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Assessing the environmental impact of energy production from hydrochar generated via hydrothermal carbonization of food wastes

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ABSTRACT

Although there are numerous studies suggesting hydrothermal carbonization is an environmentally advantageous process for transformation of wastes to value-added products, a systems level evaluation of the environmental impacts associated with hydrothermal carbonization and subsequent hydrochar combustion has not been conducted. The specific objectives of this work are to use a life cycle assessment approach to evaluate the environmental impacts associated with the HTC of food wastes and the subsequent combustion of the generated solid product (hydrochar) for energy production, and to understand how parameters and/or components associated with food waste carbonization and subsequent hydrochar combustion influence system environmental impact. Results from this analysis indicate that HTC process water emissions and hydrochar combustion most significantly influence system environmental impact, with a net negative GWP impact resulting for all evaluated substituted energy-sources except biomass. These results illustrate the importance of electricity production from hydrochar particularly when it is used to offset coal-based energy sources. HTC process water emissions result in a net impact to the environment, indicating a need for developing appropriate management strategies. Results from this analysis also highlight a need for additional exploration of liquid and gas-phase composition, a better understanding of how changes in carbonization conditions (e.g., reaction time and temperature) influence metal and nutrient fate, and the exploration of liquid-phase treatment.

1. Introduction

Hydrothermal carbonization (HTC) is a relatively low temperature thermal conversion process that is gaining significant attention as a sustainable and environmentally beneficial approach for the conversion of biomass and waste streams to value-added products (e.g., Berge et al., 2011; Hwang et al., 2012; Li et al., 2013; Libra et al., 2011; Román et al., 2013; Titirici et al., 2012; Sevilla and Fuertes, 2009). HTC is a unique process in which wet feedstocks are thermally converted at relatively low temperatures (<350 °C) and with relatively low input energy requirements (Funke and Ziegler, 2010; Libra et al., 2011; Titirici et al., 2012). As a result of this process, a carbon-rich and energy-dense solid material is formed. This solid product, often referred to as hydrochar, has garnered considerable study, as its properties make it amenable for use in a variety of environmentally-relevant applications, including as a soil amendment, energy source, environmental sorbent, and/or a material for energy and/or hydrogen storage (Libra et al., 2011; Kammann et al., 2012; Berge et al., 2011; Flora et al., 2013; Heilmann et al., 2010; Kumar et al., 2011; Sevilla et al., 2011).

The many potential environmental benefits associated with HTC have led to the recent exploration of using this process as a means to convert components of municipal solid waste (MSW) to a solid fuel source (e.g., Berge et al., 2011; Funke and Ziegler, 2010; Kaushik et al., 2014; Libra et al., 2011; Phuong et al., 2015; Ramke et al., 2009). Results from several studies indicate that hydrochar generated from the conversion of different municipal waste materials has an energy density equivalent to that of coal (e.g., Berge et al., 2011; Hwang et al., 2010; Kaushik et al., 2014; Li et al., 2013; Phuong et al., 2015). Studies have also identified potential environmental benefits associated with using HTC in this manner, such as a reduction in greenhouse gas emissions and lower energy requirements for the conversion of wet feedstocks when compared to more traditional waste conversion processes (Titirici et al., 2007; Ramke et al., 2009; Falco et al., 2011; Funke and Ziegler, 2010; Román et al., 2013).

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Although there are numerous studies suggesting hydrothermal carbonization is an environmentally advantageous process, a systems level evaluation of the environmental impacts associated with hydrothermal carbonization and subsequent hydrochar combustion has not been conducted. Such an analysis is needed to more objectively identify and quantify environmental advantages. Because using hydrothermal carbonization in this manner is in its infancy, a major obstacle associated with conducting such a comprehensive analysis of HTC is a lack of relevant data. There are many unknowns associated with carbonization, particularly with respect to process scale-up. This lack of data limits the ability to conduct a fair process comparison with other well-established processes (e.g., incineration, composting, etc.) for which such data exist (e.g., Boldrin et al., 2010; Chen and Christensen, 2010; Riber et al., 2008; Turconi et al., 2011). A systems level analysis, however, can be used to provide an understanding of how parameters and/or components associated with feedstock carbonization and/or subsequent hydrochar combustion (e.g., fate of metals and nutrients, etc.) influence system environmental impact. Understanding such relationships is critical in identifying and prioritizing research needs and data gaps.

The purpose of this work is to use a systems level analysis to understand how different factors/components associated with the HTC process influence the environmental impacts of hydrochar production and subsequent combustion for energy generation from the carbonization of food waste. Because food waste is a wet feedstock, it is better suited for hydrothermal carbonization than more traditional dry carbonization processes (e.g., pyrolysis). Accordingly, several studies evaluating the hydrothermal carbonization of food wastes for various purposes have been conducted (e.g., Kaushik et al., 2014; Li et al., 2013; Parshetti et al., 2014). Significant experimental efforts associated with the carbonization of food waste collected from restaurants located in the United States have been previously conducted (Li et al., 2013) and results from these efforts indicate that hydrochar energy contents are significant and that food waste carbonization followed by hydrochar combustion results in a net energy savings (Li et al., 2013). The specific objectives of this work are to: (1) evaluate the environmental impact of the HTC of food wastes and the subsequent combustion of the solid product (e.g., hydrochar) for energy production using life cycle assessment (LCA) to identify the most impactful processes and (2) understand how parameters and/or components associated with food waste carbonization and/or subsequent hydrochar combustion (e.g., fate of metals, fate of nutrients, electricity needs) influence system environmental impact.

2. Materials and methods

2.1. Food waste carbonization

Results from previously conducted food waste carbonization experiments were used in this modeling effort (Li et al., 2013). As described in Li et al. (2013), food waste was periodically collected from restaurants located near the University of South Carolina (Columbia, SC, USA). Visual observation of the collected food indicated the waste consisted of a variety of cooked foods (e.g., meat, seafood, French fries, vegetables), uncooked foods (e.g., vegetables, seafood) and condiments (e.g., salad dressing, ketchup, cocktail sauce). Because of processing limitations, food containing bones (e.g., chicken bones) was not used in these experiments. The packaging materials found in this waste consisted of paper, plastics, and cardboard. The elemental composition of these wastes is presented in Table 1.

Table 1
Feedstock properties.

Elements	Food waste	Components of packaging waste		
		Paper	Cardboard	Plastic
Al (%TS)[a]	0.0222	0.100	0.350	0.00730
As (%TS)[a]	2.63E−05	1.02E−05	1.02E−05	1.00E−05
Ash (%TS)[a]	5.20	9.56	5.15	4.62
C bio (%TS)[b,c]	52.4	40.6	40.0	0
C fossil (%TS)[b,c]	0	0	0	62.0
Ca (%TS)[a]	0.516	0.873	1.59	1.55
Cd (%TS) [a]	2.63E−05	1.02E−05	1.02E−05	1.00E−05
Cr (%TS) [a]	5.27E−05	0.000418	0.000194	0.00048
Cu (%TS)[a]	0.000421	0.00286	0.000153	0.0007
Energy (MJ/kgTS)[b]	22.0	15.7	13.0	25.5
Fe (%TS)[a]	0.00632	0.0171	0.0152	0.00901
H (%TS)[b]	8.30	6.43	5.95	4.75
Hg (%TS)[a]	1.32E−06	8.16E−07	5.11E−07	5.00E−07
K (%TS)[a]	0.578	0.0135	0.00572	0.00891
Mg (%TS)[a]	0.0602	0.0463	0.0357	0.0314
Mn (%TS)[a]	0.00961	0.000479	0.000286	0.00021
N (%TS)[b]	2.80	0.08	0.13	0.10
Na (%TS)[a]	0.890	0.0920	0.0563	0.0412
Ni (%TS)[a]	5.27E−05	0.000479	0.000204	0.00044
P (%TS)[a]	0.287	0.00510	0.00317	0.00370
Pb (%TS)[a]	5.27E−05	5.10E−05	3.06E−05	2.00E−05
S (%TS)[a]	0.177	0.0220	0.0185	0.00400
Se (%TS)[a]	5.27E−05	2.04E−05	2.04E−05	2.00E−05
Sr (%TS)[a]	0.00121	0.00133	0.000980	0.000901
Ti (%TS)[a]	0.000711	0.265	0.00592	0.0655
TS (%)[b]	38.0	53.7	62.8	94.1
VS (%TS)[a]	94.8	90.4	94.9	95.4
Water (%)[b]	62.0	46.3	37.2	5.87
Zn (%TS)[a]	0.00231	0.000581	0.000204	0.00650

[a] Parameters were measured by Huffman Laboratories, Inc.
[b] Parameters were measured as described in Li et al. (2013).
[c] Carbon in the food, paper, and cardboard fractions are considered biogenic; carbon associated with the plastic material is of fossil origin.

Experiments investigating carbonization of the separated food waste over a range of temperatures, reaction times, and initial solids concentrations were conducted. Experiments containing food and various percentages of packaging materials were also conducted to evaluate the influence of packaging on food waste carbonization. Specific details associated with the carbonization experiments can be found in Li et al. (2013). A summary of the results from these carbonization experiments that were used in this modeling effort is included Tables 2–4.

2.2. Modeling approach

LCA modeling was performed using the Environmental Assessment System for Environmental Technologies (EASETECH, version 2.0.0), a mass-flow based LCA tool developed by researchers at the Technical University of Denmark to evaluate the environmental impact of waste management processes (Clavreul et al., 2014). This specific tool was chosen for use in this study because it is designed to calculate and track waste flows, resource consumption and recovery, and environmental emissions through user-defined waste management systems. All input waste material fractions are specified in terms of elemental composition (e.g., carbon, hydrogen, etc.) and fraction-specific properties (e.g., moisture and energy content, etc.), and are tracked through the system. Waste management processes are modeled in EASETECH by assembling a series of default template processes, such as substance transfer and emissions to the environment, as described in more detail by Clavreul et al. (2014). Each template process is subsequently populated with user provided process input/output information. Additional details associated with EASTECH and its use in modeling various waste management systems can be found