



Co-hydrothermal carbonization of food waste-woody biomass blend towards biofuel pellets production

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ABSTRACT

Co-hydrothermal carbonization of food waste-woody biomass blend was conducted to enhance the pelletization and hydrochar-fuel properties. The hydrochar was characterized by proximate, elemental analysis and HHVs, whilst energy consumption of pelletization, tensile strength, and combustion characteristics of hydrochar pellets were evaluated. Results showed that food waste (FW) blended with 0–50% mainly decreased H/C of hydrochar, while blend ratio from 75% to 100% mainly decreased O/C. When FW blended from 0% to 75%, the energy consumption for hydrochar pelletization decreased about 12–17 J, whereas tensile strength of pellets increased about 2.4–5.5 MPa by formation of solid bridge when woody biomass (WS) ratio was increased. The hydrochar pellets from high ratio FW had decreased ignition temperature and maximum weight loss rate with wider temperature range, indicating the increased flammability and moderate combustion. These findings demonstrate that HTC of food waste-woody biomass blend was suitable for pelletization towards solid biofuel production.

1. Introduction

Since the first industrial revolution in eighteenth century, the world has consumed all kinds of fossil energy (such as coal, oil, natural gas, etc.) at an astonishing speed in the world. The large-scale use of fossil energy makes human beings face two major crises of energy shortage and global warming. Therefore, it has become an important task for twenty-first century to develop renewable energy and carbon dioxide emission reduction (Zhao et al., 2014; Zhu et al., 2017). At the same time, the burning of fossil fuels has led to a large number of CO₂ and NO_x emissions into the atmosphere, so it is urgent to find renewable energy replace traditional fuels and to reduce environmental pollution (Zhang et al., 2016). As a renewable energy source, the exploitation and utilization of biomass energy not only helps to alleviate the energy crisis caused by the depletion of fossil fuels to the global economic development, but also reduces the emission of greenhouse gases, and helps to maintain the ecological balance and improve the human living environment (Wang et al., 2018b; Zhang et al., 2018).

Attention has been focused on the thermal techniques for conversion of biomass to biofuels such as biogas, bio-oil, and biochar during

the past ten years (Wang et al., 2018b). Among these, hydrothermal carbonization (HTC) technique is special due to its high adaptability to the wet biomass like algae (Gai et al., 2015; Yu et al., 2011), food waste (Wang et al., 2018c), municipal sludge (Peng et al., 2016), animal manures (Cao et al., 2011), etc., and the water contained in the raw feedstock can be directly used as reaction medium (Prawisudha et al., 2012; Savage, 2012). Based on these, the solid product, named hydrochar, generally had improved calorific value, hydrophobicity and homogeneous properties process, since the occurrence of dehydration and decarboxylation reaction during HTC (Hoekman et al., 2011; Liu and Balasubramanian, 2014). In addition, the fuel properties like the fixed carbon content and heating values also depended much on the hydrothermal parameters mainly including the temperature, residence and time (Reza et al., 2012; Simsir et al., 2017; Wang et al., 2018a). In general, the hydrochar shows great potential to be an alternative of the solid fuel. The pelletization process in combination with the HTC is also proposed as an alternative to improve the fuel properties of biomass (Liu et al., 2014). To improve the energy density and mechanical strength of hydrochar fuel, Liu et al. used hydrochar produced from woody biomass under 250 °C to prepare pellets, and results indicated

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that hydrochar pellets had increased fixed carbon (20–30%) and heating values (4–6 MJ/kg) compared to raw biomass, and the liquid bridge enhanced the tensile strength of the hydrochar pellets (Liu et al., 2014). Meanwhile, in our previous study, results further showed that the hydrochar from 250 °C produced pellets with lower tensile strength than that from 200 °C due to the carbonized lignin which could not produce solid bridge, and the energy consumption was high (Wang et al., 2017). However, present studies focused mainly on the lignocellulose derived the hydrochar pellet, and food waste derived hydrochar has been rarely studied to prepare fuel pellets. One recent study showed that the food waste derived hydrochar pellets had poor mechanical strength since the limited lignin content because the main components in food waste were protein and carbohydrate like starch and glucose, and the binding ways in the hydrochar pellets relied on attraction forces between the hydrochar microspheres (Zhai et al., 2018). Thus, it can be concluded that the fuel properties and mechanical properties of hydrochar pellets depend much on the components of the raw materials and the preparing conditions during HTC. Considering these, since the lignocellulose-biomass derived hydrochar could produce pellets with excellent mechanical strength by providing solid bridge-type bonding within the hydrochar pellets and food waste were not suitable to form solid fuel with high mechanical strength, the woody biomass and food waste blend derived hydrochar pellets may generate a new approach to produce fuel pellets with enhanced fuel properties and mechanical strength.

In this study, hydrochar from varied food waste-woody biomass blend at 180–260 °C was used to prepare fuel pellets in combination with the pelletization process. The basic fuel properties of hydrochar proximate analysis, elemental analysis, and HHVs of the hydrochar were analyzed. Especially, the energy consumption in the pelletization process was investigated, and the mechanical strength and storage characteristics as well as the combustion characteristics of the hydrochar pellets were evaluated to assess the potential for solid biofuel production.

2. Materials and methods

Wood sawdust (WS), China fir (*Cunninghamia lanceolata*), was obtained from a furniture factory (Changsha, Hunan) and food waste (FW) was collected from the restaurants of Hunan University. Visual observation showed that the FW contained mainly cooked vegetables, rice, noodles, condiments, paper cups, and cooked meat, and the plastic and bones were separated out due to the processing limitations. The HTC process was carried out in a 500 mL 316 stainless steel reactor. Before this trial, about 10 g of mixed and dried feedstock (the mass ratios of FW were 0%, 0.25%, 50%, 75%, 100%, respectively) was loaded with 200 mL of deionized water in autoclave. The reactor was then heated for about 60 min at a rate of approximately 4 °C/min to 180 °C, 220 °C, and 260 °C. The stirring rate was controlled by an electromagnetic agitator at 100 r/min. When the reactor was cooled at room temperature, the solid residue was separated from the mixture using by vacuum filtration. After that, the hydrochar was dried at 105 °C for 24 h in a drying oven and grinded into a powder, through 40 mesh.

A single pellet press was used during the pelletization of hydrochar, and the equipment consist a cylinder-piston unit with heating tape around the cylinder and a temperature controller with a thermocouple. More details can be found in previous study (Jiang et al., 2014). Before the compression process, about 10% (w/w) of extra water was added to the hydrochar, according to previous result, because the waste could act as a lubricant during the pelletization (Jiang et al., 2014; Kaliyan and Vance Morey, 2009). For each trial, about 0.6 g of the hydrochar was filled in the cavity of the mold. When the compacting force reached the maximum value (4 kN), the force was maintained for 30 s. The die temperature was controlled at 90 °C since lignin happened glass transition at this temperature and formed a natural binder within the pellet

(Reza et al., 2012). The energy consumption for the pelletization was calculated through the integral area derived from compression force and displacement, which were recorded online. Once the pellet was pushed out, the mass, length, and diameter of the samples were measured, and the sample was then stored at 4 °C for one week. Length expansion was calculated by the following equation:

$$\text{Length expansion} = (l_i - l_0) / l_0 \quad (1)$$

where l_0 is the initial pellet length, and l_i is the pellet length after one week.

The pellet prepared under certain condition was denoted as T-w, where T is the temperature, w is the mass ratio of FW in the blend during HTC. Each experiment was made in triplicate. To measure the tensile strength (Ts) of the pellet, the pellet was horizontally placed between two anvils and a compressive force was given to it until the pellet was broken, and the maximum force was recorded. The tensile strength was calculated as follow (Liu et al., 2014; Wang et al., 2017):

$$Ts = \frac{2f}{\pi ld} \quad (2)$$

where f is maximum force, and d and l are pellet diameter and length, respectively. The surface of the pellet was characterized by scanning electron microscopy (FEI QuANTA 200, Czech Republic). For the proximate analysis, the Chinese Standard Practice for Solid Biofuels (GB/T28731-2012) was adopted to assess the fixed carbon (FC), volatile matter (VM), and ash. Elemental analysis of the pellets was determined on an Elementar Vario EL cube (Germany). The calorific value of the hydrochar was calculated by: HHVs = 0.339C + 1.443(H - 0.125O) - 0.0224(9H) + 0.0093S + 0.001464 N (Perry and Chilton, 1974). A thermogravimetric analyzer (STA 409, NETZSCH, Germany), was used to evaluate the combustion behavior, and the temperature interval was set from 30 °C to 800 °C, and the heating rate was controlled at 20 °C/min with an air (N₂ = 80%, O₂ = 20%) flow rate of 50 mL/min, and 15 mg of the sample was filled into the crucible for each test. A humidity chamber was used to measure the equilibrium moisture content (EMC) of the pellets, and the conditions were set at 25 °C and 60% relative humidity, and the mass of the pellet was measured when it reached constant value. Before that, the pellets were fully dried at 105 °C.

3. Results and discussion

3.1. Hydrochar yields and basic fuel properties of hydrochar

The hydrochar yield from different blend ratio of food waste and woody biomass is presented in Table 1. With the increase ratio of FW blend and temperature, it can be found that the hydrochar yield decreased consistently. For hydrochar prepared from 180 °C, the yield of hydrochar decreased approximately 40% with the increase ratio of FW, while this tendency was not obvious for hydrochar produced from 260 °C. It can be deduced that the FW was more easily carbonized than WS. As anticipated, the hydrochar produced from WS had relatively lower FC content than hydrochar produced with FW addition, and the VM content of all samples were further reduced when temperature was increased from 180 °C to 260 °C. It was ascribed to that the high temperature enhanced the dehydration and decarboxylation happened during HTC (Funke and Ziegler, 2010; Li et al., 2018; Titirici et al., 2008). Table 1 also illustrates elemental analysis of hydrochar. As for carbon, the content varied from 50.94% to 61.29% at 180 °C, with the feedstock blend ratio increased from 0% to 100%. With temperature increased from 180 °C to 260 °C, the carbon content increased consistently, but the nitrogen ratio in hydrochar seems relied more on the FW ratio in the blend. This was highly related to the initial nitrogen content of the FW. Generally, the nitrogen content in hydrochar was increased with temperature increased and this tendency was more obvious for hydrochar produced from high FW ratio. Similar result can be

Table 1
Mass yield, proximate analysis, elemental analysis, and HHVs of hydrochar.

Samples	Mass yield (%)	FC (%)	VM (%)	Ash (%)	C (%)	N (%)	H (%)	O ^a (%)	HHVs (MJ/kg)
180–0%	81.3	9.60	78.54	11.86	50.94	0.24	7.74	41.08	19.47
180–25%	65.3	11.92	76.11	11.97	51.25	0.55	8.69	39.51	21.04
180–50%	55.6	11.30	78.48	10.22	53.16	0.92	6.56	39.36	19.07
180–75%	46.9	19.37	70.60	10.03	56.58	1.66	7.17	34.59	21.84
180–100%	42.3	27.84	63.07	9.09	61.29	2.66	8.31	27.74	26.09
220–0%	61.5	16.05	73.83	10.12	53.37	0.19	8.27	38.17	21.47
220–25%	59.2	24.48	65.30	10.22	56.01	0.67	8.17	35.15	22.79
220–50%	53.7	30.36	60.32	9.32	60.92	1.42	6.08	31.58	22.51
220–75%	52.4	36.67	56.76	6.57	62.51	2.16	6.36	28.97	23.86
220–100%	40.2	40.05	53.28	6.67	67.02	2.83	6.92	23.23	27.12
260–0%	44.7	41.33	49.53	9.14	67.75	0.07	7.24	24.94	27.46
260–25%	42.5	44.87	46.20	8.93	67.62	1.12	7.50	23.76	27.95
260–50%	43.7	47.84	45.44	6.72	68.63	1.37	6.30	23.70	26.81
260–75%	42.2	45.95	46.38	7.67	69.86	2.60	6.37	21.17	27.78
260–100%	38.5	47.52	46.09	7.39	71.81	3.13	7.01	18.05	29.79

S% < 0.01%.

^a Calculated by difference.

found in Wang et al.'s study (Wang et al., 2018c), the nitrogen could be easily incorporated into the hydrochar at high temperature due to the carbonization and reactions between sugars and protein. As shown in Table 1, the nitrogen content of 260–100% was significantly high (3.13%). The results of HHVs calculated from elemental analysis of the obtained hydrochar are shown in Table 1. At 180 °C, it can be observed that the blend ratio of WS and FW had significantly effect on the HHVs of hydrochar, ranging from 19.07 MJ/kg to 26.09 MJ/kg. However, the HHVs of hydrochar from 260 °C ranged from 26.81 to 29.79, suggesting that the effect from blend ratio became low at high temperature.

The van Krevelen diagram in Fig. 1 illustrates the coalification degree of HTC of the blends. It can be observed that the hydrochar made from 180 °C showed relatively high O/C and H/C content, ranging from 0.34 to 0.60 and 1.46 to 2.03 for O/C and H/C, respectively, whereas the hydrochar from 220 °C and 260 °C, moved to the origin. This suggests that the increase of temperature strengthened the dehydration and decarboxylation reactions during HTC (Falco et al., 2011; Parshetti et al., 2013). More specifically, the samples of 220–50% and 220–75% located in the lignite region, while all hydrochar produced from 260 °C located between the lignite and sub-bituminous region. In consideration of effect of the blend ratio on the degree of hydrothermal carbonization, an interesting result is that the ratio of FW from 0% to 50% decreased mainly H/C ratio, while this blend ratio from 50% to 100% decreased mainly the O/C, regardless of the temperature. For example, the O/C and H/C value of hydrochar from 220 °C with 25% FW and 50% FW were 0.47 and 1.75, 0.39 and 1.20, respectively, while these values for 75% and 100% FW changed to 0.35 and 1.22, 0.28 and 1.28. This indicated that with a high ratio of WS the dehydration reactions

dominated the HTC, whereas the decarboxylation mainly happened during the HTC process (Yao and Ma, 2018). Thus, this is in line with the elemental analysis that more oxygen was lost when more FW were blended in the feedstock. And the H/C ratio even increased when the FW was blended with ratio from 50% to 100%.

3.2. Pelletization and energy consumption

The typical displacement of the hydrochar in the compression process were shown in Fig. 2. From the displacement (Fig. 2a–c), it can be clearly seen that the hydrochar made from 180 °C and 220 °C could easily be compressed to reach the maximum force, and the hydrochar from 260 °C needed a longer displacement and the pelletization profile was unstable. This may be related to the content of components in the hydrochar, because at 180 °C the hemicellulose was mainly decomposed and the cellulose and hemicellulose in hydrochar from 220 °C could be mostly decomposed, so the composition in hydrochar made from 260 °C was mainly lignin, which required more energy to compress and fold (Kang et al., 2012). Similar result can be found in Wang et al.'s study, which showed that hydrochar pellets made from 250 °C consumed more than 20 J than that from 200 °C (Wang et al., 2017). As seen in Fig. 2d, the energy consumption for hydrochar from 260 °C (9.14–36.74 J) calculated from the integral area between the compression profile between x axis were higher than that from 180 °C (13.70–25.57 J) and 220 °C (11.76–25.10 J), except for the 260–100%, because the 180–100% and 220–100% could hardly pelletized due to the fact that they were easily broken when there was no WS added during HTC. With regard to the effect on the pelletization brought by the ratio of the feedstock blend, it can be observed that sample of 260–0% consumed about 36.74 J, suggesting that solo WS derived hydrochar produced from high temperature needed a very high energy from pelletization. However, the increasing ratio of FW was beneficial to the pelletization due to the reduction of the displacement to reach the maximum force. For FW blended with 75%, the energy consumption for hydrochar could decrease about 12 J for hydrochar from 180 °C and 220 °C, while this reduced about 17 J for hydrochar from 260 °C. This may be attribute to that the hydrochar contained stable protein and tar when FW was blended after HTC (Wang et al., 2018c). These components may play a lubrication role during the compression and reduced the friction with the wall of the pelletization device and finally decreased the energy consumption.

3.3. Mechanical strength and surface characteristics

The Ts value from different temperature and blend ratio are shown in Table 2. The surfaces of hydrochar pellets are illustrated in the

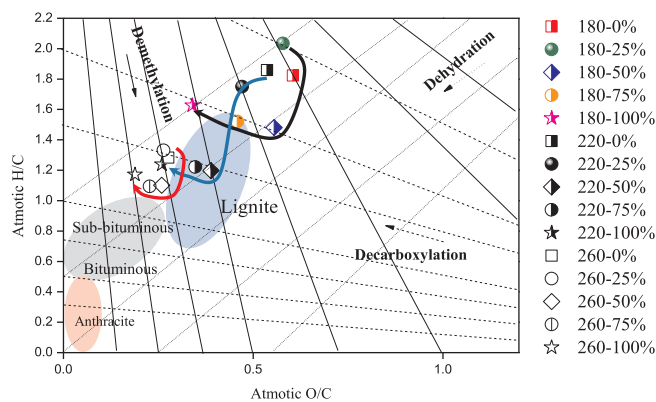


Fig. 1. Atomic ratio of hydrochar produced from different ratio of FW and temperature.

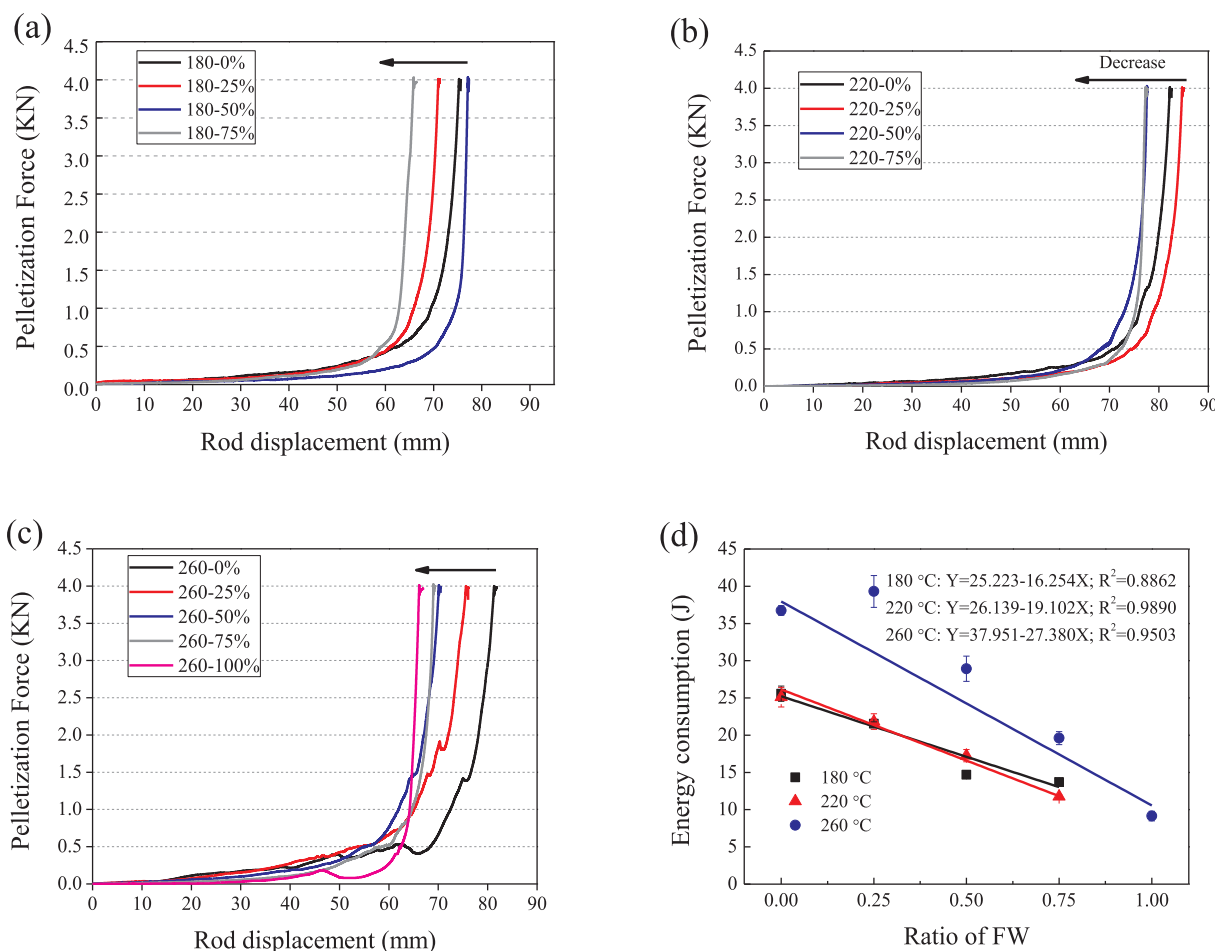


Fig. 2. Typical compression displacement of hydrochar pellets: (a) 180 °C; (b) 220 °C; (c) 260 °C; (d) energy consumption for hydrochar produced with different ratio of food waste at 200 °C, 220 °C, and 260 °C.

Table 2

Tensile strength, length expansion, mass and energy density, and EMC of hydrochar pellets.

Samples	Tensile strength (MPa)	Length expansion (%)	Mass density (Kg/m ³)	Energy density (MJ/Kg)	EMC (%)
180–0%	3.05	6.711	1136.62	22.13	6.52
180–25%	3.12	4.196	1212.91	25.52	5.37
180–50%	2.02	4.348	1255.02	23.93	4.55
180–75%	0.65	3.877	1215.30	26.54	3.57
220–0%	6.80	1.515	1348.68	28.96	4.27
220–25%	5.15	3.150	1379.56	31.44	4.04
220–50%	3.82	3.504	1330.11	29.94	3.04
220–75%	1.33	2.985	1319.59	31.49	2.76
260–0%	3.67	0.758	1358.82	37.31	3.27
260–25%	2.69	2.222	1319.15	36.87	2.84
260–50%	2.33	1.389	1328.84	35.63	2.75
260–75%	2.79	0.781	1364.95	37.92	2.08
260–100%	1.73	2.532	1195.57	35.62	1.99

images from SEM to determine inter-particle adhesion and mechanical properties. As shown in Table 2, the hydrochar pellets produced from 220 °C had generally higher Ts value (1.32–6.80 Mpa) than that of hydrochar pellets from 180 °C and 260 °C except for the sample of 220–75%. For hydrochar from solo WS derived hydrochar pellets, the Ts of 180–100% was 3.05 MPa, and the surface was coarser, and the length expansion reached 6.71% after one week, as shown in Table 2. This suggested that 180–100% easily developed resilience. Based on the SEM images of 180–100%, it can be observed that cross-linking

striations was formed on the surface, indicating the solid bridge and interlocking bonds were formed. As for hydrochar pellet of 220–0%, the solid bridge was more densified because the lignin was not decomposed, which resulted to a high Ts (6.80 MPa). However, for solo WS derived hydrochar pellets made from 260 °C, the Ts was approximately 3.67 MPa. It reported that there were mainly two ways of generating hydrochar during HTC of lignin, and one was the hydrochar formation from phenolic char derived from dissolving lignin and another was the polyaromatic hydrochar from non-dissolved lignin like a pyrolysis process (Kambo and Dutta, 2014; Kang et al., 2012). Although the hemicellulose and cellulose had been mostly decomposed with more lignin produced in the hydrochar, the lignin was “pseudo-lignin”, and the high “pseudo-lignin” content could not resulted in high Ts for the pellets. The hydrogen bonds between lignin and cellulose, and the covalent bonds between the cellulose fibers, were broken at 260 °C, so 260–0% contained more brittle lignin than 180–0% and 220–0%, which relied more on attraction forces between particles (Back, 1987; Wang et al., 2017). As shown in SEM images, many fractures were observed on the surface of 260–100%, which explained the low Ts (3.6 MPa) than that of 220–100%.

With FW addition during the HTC, the Ts of hydrochar pellets were decreased consistently, with the hydrochar pellets made from 220 °C having a drastic reduction of Ts. For example, the Ts of hydrochar pellets reduced about 5.5 MPa when the FW was added with ratio of 75%. Since the components of FW were mainly protein, carbohydrate like starch and glucose, and lipids, the limited lignocellulose content could not form solid bridge structure to enhance the mechanical strength (Wang et al., 2018c). It reported that the hydrochar from solo

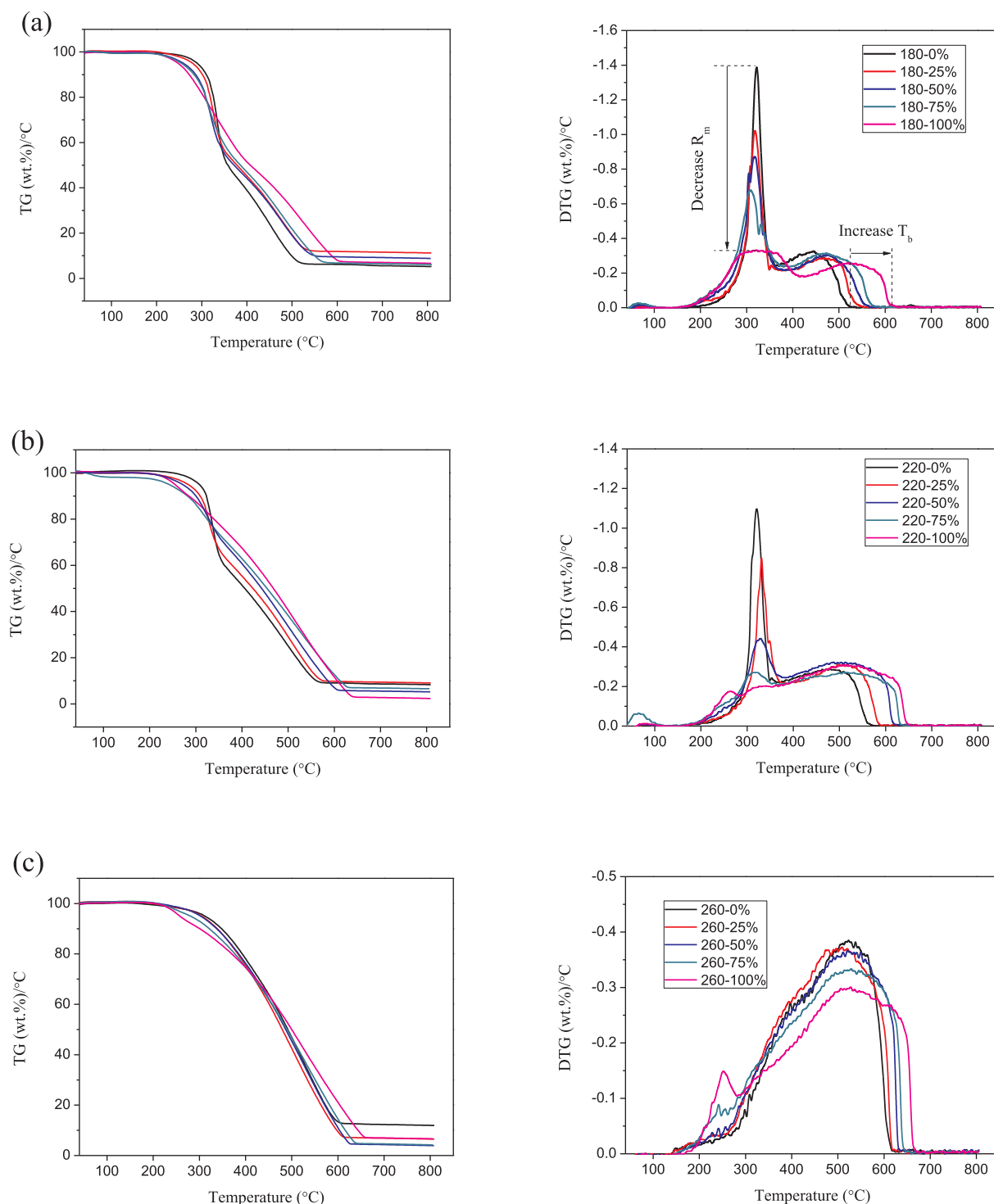


Fig. 3. TG and DTG profiles of hydrochar pellets produced from different temperature and blend ratio of FW and WS.

FW were mainly carbon-microspheres structure (Wang et al., 2018c). As shown in SEM images, carbon-microspheres structure were gather on the surface of the hydrochar pellet of 260–100%. This means that the mechanical strength of solo FW derived hydrochar pellets relied much on the attraction forces without a solid bridge between adjacent particles, which resulted in low T_s value and even could not produce pellet for hydrochar from 180 °C and 220 °C (Zhai et al., 2018). However, with the WS added HTC process, the T_s of the hydrochar pellets were increased because of the formation of solid bridge from lignocellulose. As shown in SEM images, an obvious structure, solid bridge capturing

microsphere- particles, was observed. The results indicated that the FW and WS blends derived hydrochar pellets used solid bridge structure to enhance and form strong attraction forces between adjacent particles, and this provided support for the improvement of T_s .

3.4. Mass density, energy density and EMC

The mass densities of the pellets are presented in Table 2. The hydrochar pellets prepared from high temperature (220 °C and 260 °C) had higher mass density, from 1319 to 1379 kg/m³, than that from

Table 3
Combustion characteristics parameters of hydrochar pellets.

Sample	T _i	T _m	T _b	R _m (%/°C)
180–0%	311.45	321.18	527.17	1.39
180–25%	298.29	319.23	546.64	1.02
180–50%	288.15	317.28	558.33	0.87
180–75%	274.99	307.54	575.85	0.68
180–100%	254.61	307.35	616.66	0.33
220–0%	313.91	321.18	566.11	1.10
220–25%	302.67	332.86	587.54	0.84
220–50%	279.38	327.02	616.66	0.45
220–75%	254.61	317.28	632.24	0.28
220–100%	308.53	525.31	651.71	0.31
260–0%	361.08	523.36	618.61	0.39
260–25%	348.53	507.78	622.50	0.37
260–50%	347.92	521.41	632.24	0.36
260–75%	339.14	527.25	645.87	0.33
260–100%	331.93	515.57	671.19	0.30

(1136.62–1255.02 kg/m³) except 260–100%, which had relatively lower mass densities (1195.57 kg/m³). This suggested that the hydrochar from higher temperature were easily compacted and produced hydrochar pellets with high mass density. However, since the hydrochar pellet of 260–100% produced with no WS addition during HTC, there had few lignocellulose or the solid bridge structure to support the pelletization and the mechanical strength was also low as confirmed by the Ts. As for the blend ratio, it can be found that the hydrochar pellets with FW ratio from 0% to 50% had increased mass density, which then decreased to 1215.30 kg/m³. But when the WS was used during HTC, the mass density of the pellets showed no significant changes for hydrochar pellets made from 220 °C and 260 °C, indicating that the effect from food blend ratio on the mass density of was decreased. A same tendency was also observed for the energy density of the hydrochar pellets, and the energy density for pellets from 260 °C ranged from approximately 35 MJ/Kg to 38 MJ/Kg, which means a smaller range of change.

The EMC of the pellets is closely related to the storage properties of solid fuel due to the facts that high EMC results in biodegrading, high transportation cost, and low calorific value (Hu et al., 2015; Reza et al., 2015). The EMC of the samples are shown in Table 2. EMC in the hydrochar pellets decreased with increase of FW ratio during HTC, and this was due to that the FW had a higher carbonization degree than that of WS, and the loss of hydrophilic functional groups were more serious (Hoekman et al., 2017; Reza et al., 2014). As for the effect from the temperature on the EMC, it can be clearly observed that the pellets from 260 °C had the lowest EMC content, from 1.99% to 3.27%. This was due to the dehydration at high temperature, which decreased the hydrophilic functional groups of the hydrochar (Liu et al., 2013).

3.5. Combustion characteristics

The combustion characteristics of hydrochar pellets produced with different blends ratio of FW and WS were evaluated. For comparison, samples including 180–100% and 220–100% were introduced and the TG and DTG profiles are illustrated in Fig. 3. The combustion parameters derived from the profiles were shown in Table 3 and the ignition temperature (T_i) was analyzed according to previous study (Chen et al., 2018; Wang et al., 2017). As shown in Fig. 3, there are two distinct peaks in the DTG curves for hydrochar pellets made from 180 °C and 220 °C, whereas one main continuous peak was observed for hydrochar pellet made from 260 °C. This difference was attributed to the compositions of the pellets, since hydrochar produced from low temperature had high VM content and the combustion for devolatilization dominated during combustion (He et al., 2013; Liu et al., 2014). Meanwhile, compared to hydrochar from 180 °C and 220 °C at the same blend ratio, the maximum weight loss rate (R_m) also showed sharply reduction for

hydrochar pellets from 260 °C, which ranged from 0.30 to 0.39. However, with increase of FW blend, the hydrochar pellets had generally decreased R_m regardless of the HTC temperature. For hydrochar pellets from 180 °C, the R_m decreased from 1.39%/°C to 0.33%/°C, and this tendency was weakened for hydrochar pellets from 260 °C (0.30–0.39%/°C), indicating that the combustion reactivity of hydrochar pellets became lower when FW ratio was increased during HTC (He et al., 2013). As shown in Fig. 3, the temperature at the maximum weight loss rate (T_m) for the hydrochar pellets also showed no significant change when varied the feedstock blend ratio, while it changed to higher temperature for hydrochar pellets prepared from higher HTC temperature. Especially, the T_m for hydrochar pellets from 260 °C increased approximately 200 °C excepted for 220–100% because of the sharply weakening of the first peak. Coincidentally, the burnout temperature (T_b) was increased with the increase of both HTC temperature and FW blend ratio. For example, T_b increased from 527.17 °C for 180–0% to 616.66 °C for 180–100%, and this value increased from 632.24 °C for 220–75% to 645.87 °C for 260–75%. The results suggested that an increase of FW ratio extend the combustion range and improved combustion efficiency can be expected (Zhao et al., 2013).

With regards to the ignition temperature (T_i), the hydrochar pellets produced from 260 °C were higher than that of 180 °C and 220 °C, and this was attributed to the reduction of VM at higher temperature during HTC. However, with the increase of FW blend ratio during HTC, the T_i of hydrochar pellets had lower ignition temperatures than those of hydrochar pellets made from high WS ratio during HTC except for 220–100%. For hydrochar pellets from 180 °C, the T_i decreased continuously from 311.45 °C to 254.61 °C when FW was blended from 0% to 100%. This phenomenon indicated that the hydrochar pellets could be burned more easily when FW was blended with WS during HTC. Nevertheless, these results were different from the general conclusion that solid fuels with high VM content had low ignition temperatures because the hydrochar produced with high FW had more FC content (Hu et al., 2015; Peng et al., 2016). From Fig. 3(a), it can be observed that the first peak moved to low temperature range, and there were small peaks in the range from 200 °C to 285 °C for hydrochar pellets made from 220 °C and 260 °C. Thus, easily combustible components in hydrochar pellets made from high FW ratio may be existed, which explained the decreased T_i. In general, hydrochar pellets produced with high FW ratio had generally reduced T_i, wider temperature ranges, and decreased T_m, suggesting that the hydrochar pellets from co-HTC of FW and WS were more suitable to combustion with higher thermal efficiency (Liu et al., 2014).

4. Conclusions

High FW blended ratio enhanced the carbonization degree during HTC by mainly decreasing H/C of hydrochar with ratio from 0% to 50%, while mainly decreased the O/C from 75% to 100%. Increasing ratio of FW decreased the energy consumption during pelletization, whereas the Ts of pellets were increased about 2.4–5.5 MPa when WS ratio was increased. Moreover, hydrochar pellets made from high ratio FW achieved low ignition temperature and increased temperature range. For practical applications, co-hydrothermal carbonization of food waste-woody biomass with FW ratio from 50% to 75% at 220 °C was more suitable for pelletization and producing solid biofuel.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.biortech.2018.07.059>.

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