Waste Management 33 (2013) 2478–2492

Contents lists available at SciVerse ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

# Hydrothermal carbonization of food waste and associated packaging materials for energy source generation

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ARTICLE INFO

*Article history:*
Received 17 December 2012
Accepted 28 May 2013
Available online 3 July 2013

*Keywords:*
Food waste
Hydrothermal carbonization
Energy
Packaging materials

ABSTRACT

Hydrothermal carbonization (HTC) is a thermal conversion technique that converts food wastes and associated packaging materials to a valuable, energy-rich resource. Food waste collected from local restaurants was carbonized over time at different temperatures (225, 250 and 275 °C) and solids concentrations to determine how process conditions influence carbonization product properties and composition. Experiments were also conducted to determine the influence of packaging material on food waste carbonization. Results indicate the majority of initial carbon remains integrated within the solid-phase at the solids concentrations and reaction temperatures evaluated. Initial solids concentration influences carbon distribution because of increased compound solubilization, while changes in reaction temperature imparted little change on carbon distribution. The presence of packaging materials significantly influences the energy content of the recovered solids. As the proportion of packaging materials increase, the energy content of recovered solids decreases because of the low energetic retention associated with the packaging materials. HTC results in net positive energy balances at all conditions, except at a 5% (dry wt.) solids concentration. Carbonization of food waste and associated packaging materials also results in net positive balances, but energy needs for solids post-processing are significant. Advantages associated with carbonization are not fully realized when only evaluating process energetics. A more detailed life cycle assessment is needed for a more complete comparison of processes.

## 1. Introduction

Food waste represents a significant and largely underutilized fraction of municipal solid waste (MSW). The National Resources Defense Council (NRDC, 2012) recently reported that approximately 40% of food in the US is wasted during its processing and distribution and/or while at commercial institutions and/or households. In 2010, the United States (US) discarded approximately 30.8 million tonnes of food waste, accounting for 14% of total generated MSW (EPA, 2011). Food wastes also represent large fractions of MSW in other developed countries, such as England (15% of waste, DEFRA, 2011) and Belgium (7.6% of waste, European Commission, 2010). Waste streams in developing countries generally contain even larger fractions of food waste. Bangladesh and Kuwait, for example, generate waste with 62% (Sujauddin et al., 2008) and 51% (Abdulla and Mahrous, 2001) of food, respectively.

A large fraction of discarded food in the US is landfilled, where food waste degradation rates coupled with low initial gas collection efficiencies result in little recovery of methane gas generated by decomposition of the food (Amini and Reinhart, 2011; Levis and Barlaz, 2011). The desire for greater environmental stewardship and policy requirements are leading to greater diversion of food wastes from MSW landfills. Food waste diversion is currently being practiced and promoted in several countries (e.g., Japan (Takata et al., 2012) and the European Union (EU Council, 1999)), in several states within the United States (e.g., California (Moore and Edgar, 2008)), at several commercial institutions/restaurants, and is becoming prevalent on many college campuses.

Diverted food wastes are primarily treated/managed using biological approaches, including composting (e.g., Büyüksönmez, 2012; Jambeck et al., 2006; Levis et al., 2010; Lundie and Peters, 2005; Namkoong, 1999; Sullivan, 2010; Witt, 2011; Yespan, 2009) and anaerobic digestion (Banks et al., 2011; Bernstad and la Cour Jansen, 2012; Ike et al., 2010; Levis et al., 2010). These techniques result in reductions in fugitive greenhouse gas emissions when compared to landfilling and lead to the generation of valuable resources (e.g., fertilizer, methane gas). However, these techniques also impart several operational challenges. Mixed wastes present a critical issue with these techniques (Levis et al., 2010), thus packaging wastes (often comingled with the food wastes) must be separated prior to treatment. Other disadvantages associated with these techniques include the need for large treatment footprints, little volume reduction of the wastes, and process-related odors. Although each of these techniques does

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0956-053X/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.wasman.2013.05.025

result in production of a value added product, the future market for large amounts of compost is unknown (Levis et al., 2010) and the capital costs associated with anaerobic digestion facilities may be prohibitive (Kelleher, 2007; Levis et al., 2010).

Hydrothermal carbonization (HTC) is a thermal conversion technique that has the potential to overcome many of the challenges associated with the biological treatment of discarded food. Carbonization may allow for smaller required treatment footprints, more efficient conversion of mixed wastes, and greater waste volume reductions. In addition, carbonization results in the production of an easily stored energy-rich resource. HTC is a wet, relatively low temperature (~180–350 °C) thermal conversion process that occurs under autogeneous pressures (Berge et al., 2011; Funke and Ziegler, 2010; Hoekman et al., 2011; Libra et al., 2011; Titirici and Antonietti, 2010; Titirici et al., 2007). During HTC, wet feedstocks undergo a series of simultaneous reactions, including hydrolysis, dehydration, decarboxylation, aromatization, and recondensation (e.g., Berge et al., 2011; Funke and Ziegler, 2010; Libra et al., 2011). A result of this process is the formation of a high carbon and energy density material (often termed hydrochar) that has been reported to have an energy content and composition equivalent to that of lignite coal (Berge et al., 2011). The produced chars may be easily stored and used for energy generation as needed. Because HTC is a thermochemical technique, mixed wastes may not be as significant of an operational issue as in composting and anaerobic digestion. In addition, because of the moisture requirement, food wastes are more suited for conversion via HTC than other dry, more common thermal conversion techniques.

Carbonization of feedstocks ranging from pure substances to components found in MSW has been evaluated (e.g., Berge et al., 2011; Falco et al., 2011; Kang et al., 2012; Ramke et al., 2009; Sevilla and Fuertes, 2009). Few studies have focused on the carbonization of food wastes. Berge et al. (2011), Goto et al. (2004) and Lu et al. (2012) evaluated the carbonization of rabbit food, while Hwang et al. (2012) carbonized dog food. These experiments were conducted at different conditions, spanning a range of reaction temperatures (200–350 °C) and times (0.5–120 h), and demonstrate that carbonization of model food wastes is beneficial, resulting in the generation of hydrochar that has high carbon (45–93% of initial carbon) and energy (15–30 kJ/g dry solids) contents. Lu et al. (2012) suggest energy derived from hydrochar resulting from model food waste carbonization may be greater than that expected during incineration.

A detailed study evaluating the carbonization of collected food wastes, and associated packaging materials, is needed to determine the feasibility of this technique. The purpose of this study is to evaluate the carbonization of food waste and typical food packaging materials to determine how process conditions (e.g., feedstock concentration/composition, reaction time/temperature) influence product properties and composition. The specific objectives of this study include: (1) determine the effect of food waste concentration and reaction temperature on food waste carbonization; (2) evaluate the effect of packaging materials on mixed food waste carbonization; and (3) evaluate and compare energy balances associated with HTC and incineration of food wastes.

## 2. Materials and methods

### 2.1. Feedstocks

Food waste was periodically collected from restaurants located near the University of South Carolina (Columbia, SC). All collected waste was weighed and immediately separated into four categories: (1) all food materials, except those containing bones, (2) food containing bones (e.g., chicken wings), (3) packaging materials (e.g., paper, plastic, condiment containers, paper/plastic cups), and (4) others (e.g., plastic utensils, glass bottles). Each separated fraction of the waste was weighed to allow the determination of waste composition (Table 1). Visual observation of the collected food indicates the waste consists of a variety of cooked foods (e.g., chicken, 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. Packaging materials were subsequently separated into three additional categories: (1) paper, (2) cardboard and (3) plastics (Table 1). Following separation, the food and packaging materials were shredded to ensure uniform composition and particle size. The food waste was mixed and homogenized with a food-grade blender (Ninja Master Prep, Euro-Pro Operating LLC). All packaging materials (e.g. paper, plastic, cardboard) were shredded using a titanium paper shredder (25 by 4 mm strips).

The moisture, energy, and carbon, hydrogen and nitrogen contents of these materials were measured. The moisture content of the separated components was measured using a gravimetric technique. A mass of each component was dried in a laboratory oven at 80 °C for at least 48 h, or until the dried sample mass remains constant. The carbon, hydrogen, and nitrogen contents of the samples were measured using an elemental analyzer (Perkin Elmer 2400). The energy content of the dried waste components was measured using bomb calorimetry (C-200 Calorimeter, IKA, Inc.).

### 2.2. Batch HTC experiments

All batch carbonization experiments were conducted following procedures previously described (Berge et al., 2011; Lu et al., 2012). Briefly, shredded wet feedstocks (e.g., food waste and/or packaging materials) were placed in 160-mL stainless steel tubular reactors (2.54 cm i.d., 25.4 cm long, MSC, Inc.) fitted with gas-sampling valves (Swagelock, Inc.). If required, deinonized (DI) water was subsequently added to each reactor to achieve desired moisture contents. All reactors were then sealed and heated in a laboratory oven at the desired temperature. Reactors were sacrificially sampled over a period of 96 h. All experiments were conducted in duplicate. The relative percent difference (RPD) associated with duplicate samples is less than 15%, with the majority of the duplicate RPDs less than 5%. This low level of difference suggests the sample volumes used in this study are sufficient for obtaining reproducible results.

Two sets of experiments were conducted: (1) experiments in which separated food waste was carbonized at various solid contents and temperatures and (2) experiments containing food and packaging materials to evaluate the influence of packaging on food waste carbonization. A list of the experiments conducted in this work is included in Table 2. The first set of experiments was conducted to understand how solids concentration and temperature influence the carbonization of food waste. Solids concentrations (%, dry wt.) of 32% (representing the as-received waste), 20%, and 5% were evaluated. These experiments were conducted at 250 °C. Reactors containing 32% solids (as-received food waste) were also conducted at 225 °C and 275 °C to evaluate the influence of temperature on carbonization.

To evaluate the influence of packaging materials on food waste carbonization, mixed packaging materials (added in the proportion collected, see Table 1) were mixed with food waste. Packaging concentrations of 7%, 14%, and 27% (dry wt.) were evaluated. Control experiments containing only packaging materials (in the proportion reported in Table 1) were also conducted. All experiments were conducted at 250 °C. Samples were sacrificially taken over a period of 96 h.