledge the financial support from the Regional Government of Castilla-La Mancha (Project SBPLY/17/180501/000238).

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