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Production of fuel pellets via hydrothermal carbonization of food waste using molasses as a binder

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ABSTRACT

Hydrochar was produced from food waste under varying hydrothermal carbonization (HTC) conditions, and was pelletized using molasses and molasses/lime binders for fuel pellet production. The physicochemical properties, density, mechanical properties, and water resistance, and combustion characteristics of the hydrochar pellets were investigated. The results indicated that molasses pellets and molasses/lime pellets exhibited increased compressive strength, density, and impact resistance due tothe "solid bridge" that formed from molasses recrystallization and agglomeration by lime. The hydrochar samples prepared at 230 °C and 260 °C, with long residence times of 8 h, showed excellent compressive strength and impact resistance index (IRI). Both molasses pellets and molasses/lime pellets exhibited slightly increased equilibrium moisture content (EMC), with the former showing a high water-resistance index (WRI) in the immersion test. Thermogravimetric analyses indicated that the molasses pellets had a lower ignition temperature and higher combustion interval than those of the molasses/lime pellets.

1. Introduction

Unprecedented municipal solid waste (MSW) is produced with accelerating urbanization and the continuous increase in population in China. It is anticipated that the annual generation of MSW will reach 200 MT by 2020 (Zhou et al., 2014). Landfill disposal and incineration are preferred in China, but these traditional mechanisms for waste disposal require large spaces and cause secondary environmental pollution. The organic fraction of MSW, such as food waste, is around 55.86% of the total, and is an untapped resource with great potential for energy production (Kaushik et al., 2014; Mian et al., 2016). Considering the urgency in managing waste, hydrothermal carbonization (HTC), a new thermochemical conversion technique, is highly attractive due to its suitability for transforming waste biomass into energy and chemicals (Funke and Ziegler, 2010; Wang et al., 2017a; Zhai et al., 2013). Compared with traditional techniques such as biological process and pyrolysis process, HTC process can be directly applied to biomass with high moisture (Wang et al., 2018a). It has been used successfully in converting high moisture content biomass, including microalgae, sewage sludge, and food waste, into a lignite-like solid product (hydrochar) for energy recovery (Berge et al., 2015; Chen et al., 2015; Reza et al., 2016). Compared to raw biomass, hydrochar is highly hydrophobic, more homogeneous and energy-dense (Funke and Ziegler, 2010; Liu et al., 2010; Smith et al., 2016). Additionally, the nitrogen and chlorine contained in raw biomass are largely converted or dissolved into liquid products, indicating the great potential of food waste hydrochar to provide a better alternative to conventional fossil fuels (Chen et al., 2014; Ma et al., 2015; Wang et al., 2018b).

For better handling, transportation, and storage of fuel, densification processes have been applied to hydrochar fines using solid fuel (Liu et al., 2014; Reza et al., 2012). The pelletization process results in high-density pellet (briquettes), which are characterized by increased energy, bulk density, and mechanical strength (Hamawand et al., 2017; Li et al., 2012). However, the mechanical strength and binding mechanism can be influenced by the natural composition of the feedstock and pelletization parameters such as pressure, moisture, particle size, temperature and binders (Kaliyan and Vance Morey, 2009; Wang et al., 2017b). Generally, hydrochar pelletized at lower pressures cannot achieve desirable mechanical strength owing to the highly brittle properties of lignin, especially

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as a result of high hydrothermal severity (Kambo and Dutta, 2014). Under high compression pressure, excellent mechanical strength is achieved through enhanced attraction forces, such as H-bonding and Van der Waals forces, which improve the interval between adjacent particles (Liu et al., 2014). However, a compression process that employs high pressure also leads to higher energy consumption. Studies have focused on the pelletization of lignocellulose-derived hydrochar to obtain solid fuels with acceptable mechanical strength, which is different from food waste-derived hydrochar containing decomposed solid residue from proteins and carbohydrates (Berge et al., 2015; Reza et al., 2016). The limited lignin content in food waste may not form solid bridges to capture particles. Fortunately, the stable protein produced in food waste derived hydrochar that is not denatured under high hydrothermal conditions can act as a binder to increase strength (Kaliyan and Vance Morey, 2009).

To produce high mechanical strength pellets under low pressure, binders, such as starch, lignosulphonate, crude glycerine, lignin, and molasses, have been applied to fuel particles to reinforce the pellets (Kaliyan and Vance Morey, 2009; Zhai et al., 2015). Molasses, obtained as a by-product of sugar cane production, is widely used as a binder for coal briquettes, improving their mechanical properties and fuel characteristics (Benk and Coban, 2011; Das et al., 2015). The soluble sugars contained in molasses can recrystallize after the drying processes and form solid bridges to capture more particles, which results in high mechanical strength of the pellets (Mišljenović et al., 2016). Studies have shown that hardeners, such as phosphoric acid, nitrate, and lime, further increase the pellets strength (Benk and Coban, 2011; Blesa et al., 2003a; Ward et al., 2014). However, lime can improve the green strength of pellets, is relatively inexpensive, and can enhance molasses agglomeration (D. Taulbee, 2009; Ward et al., 2014). Lime addition is also attractive for application in slagging boilers with the aim of lowering the ash-fusion temperature (D. Taulbee, 2009). Based on these described characteristics, molasses and lime were selected for preparing pellets in this study. Very few studies have focused on the characteristics of food-waste-derived hydrochar for pellet production at moderate pressure, and even fewer have addressed pelletization with molasses binders or hardeners to improve mechanical properties. The binding mechanism within the pellets is expected to be different when molasses or molasses/lime are introduced to the hydrochar under different HTC conditions for pelletization. Therefore, the fuel characteristics and combustion properties need to be fully understood.

In this study, hydrochar pellets were prepared with high mechanical strength properties from food-waste-derived hydrochar under low compact pressure using various HTC temperatures and residence times. Molasses was applied as a binder, and the addition of lime as a hardener was tested to produce pellets with strong mechanical properties. Elemental composition, energy content, and water resistance and combustion behaviour were evaluated, and the binding mechanism involved in the synthetic pellets was also explored. Special attention was paid to the optimum hydrothermal conditions for obtaining solid fuel hydrochar with excellent properties.

2. Materials and procedures

2.1. Materials

Food waste (FW) was collected from restaurants at Hunan University. Visual observation showed that the feedstock consisted of food waste (including cooked meat, vegetables, rice, noodles, fruit peels, vegetable parts, and condiments, paper cups, and woody chopsticks. Because of processing limitations, plastic and bones were immediately separated out. A blender was used to thoroughly mix and homogenize the feedstock, which was stored at 4 °C to prevent microbial decomposition before the HTC experiments. The proximate and ultimate analyses and components of the FW are presented in Table 1. The cane molasses used in the experiment was obtained from a local factory, and its properties are shown in Table 1.

The HTC experiments were performed in a 500-mL autoclave equipped with a PID controller and auto-stirred at a stirring rate of 100 rpm. For each run, approximately 20 g of dried FW with 160 mL deionized water was loaded in the reactor, which was heated at an approximate heating rate of 3 °C/min to reach the final temperatures of 200 °C, 230 °C, and 260 °C at 100 rpm. To investigate the effect of residence time on the study, 60 min, 180 min, and 480 min were used for comparison. Subsequently, the reactor was cooled down naturally. The HTC experiment at the same operating conditions was performed twice. The reaction mixture, which consisted of liquid product and solid residue, was completely removed from the reactor and separated using a vacuum filtration apparatus. The hydrochar was washed using deionized water and then dried at 105 °C overnight until it reached a constant weight. The hydrochar samples were weighed, milled, and screened into particle fractions between 180 and 200 μm.

2.2. Pelletization process

The pelletization process was performed using a FW-4A hydraulic press power pelletizer (TuoPu Co., Tianjin, China). A single pellet press consists of a stainless steel cylindrical die with a 9.5 mm interior diameter and 28 mm length, piston with a 9.4 mm diameter and 32.5 mm length, and removable backstop plate at the bottom. Prior to pelletization, the initial moisture content of the hydrochar particles under standard room conditions was measured until the equilibrium moisture content (EMC) was reached; the EMC of the samples for 200 °C-1 h, 200 °C-3 h, 200 °C-8 h, 230 °C-1 h, 230 °C-3 h, 230 °C-8 h, 260 °C-1 h, 260 °C-3 h, and 260 °C-8 h were 5.14%, 5.10%, 4.65%, 3.27%, 2.50%, 2.12%, 2.85%, 2.25%, and 1.96%, respectively. Approximately 0.6 g of powder was manually filled inside the hole, compacted to a pressure of 10 MPa for 30 s at room temperature, and then released. In this study, molasses and a combination of cane molasses and lime (CaO) were selected as additional

Table 1
Proximate analysis, ultimate analysis, HHV, main composition, and properties of the FW and molasses.

	Ultimate analysis (wt%, db)					Proximate analysis (wt%, db)			HHV (MJ/kg)	Main components (wt%, daf) and properties				
	C	H	O[a]	N	S	VM	FC	Ash		Carbohydrate and lipid	Protein[b]	Lignin	Total sugar (%)	Brix[c] (%)
FW	51.14	7.63	26.01	3.45	0.07	72.55	15.98	11.47	22.12	53.88	21.56	5.78	–	–
Molasses	47.40	7.87	41.97	2.63	0.33	77.74	7.94	14.32	21.20	–	–	–	47.10	72.90

[a] Calculated by difference.
[b] Calculated by multiplying by 6.25 (average concentration of organic N) (Li et al., 2015a); db, dry basis; daf, dry and ash-free basis.
[c] Ratio of soluble substance weight to the total weight.