Life cycle assessment of electricity generation from sugarcane bagasse hydrochar produced by microwave assisted hydrothermal carbonization

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Abstract

Microwave assisted hydrothermal carbonization (MAHTC) is a promising strategy for fuel production from sugarcane bagasse. Even though microwave heating has been reported to facilitate product (hydrochar) yield, energy properties and heating efficiency during hydrothermal carbonization (HTC) process, the environmental consequences of MAHTC treatment were still not clear. This study evaluated the environmental impact associated with 1 MJ electricity generation from sugarcane bagasse hydrochar through life cycle assessment (LCA) method, focusing on the critical role of process-based parameters to provide insights for optimization of MAHTC treatment. Specifically, two different allocation factors (energy content and economic value) and five environmental impact categories (climate change, freshwater eutrophication, freshwater ecotoxicity, human toxicity and fossil depletion) were assessed in this study. The LCA results revealed significant contribution of MAHTC process on climate change and fossil depletion because of large energy consumption used to maintain the system at designed temperature. Discharge of liquid phase from MAHTC process resulted in severe eutrophication impact especially when economic value was used as allocation factor. Gas emission from hydrochar combustion caused most toxicity related impacts indicating essential requirement of further investigation to quantify different gaseous composition. Based on LCA results, sensitivity analysis indicated hydrochar yield and carbon content as the top two influential factors on total environmental consequences. Comparison study with other fuel sources were further conducted to identify the influence of substituted energy sources. The overall results suggested MAHTC as promising method for bagasse utilization and energy retention efficiency as important indicator for optimization of MAHTC treatment or the sake of high-quality products and good environmental performance.

Key words

Life cycle assessment, Microwave assisted hydrothermal carbonization, Sugarcane bagasse, Environmental impact, Hydrochar production

1. Introduction

China, as the third largest sugar producer in the world, is manufacturing 10.25 million tonnes of sugar annually (Peng et al., 2014) and over 90% of those are cane sugar. Sugarcane bagasse, the fibrous residue after juice extraction of sugarcane, thus becomes the largest agro-industrial residue and by-product of sugar industry (Sindhu et al., 2016). Various technologies have been applied on utilising sugarcane bagasse including direct combustion for electricity generation, pulp and paper production, and fermentation for value-added products (Ahmed and Gupta, 2012). In most cases, bagasse is used directly for co-combustion to generate heat and power (Sindhu et al., 2016) and then used as primary fuel source for sugar mills (Peng et al., 2014).

The high carbon content of sugarcane bagasse, reported as 47% on a moisture and ash free basis (Wright et al., 2016), is quite desirable for fuel production. With over 50% water content in the original bagasse (Erlich et al., 2005), thermochemical processes are usually required as pre-treatment for fuel production (Bajpai, 2016). Hydrothermal carbonization (HTC), a novel thermochemical process to transform biomass with high water content into carbon-rich solid product (Kim et al., 2016), has been proposed as suitable fuel production method for biomass feedstocks like sugarcane bagasse (Melo et al., 2017). As the suitability of biomass waste for fuel production largely depends on its heating value (Wright et al., 2016), numerous studies have been focus on modification of HTC process parameters to obtain fuel product, so-called hydrochar, with better energy properties from different feedstocks, such as municipal waste streams (Berge et al., 2011), pure cellulose (Lu et al., 2013) and lignocellulosic biomass (Xiao et al., 2012). The conventional HTC treatment using sugarcane bagasse as feedstock resulted in only 20.3% increase in calorific value at 180℃ for 30 minutes (Chen et al., 2012). A more satisfying result of 34.0% increase in energy content of hydrochar was observed (Hoekman et al., 2013), however it required large amount of energy to maintain the reaction at 295℃. Microwave heating has been reported with enhancement effects on process kinetics and considerable reduction of energy consumption during

HTC of pure cellulose (Zhang et al., 2018). Through a comparison between HTC and microwave assisted hydrothermal carbonization (MAHTC) of lignocellulosic waste material (Elaigwu and Greenway, 2016a), hydrochars with similar energy properties were generated with 10 times reduction in reaction time under MAHTC. MAHTC, as a potential strategy to improve the fuel properties of biomass feedstock with less energy consumption (Elaigwu and Greenway, 2016b), has risen a particular interest of its accessibility for fuel production from sugarcane bagasse.

Although there are several studies suggesting advantages of MAHTC previously, a systems level analysis is still needed to identify and quantify environmental consequences (Berge et al., 2015) for further application. It is also essential to understand the environmental performance of electricity production from hydrochar, as it frequently account for a major portion of the total environmental burdens (Ramjeawon, 2008) identified in the life cycle of sugarcane bagasse. Life cycle assessment (LCA) is a comprehensive method for analysis of a process/system and optimization of industry (Chauhan et al., 2011). It has been successfully applied in conducting system level analysis and addressing environmental sustainability (Borrion et al., 2012). There are few existing studies using LCA to estimate the environmental impacts of electricity generation from hydrochar. Berge et al. (2015) evaluated 9 types of environmental impacts associated with HTC of food waste and the subsequent combustion of the generated hydrochar for energy production using lab scale data. The LCA results indicated that treatment of process water HTC process and the energy sources being replaced by hydrochar should be concerned to reduce environmental loads. Another study conducted by Owsianiak et al. (2016) assessed 15 impact categories from the International Reference Life Cycle Data System (ILCD) handbook of HTC using four types of wet biomass waste streams as feedstock at industry-relevant scale. Although the application of HTC treatment with hydrochar as solid fuel shown to be environmentally attractive (Owsianiak et al., 2016), their results also suggested a range of factors like plant size and geographic location could largely influence the overall environmental performance.

Previous LCA studies of HTC have shown interests in comparing environmental impacts of HTC and other waste treatment methods (Berge et al., 2015) or HTC treatment using different feedstock (Owsianiak et al., 2016). Not enough attention was offered on HTC process itself and the parameters related with hydrochar production when conducting LCA on HTC. Only hydrochar moisture and energy content have been discussed in LCA study of HTC using olive mill waste as feedstock (Benavente et al., 2017). More process related parameters should be considered in LCA to reveal how these parameters contribute to system environmental impacts, which could also provide guidance for optimization of current MAHTC treatment. Moreover, the function of allocation method in the previous LCA studies of HTC was ignored and required further investigation to uncover its impact. As the whole electricity generation from hydrochar production by MAHTC involves several multifunctional stages in the life cycle, allocation is an important issue in this biorefinery system (Karka et al., 2015). Since sugarcane bagasse is the major by-product from sugar industry, it is also essential to combine the environmental impact of MAHTC process with initial bagasse production and the final use of hydrochar to understand the whole system instead of focusing on the process itself.

A process based LCA was conducted on the MAHTC of sugarcane bagasse and electricity generation from subsequent hydrochar to evaluate environmental performance and facilitate optimization of MAHTC treatment. As far as we know, evaluation of environmental impacts associated with hydrochar from MAHTC treatment for electricity generation has not been carried out. The aim of this paper is to conduct LCA of electricity generation from sugarcane bagasse hydrochar to evaluate the system environmental impact with two different allocation methods and identify critical MAHTC process parameters on environmental burdens for future optimization. This work has three specific objectives, (1) to investigate the environmental hotspots of electricity production from sugarcane bagasse hydrochar generated from MAHTC with allocation of economic benefit and energy content respectively; (2) to understand the effects of different process related parameters on LCA results to minimize environmental impacts for optimization of MAHTC treatment; (3) to evaluate the feasibility of sugarcane bagasse for fuel production through MAHTC treatment from environmental perspective with comparison of other fuel sources. The novelty of this research is to establish the connection between detailed MAHTC process design with systematic environmental impact of electricity generation from bagasse hydrochar. By expanding the lab-scale result into practical system level, this study presents a holistic understanding of the environmental consequences of the implement of MAHTC as a promising waste-to-energy treatment for other biomass waste like sugarcane bagasse. The LCA results from this study can also provide useful insights for both biomass waste treatment and sugarcane bagasse biorefinery.

2. Methods

LCA modelling was performed based on ISO 14040 and 14044 standards (Finkbeiner et al., 2006) to evaluate the environmental impact associated with material balance and energy flow of electricity generation from sugarcane bagasse hydrochar. This study comprises four main phases as goal and scope, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA) and interpretation.

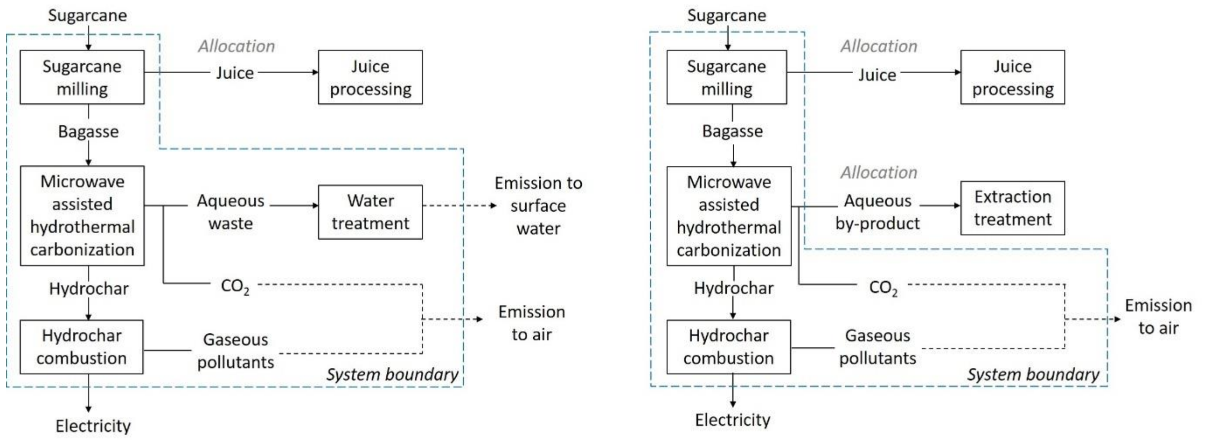
2.1 Goal and scope

2.1.1 Goal of the study

The goal of the present research is to quantify environmental impacts of electricity production from sugarcane bagasse hydrochar generated via MAHTC, identify critical process parameters from sensitivity analysis and compare the environmental consequences with other fuel resources.

2.1.2 Scope of the study and functional unit

The system boundary of this study is illustrated in Fig.1. Two scenarios (S1 and S2) are discussed based on two allocation methods and different treatment of liquid phase product from MAHTC of bagasse. In both scenarios the system starts from sugarcane collection and transportation to the electricity generation from combustion plant, including three main processes as sugarcane milling, MAHTC of sugarcane bagasse and combustion of hydrochar. Sugarcane production process is not included in the system since it has been discussed previously in detail in LCA studies focusing on sugar industry from Australia (Renouf et al., 2010), South Africa (Mashoko et al., 2010) and worldwide (Chauhan et al., 2011).



(a) (b)

Figure 1. System boundary of (a) S1: using economic value as allocation factor and treat liquid phase from HTC treatment as wastewater; and (b) S2: using energy content as allocation factor and recover liquid product from HTC treatment for further chemical extraction

An MAHTC plant is assumed to treat 4,000 t/y sugarcane bagasse on wet basis after sugarcane milling. The plant with two reactors system is assumed to run 300 d annually, which resembles to the capacity of an in-used HTC plant in Germany run by HTCycle company (HTCycle, 2018). Each reactor contains four batches with capacity of treating 200 kg sugarcane bagasse on wet basis. Eight batches of experiment are assumed to run per day to produce 3.35 t energy-enriched hydrochar. The HTCycle case is selected as reference in this study because there is no existing in-used HTC plant in China up to now and HTCycle is cooperating with several Chinese companies to implement their technology (HTCycle, 2019), such as Huizhou Tongyong, Beijing Tempro Technologies Inc etc. After MAHTC treatment the hydrochar will be made into briquette (Liu et al., 2017) and sent to incineration plant to produce 6.53 x 10^{10} J electricity per day.

The functional unit in this study is generation of 1 MJ (10^6 J) electricity from sugarcane bagasse hydrochar produced from MAHTC treatment. As hydrochar being assumed as potential fuel, using electricity as functional unit would benefit the comparison of environmental impact between different fuel sources.

2.1.3 Allocation method

Table 1 lists the value of allocation factors used in two scenarios. The allocation factors for sugarcane milling process are adopted from previous research and experimental results are used for allocation in MAHTC of sugarcane bagasse. Both economic benefit (Gnansounou et al., 2015) and energy content (Renó et al., 2011) have been used as allocation factors for sugarcane based biorefineries. Bagasse is generally regarded as a processing waste with limited value in sugarcane industry, in which way the economic performance is sensitive to sugarcane milling process. As presented in Table 1, allocation factor is calculated by economic value in S1, where the liquid phase generated after MAHTC process without further treatment has no actual economic value and is assumed as direct discharge to wastewater treatment facility. However, the distribution in bagasse and juice as well as solid and liquid products from MAHTC treatment would largely change when the energy content is taken as allocation factor. In S2, the allocation is based on the energy content of products from both milling process and MAHTC treatment, where the liquid phase was taken as by-product with further extraction treatment to recover organic compounds. The environmental impact associated with further treatment of liquid phase after MAHTC treatment is not discussed in the designed system boundary as the focus of this study is on application of solid products.

Table 1. Allocation factors in two different scenarios

Scenario		**Sugarcane milling**		**MAHTC of sugarcane bagasse**		**Reference**
S1 **(Economic value)**	*Products*	Bagasse	Juice	Hydrochar		(Gnansounou et al., 2015)
	Allocation factor	17%	83%	100%		
S2 **(Energy content)**	*Products*	Bagasse	Juice	Hydrochar	Liquid products	(Renó et al., 2011); Experimental result
	Allocation factor	49%	51%	74.2%	25.8%	

2.2. Life cycle inventory analysis

Existing literature with LCA of HTC treatment and other energy recovery methods of sugarcane bagasse is used to provide secondary data for sugarcane milling and hydrochar combustion processes. For the MAHTC treatment of sugarcane bagasse, our lab-scale experiment of sugarcane bagasse is used as primary source to model the scale-up plant. Life cycle inventory data from Ecoinvent 3.0 database is employed in this study.

2.2.1 LCI calculation

2.2.1.1 Sugarcane milling

The sugarcane milling process is adopted from the ED scenario in the research of Gnansounou et al. (2015), where bagasse and juice are the only products from this process. Tap water is used for feedstock washing and imbibition. Sugarcane juice and bagasse are separated after going through steam for dirt and impurities removal. A small amount of lime is added in the end to adjust the pH value of sugarcane juice. Data of bagasse production are summarized from sugarcane based biorefinery researches in Brazil (Gnansounou et al., 2015), Thailand (Nguyen et al., 2008), Mauritius (Ramjeawon, 2008) and China (Peng et al., 2014) and results in consistence that the yield of sugarcane bagasse is about 30% with 50% water content. Emission of sugarcane milling process is ignored in this study since the main emission is generated during further treatment of sugarcane juice (Ensinas et al., 2007).

2.2.1.2 HTC treatment of sugarcane bagasse

Energy and mass balance of MAHTC process is calculated based on lab experimental results. The hydrochar sample using sugarcane bagasse as feedstock was obtained at 240℃ for 30 minutes in the same batch reactor described in our previous study (Zhang et al., 2018), resulting in 38.9% increase in carbon content and 36.3% increase in calculated high heating value (HHV) comparing to raw bagasse. The optimum condition is selected from temperature range of 200℃ to 250℃ and time range of 0 to 90 minutes and identified as the condition when the highest energy retention efficiency (ERE) is reached (Wang et al., 2018). ERE is an indicator usually used to evaluate the extent of HTC treatment in previous research (Lu et al., 2013), which is calculated by solid yield multiply energy densification ratio as a measure of the fraction of feedstock energy retained within generated hydrochar. The properties of sugarcane bagasse and hydrochar generated by MAHTC and conventional HTC from research of Hoekman et al. (2013) are listed in Table 2.

Table 2. Physicochemical properties of sugarcane bagasse and generated hydrochar

	Moisture content (%)	**(dry mass)**					
		Elemental analysis (%)				**HHV (MJ/kg)**	**ERE (%)**
		C	N	O	H		
Sugarcane bagasse	50.3	44.2	0.4	35.0	6.4	17.9	-
Hydrochar MAHTC, 240℃, 30 min	-	61.4	0.9	18.4	5.3	24.4	84.8
Hydrochar Conventional HTC, 255℃, 30 min	-	62.3	1.1	18.5	4.7	23.4	56.33

According to Bermúdez et al. (2015), when the microwave assisted process is scaled-up from 5 g to 100 g, there is a decrease in specific energy consumption of 90% to 95% with both water heating and carbon heating methods and will further decrease with lager capacity on the basis of model prediction. In this study we assume the material input per unit is assumed to be not affected by scaling-up while the energy input per unit is assumed to decrease accordingly. The energy consumption would therefore decrease 95% per kg with increasing capacity from 10 g bagasse at lab-scale to 200 kg per batch for industrial plant. The comparison between parameters of lab-scale batch equipment and the hypothetical scale-up plant is listed in Table 3.

Table 3. Parameters of lab-scale MAHTC process and scaled-up MAHTC plant per batch

	Lab-scale	**Scale up**
Batch Capacity	0.1 kg (dry mass)	200 kg (wet mass)
Deionized water	300.0 mL	2.9 m^3
Hydrochar yield	62.5%	
Electricity for microwave heating	414 MJ/kg	20.7 MJ/kg

The liquid phase after MAHTC treatment can be easily separated by gravity drainage. Several organic compounds in liquid phase were detected including various sugars and organic acids, where 5-HMF and furfural were detected as main products by GC-MS analysis as the degradation products of sugars. Although it has been suggested that the liquid phase could be utilized by recovery of valuable organic chemicals, without practical extraction method such a complex mixture would possess no economic value. The liquid phase is therefore usually regarded as waste aqueous phase that should be treated before discharge (Pala et al., 2014). According to our experimental results, the liquid phase still represents more than 25% energy content of initial feedstock at selected condition. Whether to take the liquid phase as by-products or wastewater is therefore depends on the chosen allocation method, which has been discussed in section 2.1.3.

The composition of gas phase was not detected since less than 5% of carbon in sugarcane bagasse has been transferred into gas phase according to our experimental result. It is well known that CO_2 is the dominant gaseous species for most biomass waste (Hoekman et al., 2011), which accounts for over 95% of the total gases quantified from HTC treatment of sugarcane bagasse (2013). In this study, the gas phase discharged into atmosphere from HTC process in this study is assumed to be CO_2 emission.

2.2.1.3 Hydrochar combustion

In the recent research of Liu et al. (2017), a boiler was used for co-combustion of hydrochar and coal fines at different mixing ratios. The energy consumption data of the boiler is adopted in this study under the circumstance that hydrochar being used as the only fuel source. The gaseous pollutant emission from 1 kg hydrochar combustion is assumed as the same amount of the emission from 1 kg MSW incineration since combustion of hydrochar could resemble the same process of municipal solid waste (MSW) according to Berge et al. (2015).

2.2.1.4 Transportation

Collection and transport distance of sugarcane from field to the milling plant is calculated following the logistics of Wang et al. (2014) according to the average haul distance equation (1), where C_p (10^3 t of sugarcane crushed per year) is 4000 as the assumed capacity of milling plant and Y is the sugarcane yield with a value of 60.9% as the average sugarcane yield in china from 2004 to 2013 (Li and Yang, 2015). Other relative parameters in the equation are adopted from the mentioned reference, including α (the proportion of distillery catchment area covered by sugarcane), σ (the actual distance travelled to the straight-line distance) and n (the harvest area would be constrained to 1/n as a result of geography).

$$d = 2 \times \sigma \times \frac{2}{3}\sqrt{\frac{n \times C_p}{100 \times \alpha \pi Y}} \tag{1}$$

The average distance to waste treatment facility in EcoInvent database is 10 km (Milà i Canals et al., 2007) which is also adopted in the current research as the distance from sugarcane milling plant to MAHTC plant. For the transportation distance of hydrochar briquette to the combustion plant by train is assumed as 160.93 km (100 miles) as suggested by Liu et al (2017).

2.2.2 Life cycle inventory

Table 4 summarizes all the material flow data in the system boundary referring to 1 MJ electricity generation from sugarcane bagasse hydrochar.

Table 4. Material flow data of 1 MJ electricity generation from sugarcane bagasse hydrochar

	Value	**Units**	**Data source**
Sugarcane milling			
Input			
Sugarcane (wet mass)	0.653	kg	(Ensinas et al., 2007; Gnansounou et al., 2015; Nguyen et al., 2008; Ramjeawon, 2008)
Transport sugarcane by agricultural tractor and trailer	0.015	tkm	Calculated based equation (Wang et al., 2014)
Tap water (used for washing)	0.245	kg	(Gnansounou et al., 2015)
Tap water (used for imbibition)	0.042	kg	(Gnansounou et al., 2015)
Electricity from natural gas	0.059	MJ	(Nguyen et al., 2008)
Steam consumption	0.163	kg	(Nguyen et al., 2008)
Lime hydrated	0.001	kg	(Gnansounou et al., 2015)
MAHTC of sugarcane bagasse			
Input			
Deionized water for MAHTC reaction	2.842	kg	Experiment result
Transport sugarcane bagasse by unspecified lorry	0.002	tkm	EcoInvent database
Electricity from natural gas for MAHTC reaction	0.749	MJ	Experiment result and calculation based on equation (Bermúdez et al., 2015)
Electricity from natural gas for briquette production	0.341	MJ	(Liu et al., 2017)
Output			
Aqueous phase	0.003	m^3	Experiment result
CO_2 emission	0.003	kg	Experiment result
Combustion of hydrochar briquette			
Input			
Transport briquette to combustion plant using train	0.042	tkm	(Liu et al., 2017)

Electricity from natural gas for heater	0.073	MJ	(Liu et al., 2017)
Output			
Gaseous pollutants emission	0.051	kg	Data of MSW incineration process from EcoInvent database

2.3 Impact assessment and interpretation

Five environmental impact categories, i.e. Climate Change (as Global warming Potential, GWP), Freshwater Eutrophication (FEP), Freshwater Ecotoxicity (ET), Human Toxicity (HT) and Fossil Depletion (FD) are evaluated based on the ReCiPe midpoint methodology. The interpretation phase of this study discusses the LCA results of two scenarios with different allocation methods and provided critical and feasible advices for technical improvement from environmental perspective.

3. LCA results

The LCA results from this study presents the potential environmental impacts of bagasse generation, MAHTC treatment of sugarcane bagasse and hydrochar combustion processes under two scenarios with different allocation factors. For each individual impact, the inputs and outputs have been classified into four categories as emission, transport, fuel, and material to discuss their different influence on causing environmental burdens. Based on LCA results, sensitivity analysis and comparison with other fuel sources are further investigated to identify the influence from key process parameters and substituted energy sources on the results.

LCA results of GWP, FEP, ET, HT and FD impacts under S1 and S2 are listed in Table 5. All five impacts under of evaluated scenarios have resulted in similar value, confirming both allocation methods are suitable from systematic view. The GWP, HT and FD impacts are slightly lower in S2 than S1, as a small portion of impact related with energy consumption initially associated with hydrochar generation would be allocated in liquid by-product when energy content is used for allocation. While the FEP and ET impacts slightly increase, implying increasing amount of freshwater use in S2. The

GWP impact is 0.264 and 0.231 kg/MJ CO_2 eq under S1 and S2, both of which are less than half of the value reported by Liu et.al (2017) using conventional HTC treatment (0.149 kg/kwh CO_2 eq for 100% hydrochar). Although the former research used wood chips as feedstock, several parameters are similar to the current study including the water content of feedstock and hydrochar properties. This comparison result suggests MAHTC as an environmental-friendly way for fuel production from biomass waste comparing to conventional HTC. To better understand the contribution of environmental burdens from individual process, each environmental impact will be broken down into three main processes and analysed in detail with inputs and outputs classified into four categories.

Table 5. Impact categories and the corresponding results under with two scenarios

Impact category	**Abbreviation**	**Unit/MJ**	**S1**	**S2**
Climate change	GWP	kg CO_2 eq	2.64×10^{-1}	2.31×10^{-1}
Freshwater eutrophication	FEP	kg P eq	1.13×10^{-5}	1.18×10^{-5}
Freshwater ecotoxicity	ET	kg 1,4-DB eq	8.13×10^{-3}	8.14×10^{-3}
Human toxicity	HT	kg 1,4-DB eq	2.15	2.01
Fossil depletion	FD	kg oil eq	8.82×10^{-2}	7.57×10^{-2}

4.1 LCA results of Scenario 1

Results from LCA analysis of S1 are presented in Fig.2. The percent contribution of three main processes in Fig.2(a) – bagasse generation from sugarcane milling, MAHTC of sugarcane bagasse and hydrochar combustion for electricity generation are compared on each individual impact category. Sugarcane milling has the least contribution on all the selected impact categories comparing to the other two processes. For GWP, FD, FEP and HT impacts, the LCA results indicate MAHTC of bagasse have the most significant roles in causing environmental loads, where ET impact is shown to be mainly affected by hydrochar combustion process.

In order to investigate the influence of different factors related to each process, the impact potential is presented with absolute value in Fig.2(b)-(f). As shown in Fig.2(b) and (f), the GWP and FD impacts have similar distribution that majority of the burden comes from fuel consumption while a small contribution from hydrochar combustion emission is not neglectable on GWP impact. It is not surprising to find out that MAHTC process represents the largest contribution in these two fuel related categories because of large amount of heat consumption during MAHTC to maintain the system at designed temperature.

Two types of freshwater related impacts, i.e. FEP and ET impacts, are illustrated in Fig.2(c) and (d) with large distinction in process distribution. There is a great complexity in the attributed factors in FEP impact. In sugarcane milling process, water use is shown to be the main factor since large amount of water is consumed for steam generation during milling process (Lobo et al., 2007). When it comes to the MAHTC process, material and fuel use represent half contribution with the other half comes from discharge of the liquid product after wastewater treatment. For the last process when hydrochar is combusted for electricity, there is a reasonable finding that gaseous pollutants emission from hydrochar combustion has largest impact on eutrophication. These gaseous pollutants also represent the cause of over 94% ET impact presented in Fig.2(d), indicating the major ET impact is caused by traditional combustion process. Another 3% of ET impact is observed to be caused by fuel consumption during MAHTC treatment, which is originated from electricity generation plant.

The last but the most intuitive category discussed in this research is HT impact as shown in Fig.2(f). Sugarcane milling process represents the least contribution on HT impact with fuel use as the main cause. Unlike the results from Berge et al. (2015), the contribution of MAHTC treatment on human toxicity in this study mainly comes from fuel use rather than water emission since the liquid product is assumed to be treated prior to discharge. The largest HT impact among all the concerned factors is again associated with gaseous pollutants emission from hydrochar combustion process. Since the impact of gas emission from hydrochar combustion is assumed as same as the impact from MSW combustion, it is suggested less impact would associate with real hydrochar combustion condition because of relatively simple composition of the combust. The negligible environmental impact associated with gaseous pollutants on toxicity related impact categories indicates essential requirement of further investigation to quantify different composition in gas emission from hydrochar combustion.

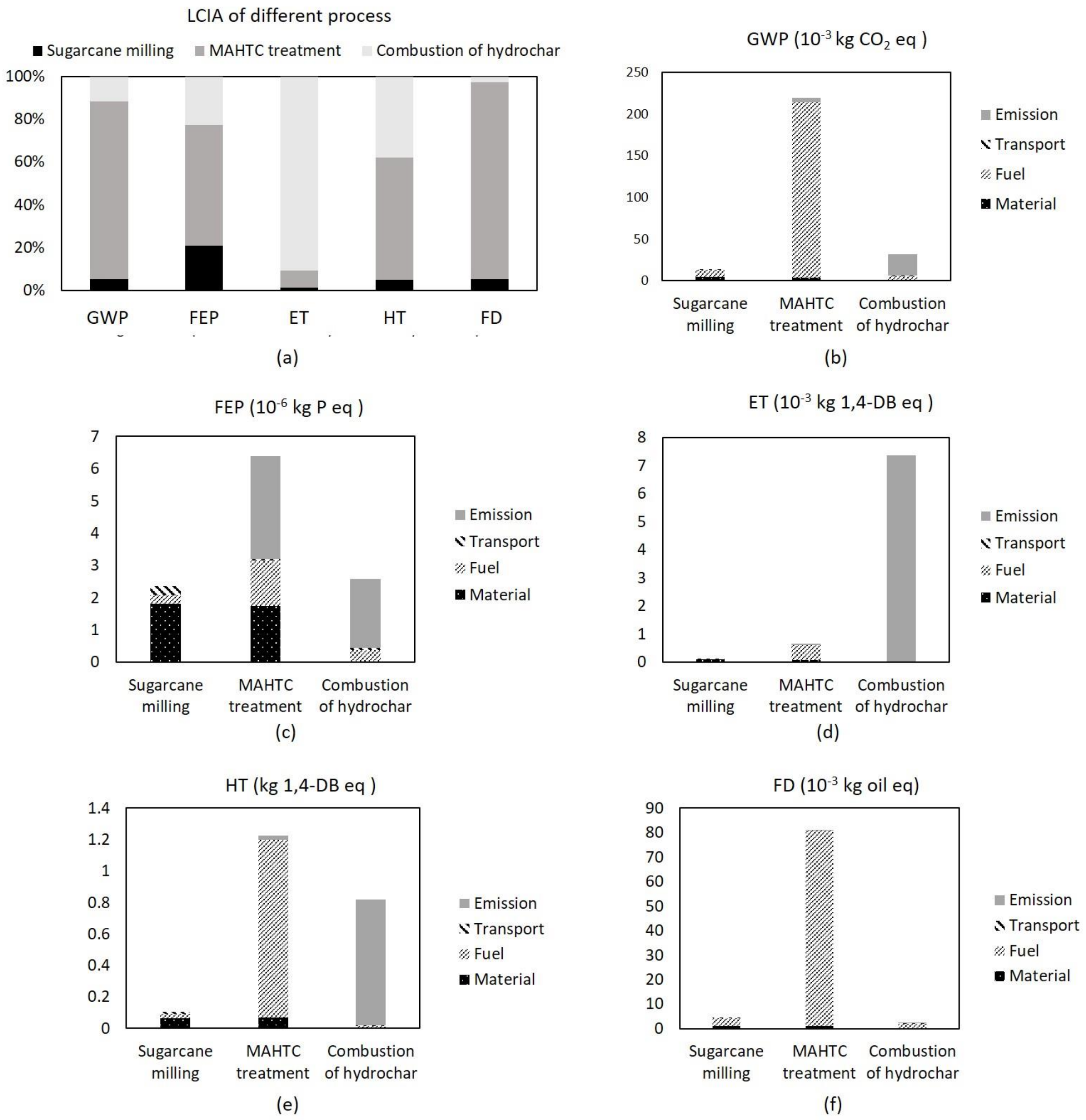


Figure 2. LCA results of five environmental impact categories under S1, (a) percentage contribution of different processes and impacts from emission, transportation, fuel, and material use on (b) GWP; (c) FEP; (d) ET; (e) HT and (f) FD

4.2 LCA results of Scenario 2

As discussed previously in Table 5, the total environmental impact value of each categories under two scenarios are approximately similar. Yet obvious differences are revealed between these two scenarios as environmental impacts being allocated into each process. Comparing the contribution of three main processes in Fig.3(a) with Fig.2(a), a significant increase of the environmental burden caused by sugarcane milling process (displayed in black) can be observed in S2 with simultaneous decrease in the burden caused by MAHTC process (displayed in dark grey). The change of process distribution in two scenarios is mainly caused by two different allocation methods that have changed impact allocated to different products. The distribution of hydrochar combustion process is almost unaffected since no allocation is involved in this process.

In the two main products from sugarcane milling process, bagasse possesses very little economic value comparing to juice but occupies half of the energy content because of its large volume. When the environmental impacts are allocated by energy content in S2, the impact associated with bagasse generation would increase and therefore result in higher contribution of sugarcane milling process than S1. Another process being largely affected by allocation method is MAHTC treatment of bagasse to produce hydrochar. In S1 when the liquid product from MAHTC process is regarded as wastewater, the environmental impact largely associates with treatment and discharge process, while in S2 the liquid phase is regarded as a by-product of MAHTC process with appropriate treatment to retrieve energy. As mentioned before, the liquid product from lab-MAHTC process possesses 25% of total carbon contribution in initial feedstock that cannot be ignored when energy content is used for allocation. It has been discussed in previous research that the recovery of liquid phase is critical for the environmental performance of HTC treatment from both technical (Pala et al.,

2014) and environmental (Berge et al., 2015) perspective. Hoekman et al. (2013) suggested a multistep HTC process for recovery of valuable organic chemicals to maximize them at different temperature ranges, however studies on successful extraction of organic compounds from the complex aqueous products are barely published.

The impact potential of five categories in S2 related with emission, transportation, fuel and material use contribution in different processes are presented in Fig.3 (b)-(f). The high energy consumption of MAHTC process still makes it as the biggest contribution of GWP and FD impacts, though the increased contribution from sugarcane milling process indicates fuel use during bagasse generation is also an important influential factor on these two impacts. The increasing load represented by impact potential of sugarcane milling process is also observed in FEP, ET and HT impacts. A visible difference in the contribution of FEP impact between two scenarios in Fig.2(c) and Fig.3(c), indicating this impact category is sensitive to process with high amount of water use and wastewater treatment. The increasing environmental impact from water use during bagasse generation makes sugarcane milling process become the dominant contribution for eutrophication impact in this scenario. It also explains the desirable decrease of FEP impact in S2 because of liquid phase recovery from MAHTC process. These results not only indicate the unavoidable environmental impact from fuel use in sugarcane milling process, but also highlight the importance of environmental burdens caused by material use, i.e., water and sugarcane. As for ET and HT, gaseous emission from hydrochar combustion is still playing a determining role in both toxicity related impacts in accordance with the environmental performance of S1.

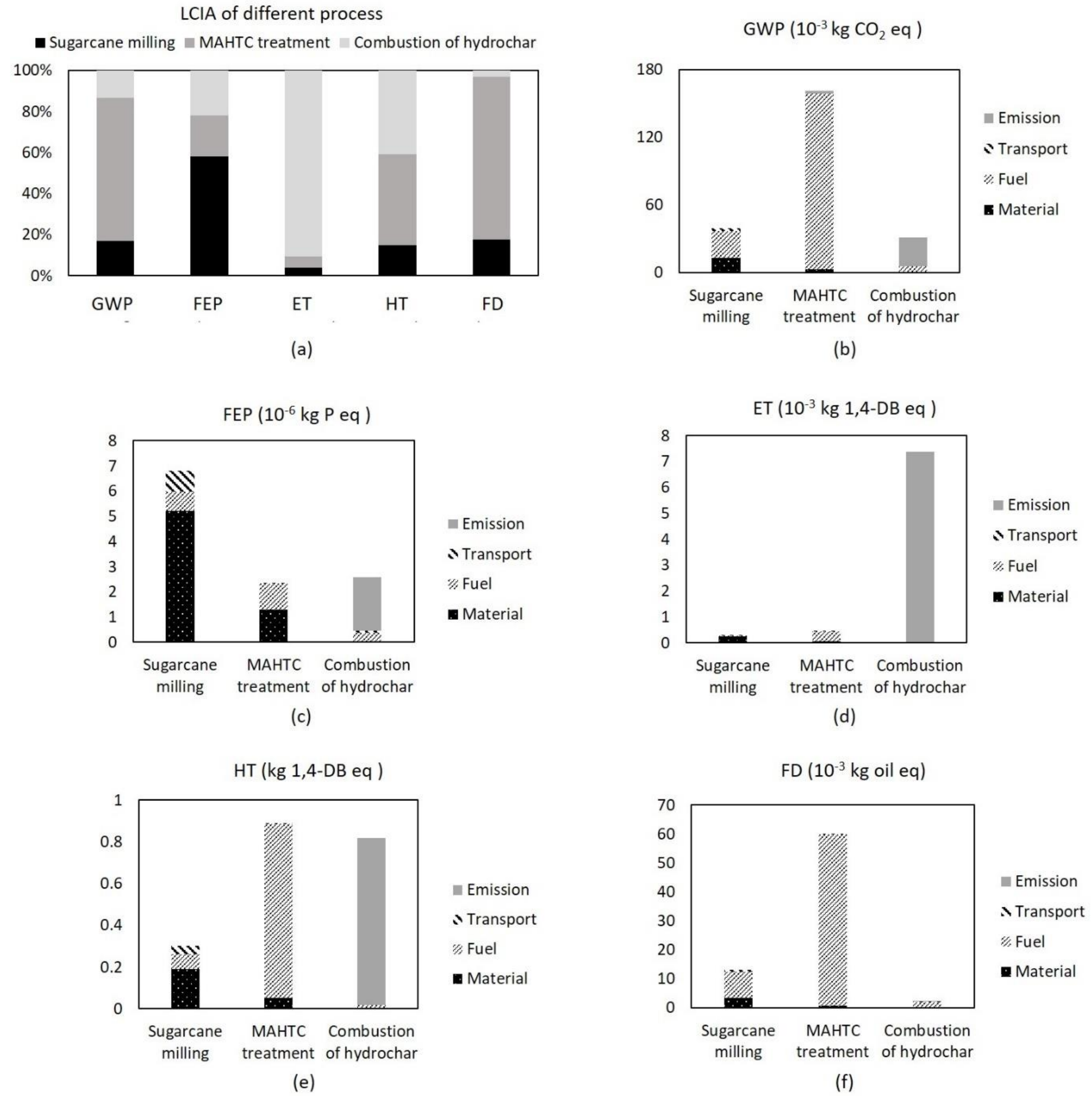
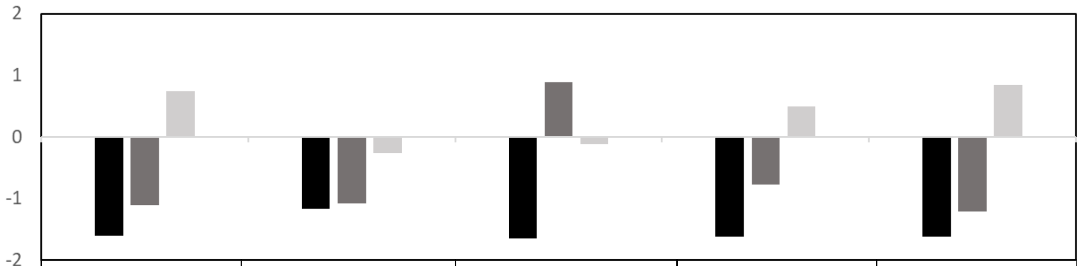


Figure 3. LCA results of five environmental impact categories under S2, (a) percentage contribution of different processes and impacts from emission, transportation, fuel, and material use on (b) GWP; (c) FEP; (d) ET; (e) HT and (f) FD

4.3 Sensitivity analysis

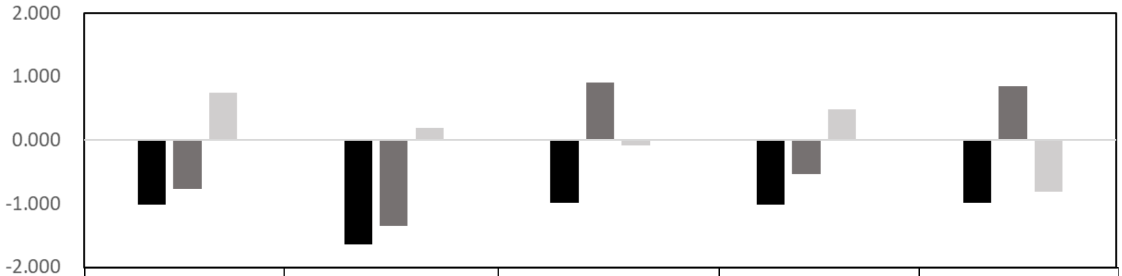
Sensitivity analysis is conducted with ten potential parameters based on previous analysis to understand how changes of parameters in different processes would influence environmental impacts. For sugarcane milling process, bagasse yield and energy use are selected as primary factors since both material and fuel use have large impact on the total environmental impact. Transport distance from sugarcane field to milling plant is also selected because there could be an uncertainty during the calculation of the distance under real circumstance. The influence of energy use during MAHTC treatment on the environmental impact is proved critical to the system, thus electricity use during MAHTC process. Other three parameters related with MAHTC reaction including hydrochar yield, water/solid ratio and carbon content of hydrochar are also selected for sensitivity analysis. For combustion of hydrochar, the emission is evaluated for its essential impact as well as fuel use and railway transportation.

Sensitivity ratio (SR) is introduced and calculated to quantify the influential extent of each parameter. It is defined as the percent change of the result divided by the percent change of parameter (Berge et al., 2015). LCA results from S1 is selected as base case since the economic value is more frequently used as the allocation method in biorefinery research and the total environmental impact value from the two scenarios are similar. For all the selected parameters, simulations are conducted in 20% increasing and 20% decreasing of the value in base case for comprehensive analysis (except for water/solid ratio used in MAHTC process, 15/1 and 40/1 are selected as the same one used for test in lab-scale experiment), which are recorded as ‘+20%’ and ‘-20%’ respectively to facilitate the discussion. Fig.4 and Fig.5 illustrate the correlation of three most sensitive parameters (selected with top three absolute value of SR) in each impact category under two circumstances with their corresponding value listed in the table.



	Climate change	Freshwater eutrophication	Freshwater ecotoxicity	Human toxicity	Fossil depletion
■ 1	Carbon content	Carbon content	Carbon content	Carbon content	Carbon content
	-1.608	-1.170	-1.654	-1.624	-1.627
■ 2	Hydrochar yield	Hydrochar yield	Emission to gas from combustion	Hydrochar yield	Hydrochar yield
	-1.107	-1.084	0.888	-0.777	-1.215
■ 3	Fuel use in HTC	Bagasse yield	Hydrochar yield	Fuel use in HTC	Fuel use in HTC
	0.743	-0.264	-0.118	0.488	0.842

Figure 4. Top three sensitive factors for each impact category with corresponding sensitivity ratio (+20%)



	Climate change	Freshwater eutrophication	Freshwater ecotoxicity	Human toxicity	Fossil depletion
■ 1	Carbon content	Carbon content	Carbon content	Carbon content	Carbon content
	-1.022	-1.641	-0.993	-1.010	-0.992
■ 2	Hydrochar yield	Hydrochar yield	Emission to gas from combustion	Hydrochar yield	Fuel use in HTC
	-0.769	-1.347	0.906	-0.540	0.842
■ 3	Fuel use in HTC	Emission to gas from combustion	Hydrochar yield	Fuel use in HTC	Hydrochar yield
	0.743	0.188	-0.090	0.488	-0.810

Figure 5. Top three sensitive factors for each impact category with corresponding sensitivity ratio (-20%)

It is not surprising to discover carbon content of hydrochar as most influential factor which has negative correlation on all the five impact categories in this study. With hydrochar being used for electricity generation, the change of carbon content closely relates with the demanded quantity of hydrochar and thus all the parameters associated with hydrochar generation, especially material and energy use in MAHTC process. Gaseous emission from combustion is also highly influenced by the amount of provided hydrochar. Hydrochar yield lists second influential for GWP, FEP, HT and FD impacts in the +20% simulation as shown in Fig.4. It is also observed as second influential factor for GWP, FEP and HT impacts in the -20% simulation as shown in Fig.5. As explained before, there is no doubt with the importance of hydrochar generation related parameters as the critical role of MAHTC process plays in total environmental impact. Results from sensitivity analysis highlight the importance of increasing product yield and carbon content of hydrochar simultaneously during MAHTC treatment, which has been ignored in previous LCA studies since energy consumption is always recognized as the most influential factor in the case of environmental performance. As a combined indicator to evaluate carbon content and hydrochar yield in the same time, ERE is not only an indicator to improve energy properties of hydrochar, but also can be used to evaluate the potential environmental performance of hydrochar for electricity production.

As for the electricity use during MAHTC treatment, sensitivity analysis shows that the results are quite sensitive with GWP, HT and FD impacts. GWP and FD represent the impacts from energy use thus are tightly related with the electricity use. However, it should be highly noticed that the HT impact also obtains considerable influences from energy consumption. Another sensitive parameter is gaseous emission from hydrochar combustion as illustrated by the analysis, especially for ET impact. The explanation of this result could be the toxic gas emission from conventional combustion, as the impact of hydrochar combustion is assumed as the same of MSW incineration. Gas emission from hydrochar combustion and bagasse yield respectively list as the third influential factor for FEP impact under +20% and -20% simulation. Discrepancy in results from two simulation scenarios is due to the uneven percentage each process contributed to the total environmental impact.

4.4 Comparison with other electricity generation method

The importance of substituted energy sources has been highlighted in previous LCA studies using food waste (Berge et al., 2015) and biomass waste (Owsianiak et al., 2016) as feedstocks when the electricity production from hydrochar is used to offset other types of electricity generation. It is critical to understand at what level was the environmental impact caused by electricity generation from hydrochar combustion when compared with other fuel sources. Fig.6 presents the comparison of environmental impact of 1 MJ electricity generation from bagasse hydrochar combustion in two scenarios and six other electricity sources with impact potential data adopted from EcoInvent database, including the average high voltage electricity generation (CN, China), electricity from co-generation of sweet sorghum bagasse (GLO, Global), incineration of MSW (RoW, Rest of the world), conventional natural gas power plant (CN), hard coal combustion (CN) and lignite combustion (RoW).

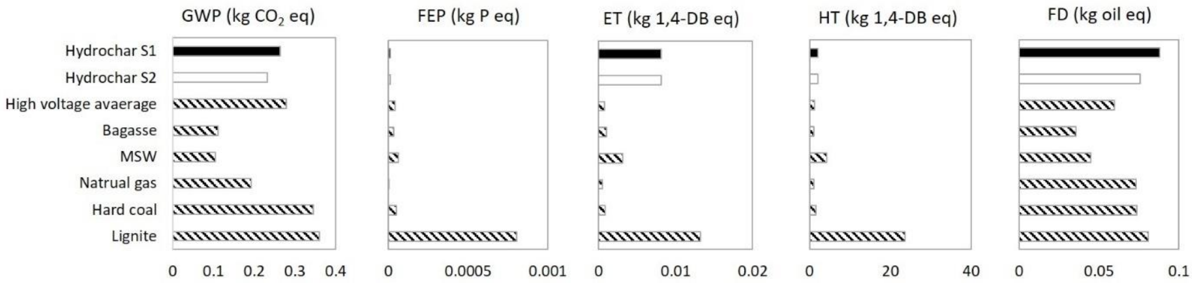


Figure 6. Comparison of environmental impacts from different electricity sources

As illustrated in Fig.6, electricity production from hydrochar combustion generally causes more environmental burdens in GWP, ET and FD impacts. On the other hand, less impact is caused by hydrochar combustion in FEP and HT categories than other fuel sources. Comparing with combustion of lignite, hard coal, and average high voltage electricity generation, hydrochar combustion results in lower GWP impact, indicating it possesses large potential to substitute traditional coal. The results are not ideal comparing with electricity production from sorghum bagasse, MSW and natural gas, suggesting hydrochar for combustion is not competitive with other biomass or equivalent clean fuel sources. This result is consistent with the conclusion of Berge et al. (2015) that electricity generated from hydrochar combustion would result in environmental savings when offsetting coal-based energy sources but biomass. Disappointingly, FD impacts under both S1 and S2 appear to be even larger than that of hard coal and lignite combustion. This observation is mainly caused by the large amount of electricity consumption during heating and reaction period of MAHTC process, which could be the main obstacle for its industrial application.

For other three impact categories, a big disappointing fact is the high impact potential of ET impact associated with electricity production from hydrochar combustion. Under both scenarios, this impact is shown to be far larger than electricity generated from other sources except lignite. This result is mainly caused by the assumption that the gaseous pollutants from hydrochar combustion was as same as MSW incineration, which has a great influence on toxicity related environmental impacts. The low value of FEP and HT impacts associated with electricity production from hydrochar generation when compared to other sources indicates the attracting aspects for implementation of MAHTC treatment for fuel production from sugarcane bagasse.

5. Discussion and implications

The LCA results from this study indicates the critical position of MAHTC treatment and hydrochar combustion process of causing environmental burdens in the system boundary, suggesting technical improvement should be done in these two processes when using hydrochar for electricity generation. Although the change of process-related parameters is micro under lab-scale, it could result in variable differences in material balance and energy consumption from the view of life cycle. For the first time, results from the sensitivity analysis have highlighted both solid yield and carbon content of generated hydrochar have adequate critical influences on the environmental performance of HTC treatment. As a combined index for carbon content and hydrochar yield, ERE is thus suggested as useful indicator to minimize potential environmental burdens. In the life cycle analysis of conventional HTC of two-phase olive mill waste, Benavente et al. (2017) also observed desirable environmental benefits being obtained at highest ERE, which was described as “the percent of energy initially present in the olive mill waste that is recovered in the hydrochar reached maximum”. Our recent research (Zhang et al., 2018) has proved that using microwave heating during HTC treatment could further enhance both solid yield and energy content of hydrochar and result in high ERE value, indicating MAHTC could provide attracting improvement in environmental performance comparing with conventional HTC.

The largest portion of environmental burdens associated with electricity generation from bagasse hydrochar still appears to be energy consumption even with microwave assisted heating during HTC treatment. As energy consumption has been proved to decrease with reduction of heating time during MAHTC, the environmental burdens mainly attribute to the energy source being used to generate heat. For conventional HTC, the heat is usually generated from direct combustion of natural gas or other fuel. Though there could be heat loss due to limited transfer efficiency, environmental burdens associated with direct combustion is still less than that from electricity. Microwave dielectric heating requires significantly more energy than conventional heating techniques as a consequence of the comparably low transfer efficiency of magnetrons in converting electrical to microwave energy (Razzaq and Kappe, 2008). When microwave is used as the only energy supply, MAHTC process could result in more environmental load than conventional HTC using electricity or heat as sources. Considering both process enhancement effect and low transfer efficiency of magnetrons associated with microwave heating, an ideal option could be using natural gas as heating source to reach the designed reaction temperature first and then adding microwave as enhancement method to obtain hydrochar with desirable properties.

Substitutional energy is critical for industrial expansion of sugarcane bagasse hydrochar for electricity generation. Comparing with other energy sources in China, electricity generation from sugarcane bagasse hydrochar could result in environmental savings when it is used to replace traditional coal combustion and average electricity generation. Nevertheless, it is not as competitive as other energy source with less environmental loads such as biomass or natural gas. Water emission from MAHTC treatment remains a big issue for industrial application of MAHTC treatment from environmental perspective. If the liquid phase from MAHTC process could be partially recycled, all the environmental impact categories discussed in the study especially FEP impact can be largely reduced. If the economic value of liquid product could increase with proper recovery, a small portion of impact initially associated with hydrochar generation would be allocated with the final liquid product thus results in less impact with hydrocar. As for hydrochar combustion process, further investigations should be conducted with gaseous composition to understand the unneglectable toxicity related impacts to benefit the industrial use of hydrochar as alternative fuel.

6. Conclusion

A comprehensive life cycle assessment (LCA) has been conducted in this study to evaluate environmental impacts associated with microwave assisted hydrothermal carbonization (MAHTC) of sugarcane bagasse and electricity generation from subsequent hydrochar to provide practical advices for future optimization of MAHTC treatment. Both economic benefit and energy content are suitable for allocation with slightly difference in total environmental impacts. Comparing the two scenarios discussed in this article, the Climate change, Human toxicity, and Fossil depletion impacts are slightly lower when energy content was used for allocation, as a small portion of impact initially associated with hydrochar generation would be allocated in liquid product. Results indicate MAHTC as an environmental-friendly treatment for fuel production from biomass waste comparing to conventional hydrothermal carbonization in the case of Climate change impact for both scenarios. Environmental burdens associated with electricity generated from hydrochar combustion are mainly attributed liquid phase treatment and fuel use from MAHTC treatment process and gaseous emission from hydrochar combustions. Comparing with other electricity sources in China, hydrochar combustion could result in environmental savings when substitutes traditional coal and average electricity generation. It is important to note, however, using hydrochar for fuel is not as competitive as biomass and natural gas.

LCA Results from this study has successfully established linkage between the environmental performance and the process parameters from MAHTC treatment when hydrochar is used for fuel production. As suggested by sensitivity analysis, carbon content and hydrochar yield have neglectable influences on environmental performance that have been overlooked previously. Both hydrochar properties and environmental performance can be optimized with high energy retention efficiency indicator which can be effectively improved with assistance of microwave heating. MAHTC is suggested as an environmentally friendly way for fuel production from biomass waste like sugarcane bagasse to substitute traditional coal. It is recommended that multistep treatment for recovery of valuable organic chemicals from liquid phase and mixed heating method are favourable to reduce associated environmental impacts for future optimizations of hydrothermal carbonization process.

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