

Effect of Wet and Dry Torrefaction Process on Fuel Properties of Solid Fuels Derived from Bamboo and Japanese Cedar

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Torrefaction is a promising pretreatment process to convert biomass into high energy density solid fuel for further thermal conversion systems. In this study, the effects of wet and dry torrefaction on the properties of solid fuels prepared from bamboo and Japanese cedar were investigated in a batch reactor. The yields of solid fuels decreased with increasing treatment temperature in both torrefaction processes, mainly due to the decomposition of cellulose and hemicellulose. Cellulose showed higher reactivity than hemicellulose in both biomasses. The higher heating values (HHV) of solid fuels prepared at the treatment temperatures higher than 240 °C in both torrefaction processes reached the same level as those of commercial coals. Wet torrefaction was better than dry torrefaction for decomposing bamboo and Japanese cedar. Dry torrefaction had more favorable impact than wet torrefaction on improving the fuel properties of bamboo and Japanese cedar because of its lower energy input, higher solid fuel yield, higher energy yield, and similar HHV under the same conditions. The crystalline structure of solid fuel had no great change below 260 °C in both torrefaction processes and was completely destroyed at 300 °C during dry torrefaction.

Keywords: Biomass; Dry torrefaction; Wet torrefaction; Solid fuel; Fuel properties

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INTRODUCTION

With the growing problems of energy deficiency and environmental pollution, production of clean and sustainable power from renewable resources, such as solar, hydro, wind, and biomass, has attracted intense interest in recent years. Of the renewable aforementioned resources, biomass, with an annual production of 146 billion tons, is a promising alternative to fossil fuel because a mere one-eighth of the biomass produced every year could supply the annual energy needs of humans (Asghari and Yoshida 2010). Furthermore, biomass has lower environmental impact than fossil fuel and is the only natural resource with the potential to produce liquid, gas, and solid fuels. However, the natural drawbacks of biomass such as high moisture content and low energy values have limited the direct utilization of biomass as bio-fuel (Wannapeera and Worasuwanarak 2012). Conversion of biomass to charcoal is one of the traditional methods to overcome these disadvantages. However, the resultant charcoal has lower energy yield (20% to 55%) compared with the raw biomass (Pentananunt *et al.* 1990). Torrefaction is a

thermochemical pretreatment process for biomass feedstocks that could efficiently address the limitations of charcoal-making processes (Ben and Ragauskas 2012).

Torrefaction can be classified as wet or dry. Wet torrefaction is conducted in subcritical water within the temperature range of 180 to 260 °C and pressure up to 700 psi, resulting in three products: gas, aqueous chemicals, and solid fuel (Sasaki *et al.* 2003; Yan *et al.* 2009; Yang *et al.* 2015). The product distribution is mainly dominated by the biomass species, treatment temperature, and time. On the other hand, dry torrefaction is conducted from 180 to 300 °C in an inert atmosphere with the treatment time of 0.25 to 8 h. The major final products are gas, bio-oil and 30% to 95% solid fuel by weight of biomass, which greatly depend on biomass species (Chew and Doshi 2011; Ben and Ragauskas 2012).

There are many reports on upgrading fuel properties of biomass by torrefaction (Donar *et al.* 2016; Zhang *et al.* 2016; Afolabi *et al.* 2017; Huang *et al.* 2017). For example, Bach *et al.* (2013) evaluated the effect of various conditions on the fuel properties of solid fuels derived from Norway spruce and birch through wet torrefaction. They found that the fuel properties of solid fuel including elemental content, higher heating value (HHV), and H/C and O/C atomic ratios were significantly affected by reaction temperature and time. They also concluded that wet torrefaction could produce solid fuel with greater HHV at lower temperature and shorter holding time by comparing with that of dry torrefaction. Yan *et al.* (2009) wet-torrefied loblolly pine and found that solid fuel with higher HHV and lower mass yield could be produced at higher treatment temperature. Wet torrefaction of various biomasses for solid fuel production has been studied previously (Yang *et al.* 2015, 2016). The fuel properties of prepared solid fuel are comparable to some commercial coals, and the reactivity of cellulose and hemicellulose is affected by the weight ratio of biomass components (*i.e.* cellulose, hemicellulose, and lignin). However, there have been few studies comparing the fuel properties of solid fuels prepared by different torrefaction processes in the same treatment conditions, as the treatment conditions and processes significantly affect the fuel properties of solid fuel. Furthermore, the decomposition behaviors of biomass components during dry torrefaction remain unclear.

In the present study, the effect of torrefaction processes on the fuel properties of solid fuels derived from two biomass species (bamboo and Japanese cedar) was investigated. The functional group, structural, and component changes of solid fuels were also characterized to elucidate the decomposition behaviors of biomass components.

EXPERIMENTAL

Materials

Bamboo and Japanese cedar, which are abundant biomass resources in Japan, were employed as raw materials. Both were pulverized by a milling machine (WB-1, Osaka Chemical Corporation, Osaka, Japan) and screened to segregate the particles with a diameter under 0.3 mm. The obtained particles were dried at 105 °C for 24 h.

Torrefaction of Bamboo and Japanese Cedar

Wet torrefaction was carried out in a SUS316 stainless steel batch reactor with the working volume of 10 mL. In a typical experiment, 300 mg of biomass sample combined with 7 mL of Mill-Q water was placed in the batch reactor, which was then tightly closed. The reactor was then charged into a ceramic furnace with a TP1000C digital temperature controller that was preheated to 500 °C. The temperature inside the reactor was monitored

by a thermocouple inserted into a tube installed in the middle of the reactor. When the temperature inside the reactor reached to a temperature near the desired temperature, the digital temperature controller was turned off and the temperature inside the reactor was regulated by the heat that remained in the furnace. It took 8.1, 9.3, 10.3, 11.4, and 12.6 min for the temperature inside the reactor to reach 180, 200, 220, 240, and 260 °C, respectively. The treatment time was calculated when the temperature inside the reactor reached the desired level. To stop the reaction, the reactor was immersed into an ice bath as soon as the specified treatment time elapsed. The mixture in the reactor was filtered by a G-4 glass filter. Subsequently, the solid fuel was washed with 50 mL acetone to remove the acetone-soluble substances on the solid fuel surface and then dried at 105 °C for 24 h.

Dry torrefaction was conducted in the same reactor as wet torrefaction. The reactor was purged by N₂ with the flow rate of 3 L/min before the experiment. A total of 300 mg of biomass sample was charged into the reactor, which was tightly closed, and the reactor was then placed in the ceramic furnace. It took 7.9, 9.1, 10.2, 11.1, 12.4, 13.7, and 15.2 min for the temperature inside the reactor to reach 180, 200, 220, 240, 260, 280, and 300 °C, respectively. The reactor was treated for 10 min at each temperature and then cooled by an ice bath. The solid fuel inside the reactor was then filtered, washed with 50 mL acetone, and dried at 105 °C for 24 h.

The solid fuels obtained from the above-mentioned torrefaction processes were defined as xx-WT-xxx or xx-DT-xxx, where “xx” was the abbreviated names of bamboo (BB) and Japanese cedar (JC), and “xxx” was the treatment temperature; WT and DT were the abbreviated names of wet and dry torrefaction, respectively.

Characterization of Solid Fuel

The cellulose, hemicellulose, and lignin contents of solid fuels were determined as described previously (Yang *et al.* 2017).

The element contents were analyzed by a PerkinElmer 2400II elemental analyzer (Kanagawa, Japan). The HHV was calculated by Eq. 1 (Friedl *et al.* 2005),

$$\text{HHV (MJ/kg)} = 5.22\text{C}^2 - 319\text{C} - 1647\text{H} + 38.6\text{CH} + 133\text{N} + 21028 \quad (1)$$

where C, H, N are the dry mass percentages of carbon, hydrogen, and nitrogen in as-prepared solid fuel, respectively. The energy yield was calculated from the HHV as well as solid mass yield by the following equation,

$$\text{Energy yield (\%)} = \text{HHV}_{\text{solid fuel}} / \text{HHV}_{\text{raw biomass}} \times \text{Solid fuel mass yield} \quad (2)$$

where $\text{HHV}_{\text{solid fuel}}$ and $\text{HHV}_{\text{raw biomass}}$ represent the HHVs of solid fuel and raw biomass, respectively.

The functional groups were characterized by Jasco 4100 Fourier transform infrared spectroscopy (FTIR; Jasco, Tokyo, Japan). The crystalline changes were examined using powder X-ray diffraction (XRD) with monochromated CuK α radiation, using a Rigaku Geiger flex RAD-C and RINT2000 diffractometers (Tokyo, Japan). The crystallinity index was calculated as follows (Yang *et al.* 2017),

$$\text{CI (\%)} = 100 \times (I_{200} - I_{\text{am}}) / I_{200} \quad (3)$$

where I_{200} and I_{am} represent intensities at $2\theta = 22.5^\circ$ (crystalline area) and 18.5° (amorphous area), respectively.

RESULTS AND DISCUSSION

Effect of Treatment Temperature on the Yield of Solid Fuel

Temperature is an important factor that reflects the thermal stability of biomass during torrefaction. This study investigated the effect of treatment temperature on yields of solid fuels derived from torrefaction of bamboo and Japanese cedar. As demonstrated in Fig. 1a, the yields of solid fuel derived from bamboo decreased with increasing treatment temperature in both torrefaction processes. The decrease rate of solid fuel yield in wet torrefaction was much faster than in dry torrefaction in the same conditions (*i.e.*, treatment temperature and time), indicating that wet torrefaction was better than dry torrefaction on decomposition of bamboo. The faster decrease rate of solid fuel yield in wet torrefaction was caused by the high ion product of subcritical water that accelerated the decomposition of biomass. Similar results were obtained during the torrefaction of Japanese cedar. The yield of solid fuel prepared by wet torrefaction decreased to 30.5% (a 69.5% decrease) at treatment temperature up to 260 °C, whereas it only decreased 43.7% at 300 °C during dry torrefaction (Fig. 1b).

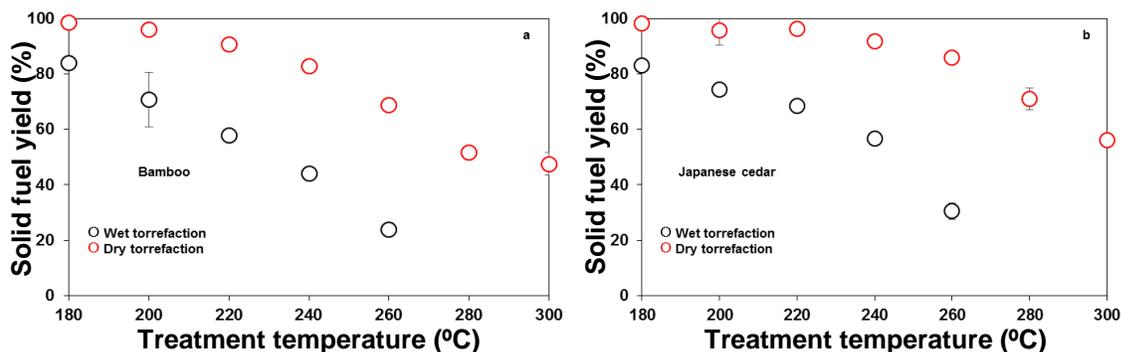


Fig. 1. Effect of treatment temperature on the yields of solid fuel derived from (a) bamboo and (b) Japanese cedar (n = 3)

Effect of Treatment Temperature on the Component Changes of Solid Fuel

To explore the causes of yield reduction in both torrefaction processes, the component changes of solid fuels obtained at all treatment temperatures were measured. As shown in Table 1, 144.1 ± 7.6 , 72.4 ± 7.6 , and 83.5 ± 2.6 mg of cellulose, hemicellulose, and lignin, respectively, were presented in 300 mg of raw bamboo. The weights of all components in solid fuel decreased with elevated treatment temperature during wet torrefaction. The weights of cellulose, hemicellulose, and lignin dropped to 5.9 ± 1.5 (a 95.9% decrease), 34.4 ± 1.5 (a 53.2% decrease), and 29.5 ± 7.6 mg (a 64.7% decrease), respectively, at treatment temperature up to 260 °C. The weights of cellulose and hemicellulose in solid fuel also decreased from 144.1 ± 7.6 to 18.6 ± 4.9 mg and 72.4 ± 7.6 to 41.6 ± 4.9 mg—decreases of 87.1% and 41.2%, respectively—when the treatment temperature rose to 260 °C during dry torrefaction. Both were completely decomposed as the treatment temperature further increased. In contrast, the weight of lignin decreased at treatment temperatures lower than 200 °C, and then increased as the treatment temperature rose to 280 °C. However, the weight of lignin further reduced as the treatment temperature increased to 300 °C. Similar results were also observed for Japanese cedar. The weights of cellulose, hemicellulose, and lignin in 300 mg of Japanese cedar were 120.4 ± 6.4 , 95.9 ± 6.4 , and 93.7 ± 1.3 mg, respectively.

Both cellulose and hemicellulose were decomposed with increasing treatment temperature, and their weights decreased to 13.5 ± 3.8 (a decrease of 88.8%) and 24.0 ± 3.8 mg (a decrease of 75.0%), respectively, as the treatment temperature increased to 260 °C during wet torrefaction. The weight of lignin dropped to 61.0 ± 1.3 mg (34.9% decrease) at the same time. The weights of cellulose and hemicellulose also decomposed with increasing treatment temperature during dry torrefaction, and both were completely decomposed at 300 °C. In contrast, the weight of lignin decreased at treatment temperatures lower than 200 °C but increased at higher treatment temperatures. The cellulose showed higher reactivity than hemicellulose during torrefaction of bamboo and Japanese cedar. In previous reports, hemicellulose was much more reactive than cellulose, and nearly all the hemicellulose was decomposed after the 200 °C treatment in subcritical water (Mok and Antal 1992; Lyman *et al.* 2011). The higher reactivity of cellulose might result from the interactions among biomass components (Hosaya *et al.* 2007; Fushima *et al.* 2009), although the detailed reasons remain unclear. This will be investigated in our future research. The increased lignin content during dry torrefaction was due to the generation of aromatic-linked polymer char derived from the decomposition products of cellulose and hemicellulose (Shafizadeh 1975; Boon *et al.* 1994). Aromatic-linked polymer char is formed at treatment temperatures higher than 270 °C during subcritical water treatment of cellulose (Fang *et al.* 2004). However, increased lignin content in bamboo and Japanese cedar during wet torrefaction was not observed, because of the low treatment temperature.

Table 1. Component Changes of Solid Fuels

Solid fuel	Cellulose mg	Hemi-cellulose mg	Lignin mg	Solid fuel	Cellulose mg	Hemi-cellulose mg	Lignin mg
Bamboo	144.1±7.6	72.4±7.6	83.5±2.6	Japanese cedar	120.4±6.4	95.9±6.4	93.7±1.3
BB-WT-180	127.4±2.4	56.6±2.4	67.4±0.5	JC-WT-180	115.4±0.5	62.0±0.5	81.7±0.7
BB-WT-200	102.1±1.1	46.1±1.1	55.1±1.3	JC-WT-200	110.5±4.0	35.5±4.0	78.2±3.7
BB-WT-220	81.3±4.5	40.9±4.5	40.8±1.4	JC-WT-220	98.8±4.3	33.1±4.3	77.4±7.2
BB-WT-240	61.5±3.4	37.2±3.4	40.2±1.2	JC-WT-240	77.1±2.3	27.5±2.3	61.4±0.2
BB-WT-260	5.9±1.5	34.4±1.5	29.5±3.7	JC-WT-260	13.5±3.8	24.0±3.8	61.0±1.3
BB-DT-180	123.0±9.0	71.4±9.0	90.8±9.1	JC-DT-180	107.2±2.9	96.1±2.9	92.8±4.1
BB-DT-200	91.3±2.7	69.4±2.7	87.5±0.4	JC-DT-200	103.9±0.5	91.9±0.5	87.4±1.9
BB-DT-220	70.4±2.8	48.5±2.8	89.4±0.5	JC-DT-220	91.3±4.3	87.6±4.3	96.4±4.9
BB-DT-240	67.7±12.4	45.1±12.4	112.9±3.1	JC-DT-240	80.2±3.1	86.3±3.1	108.3±1.4
BB-DT-260	18.6±4.9	41.6±4.9	136.2±2.6	JC-DT-260	72.2±4.6	61.4±4.6	125.2±1.5
BB-DT-280	0	0	140.4±0.6	JC-DT-280	14.2±2.5	51.8±2.5	134.8±3.4
BB-DT-300	0	0	119.8±3.4	JC-DT-300	0	0	165.0±1.6

The values after ± show the standard deviations, n=3

Fuel Properties of Solid Fuel

Elemental content plays a significant role in the fuel property changes of biomass before and after torrefaction. Generally, solid fuel with high carbon content and low oxygen content has good fuel properties. The elemental contents of biomass and solid fuel are listed in Table 2. As expected, the carbon contents of solid fuels derived from bamboo and Japanese cedar increased with elevating treatment temperature in both torrefaction processes, whereas the oxygen contents were reduced at higher treatment temperatures. The hydrogen and nitrogen contents of solid fuels had no distinct change compared with raw biomass. The element contents of some resultant solid fuels (*i.e.*, BB-WT-260, BB-DT-260, BB-DT-280, JC-WT-260, JC-DT-300) reached to the similar level to those of lignite whose carbon, hydrogen, and oxygen contents were 61.6%, 5.7%, and 30.1%, respectively (Liu *et al.* 2013). Additionally, dry torrefaction had effectiveness similar to wet torrefaction on elevating the carbon contents of bamboo and Japanese cedar in similar treatment conditions.

Table 2. The Element Contents, HHVs, and Energy Yields of Bamboo, Japanese Cedar, and their Derived Solid Chars

Solid char	C (wt%)	H (wt%)	N (wt%)	O ^a (wt%)	HHV (kJ/mol)	Energy yield (%)
Bamboo	47.9	6.1	0.4	45.6	19.0	-
BB-WT-180	48.2	6.1	0.3	45.4	19.1	84.3
BB-WT-200	48.7	6.1	0.3	44.9	19.4	72.3
BB-WT-220	49.3	6.0	0.3	44.4	19.6	59.5
BB-WT-240	51.9	6.0	0.4	41.7	20.7	47.9
BB-WT-260	53.3	5.8	0.4	40.5	21.3	26.6
BB-DT-180	48.1	6.0	0.4	45.5	19.1	98.9
BB-DT-200	48.9	6.0	0.4	44.7	19.4	97.9
BB-DT-220	50.5	6.0	0.4	43.1	20.1	95.7
BB-DT-240	53.5	5.9	0.4	40.2	21.4	93.3
BB-DT-260	59.4	5.6	0.5	34.5	24.2	87.5
BB-DT-280	69.1	5.3	0.5	25.1	29.4	79.9
BB-DT-300	70.6	5.0	0.6	23.8	30.0	75.0
Japanese cedar	48.3	6.3	0	45.4	19.2	-
JC-WT-180	48.6	6.2	0	45.2	19.3	83.6
JC-WT-200	49.5	6.1	0	44.4	19.6	76.1
JC-WT-220	49.9	6.0	0	44.1	19.8	70.7
JC-WT-240	50.6	6.0	0	43.4	20.1	59.5
JC-WT-260	57.3	5.5	0.1	37.1	23	36.7
JC-DT-180	48.4	6.1	0.1	45.4	19.2	98.4
JC-DT-200	49.1	6.0	0	44.9	19.4	97.2
JC-DT-220	49.6	6.0	0	44.4	19.7	98.8
JC-DT-240	51.9	5.9	0.1	42.1	20.6	98.9
JC-DT-260	53.2	5.7	0.1	41.0	21.2	94.8
JC-DT-280	62.5	5.3	0.1	32.1	25.6	94.7
JC-DT-300	70.5	5.0	0.1	24.4	29.9	87.7

a: calculated by difference

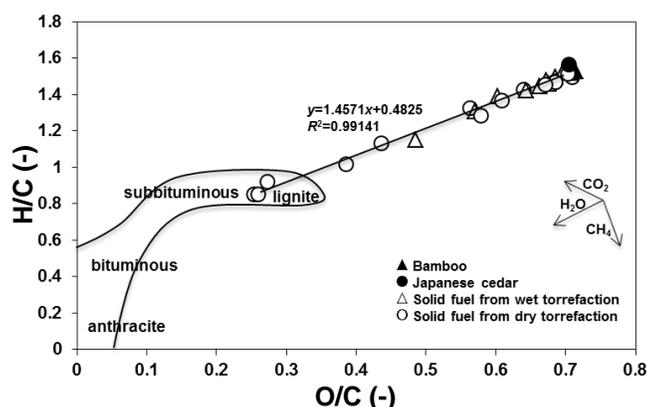


Fig. 2. Van Krevelen diagram of bamboo, Japanese cedar, solid fuels, and coal band (Line was drawn by linear fitting of the experimental data)

To evaluate the fuel grade of prepared solid fuel and main reactions that occurred during torrefaction of biomass, the H/C vs. O/C values of bamboo, Japanese cedar, and solid fuels, as well as coal band were plotted on a van Krevelen diagram, which is depicted in Fig. 2. The atomic H/C and O/C ratios of raw bamboo and raw Japanese cedar were 1.53 and 0.71, and 1.57 and 0.7, respectively. The atomic H/C and O/C ratios of solid fuels were lower than those of raw biomasses in both torrefaction processes, and they decreased with increasing treatment temperature. The atomic H/C and O/C ratios of solid fuel prepared at 260 °C by wet torrefaction reached the same level to those of peat with the H/C and O/C values of 0.64 and 1.36, respectively (Hirai *et al.* 1990). In contrast, the H/C and O/C values of solid fuel prepared by dry torrefaction moved towards those of lignite that had better fuel properties than peat, due to the higher treatment temperature. Generally, solid fuel with lower atomic H/C and O/C ratios meant less energy loss, less water vapor, and smoke generation during combustion. It also meant lower impacts of flame characteristic during co-combustion with commercial coal (Lu *et al.* 2008). Therefore, the fuel properties of biomass could be remarkably improved through torrefaction. A variety of reactions, such as decarbonization, dehydration, and demethanation, occurred during torrefaction, which responded to the decreases of atomic H/C and O/C ratios. The atomic H/C and O/C ratios of all solid fuels moved along with dehydration reaction line and exhibited a strong linear ($y = 1.4571x + 0.4825$, $R^2 = 0.99141$; where y and x are the atomic H/C and O/C ratios of solid fuel, respectively), indicating that the decreases of atomic H/C and O/C ratios were mainly due to the dehydration reaction.

The HHV—*i.e.*, the amount of heat released from a specified amount of fossil fuel during combustion—is a crucial index to evaluate the performance of torrefaction. Therefore, the HHVs of as-prepared solid fuels were calculated based on their element contents. Torrefaction had a noticeable effect on the HHVs of solid fuel. As shown in Table 2, the HHV of solid fuel derived from bamboo increased with increasing treatment temperature during wet torrefaction. It reached 21.3 MJ/kg (12% increase) when the treatment temperature rose to 260 °C, compared with that of the raw bamboo (19 MJ/kg). At the same time, the energy yield decreased from 84.3% to 26.6% as the treatment temperature increased from 180 to 260 °C. The HHV of BB-WT-260 was higher than that of hydrochar (20.3 MJ/kg) derived from bamboo waste prepared at the same conditions (Yang *et al.* 2016); however, the elevation was much lower, probably due to the difference in bamboo component ratios. The HHV of solid fuel also increased during dry torrefaction

of bamboo, reaching 30 MJ/kg (57.9% increase) as the treatment temperature reached 300 °C. Additionally, the energy yield decreased during dry torrefaction of bamboo; however, it only showed a decrease of 25%, even the treatment temperature increased to 300 °C. The increases of HHVs in both torrefaction processes were due to the decrease of low-energy chemical bonds, release of volatiles, and increase of high-energy bonds through decarbonization, dehydration, and demethanation reactions, as suggested in Fig. 2 (Liu *et al.* 2013; Brachi *et al.* 2016). Similar results were observed during torrefaction of Japanese cedar. The HHVs of solid fuels derived from both torrefaction processes increased with increasing treatment temperature, whereas the energy yields decreased at higher treatment temperatures. The energy yield in dry torrefaction displayed a slower decrease rate than that in wet torrefaction at the same conditions. The energy yield of JC- DT-300 was even 2.4 times higher than that of JC-WT-260, indicating the higher energy recovery of dry torrefaction. The HHVs of some solid fuels could be comparable with those of commercial fuels. For example, the HHVs of BB-DT-260, JC-WT-260, and JC-DT-280 reached to the similar level to those of Northumberland No. 81/2 Sem. Anth. Coal and Jnanjra Bonbahal Seam Coal–R–VII with the HHVs of 24.73 and 24.1 MJ/kg, respectively. The HHVs of BB-DT-280, BB-DT-300 and JC-DT-300 were much higher than those of above commercial coals and could even be comparable with those of Anthracite coal (31.84 MJ/kg) and Northumberland No. 8–Anth. Coal (32.86 MJ/kg) (Channiwala and Parikh 2002).

These results suggested that the fuel properties of bamboo and Japanese cedar were significantly enhanced through both torrefaction processes. Dry torrefaction was better than wet torrefaction in improving fuel properties of bamboo and Japanese cedar in view of its lower energy input, higher solid fuel yield, higher energy yield, and similar HHV at the same conditions.

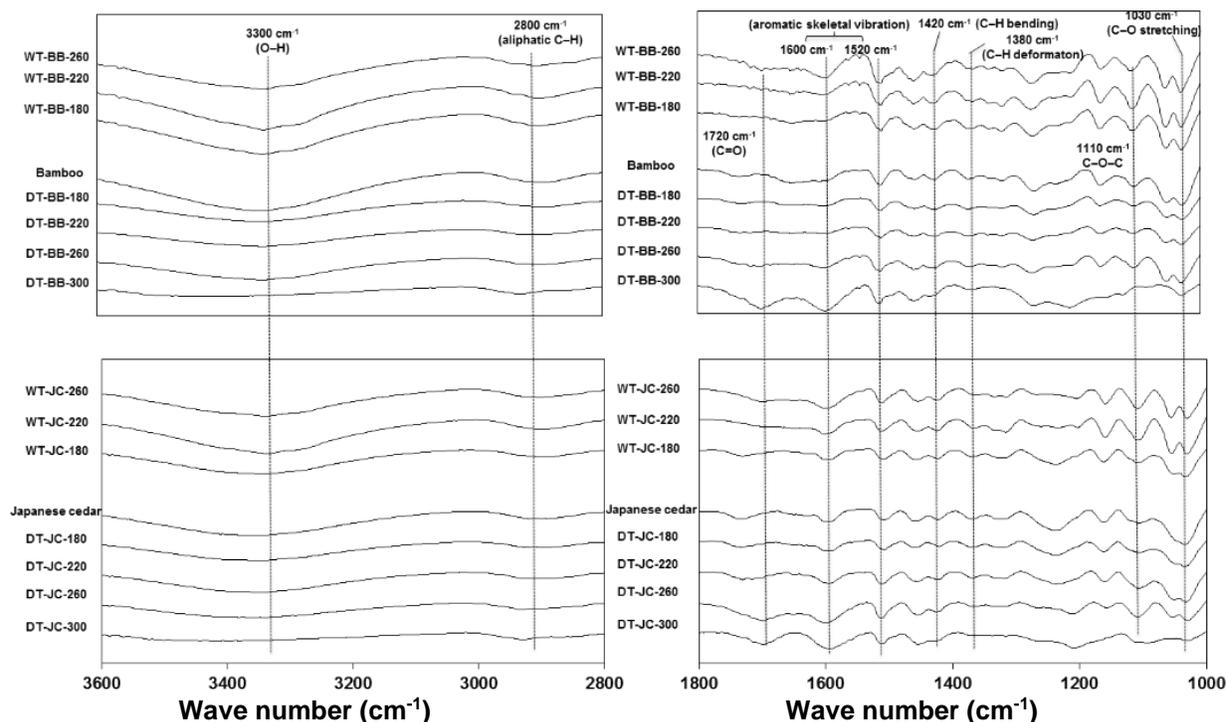


Fig. 3. FTIR spectra of bamboo, Japanese cedar, and their derived solid fuels

FTIR Spectra and XRD Patterns of Solid Fuel

Demethanation, dehydration, and decarbonization occurred in both torrefaction processes, resulting in changes in the crystalline structure and functional groups in solid fuel. Therefore, FTIR spectra and XRD patterns were recorded to illuminate the functional group and crystalline evolution of solid fuel. As presented in Fig. 3, the O–H stretching vibration around 3300 cm^{-1} became weaker with increasing treatment temperature, and completely disappeared at $300\text{ }^{\circ}\text{C}$ during the dry torrefaction of bamboo and Japanese cedar. The loss of O–H groups was mainly due to dehydration reactions, as shown in van Krevelen diagram of Fig. 2. The disappearance of O–H groups at $300\text{ }^{\circ}\text{C}$ was mainly caused by the complete decomposition of cellulose and hemicellulose that are rich in O–H group (Table 1). The peak of 2800 cm^{-1} that was assigned to aliphatic C–H showed a similar trend. In contrast, the peak strength of 1720 cm^{-1} that was attributed to C=O stretching became stronger at higher treatment temperatures in both torrefaction processes due to the dehydration of hydroxyl groups in hemicellulose and cellulose. The peaks of 1380 cm^{-1} and 1100 cm^{-1} that attributed to the C–H deformation and ether-bond (C–O–C) of cellulose and hemicellulose, respectively, presented at treatment temperatures lower than $260\text{ }^{\circ}\text{C}$. However, these two peaks nearly disappeared at $300\text{ }^{\circ}\text{C}$, indicating the complete decomposition of cellulose and hemicellulose, which was also suggested in Table 1. Similar results were observed in the peak of 1030 cm^{-1} , which was assigned to C–O stretching. The lignin characteristic peaks of 1420 cm^{-1} (C–H bending in lignin), 1600 and 1520 cm^{-1} (aromatic skeletal vibration) occurred in all treatment temperatures in both torrefaction processes, indicating a highly stable lignin structure.

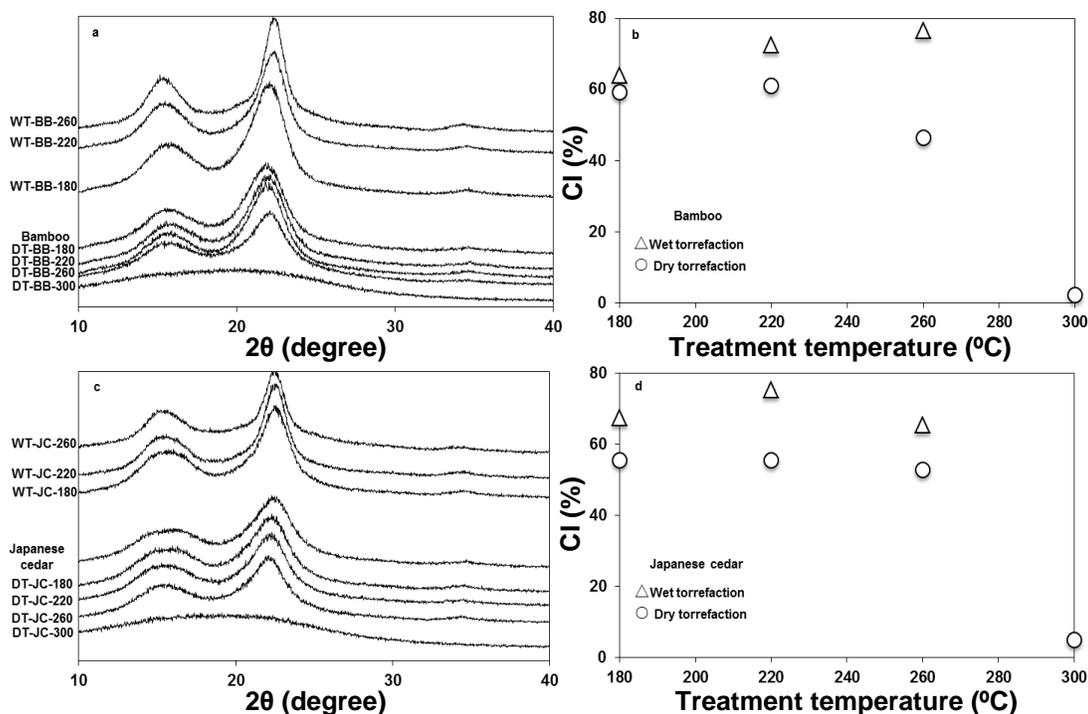


Fig. 4. XRD patterns and crystalline index of bamboo, Japanese cedar, and their derived solid fuels.

The XRD patterns and CI of bamboo, Japanese cedar, and their derived solid fuels are shown in Fig. 4. The crystalline peaks of solid fuel derived from bamboo indicated no obvious change at the treatment temperature ranged from 180 to 260 °C during wet

torrefaction, although 76.2% of bamboo was decomposed at 260 °C (Fig. 1a). In contrast, the CI of solid fuel increased with increasing treatment temperature. The crystalline peaks of solid fuel also had no great change at treatment temperatures of 180 to 260 °C during dry torrefaction of bamboo. However, they disappeared as the treatment temperature reached 300 °C. The increase in CI was due to the decomposition of amorphous structures in cellulose and hemicellulose during torrefaction, while the decrease in CI was caused by the destruction of crystalline structure. Similar results were found during the torrefaction of Japanese cedar. The crystalline peak of solid fuel had no significant change at the treatment temperatures below 260 °C in both torrefaction processes, and it disappeared when the treatment temperature increased to 300 °C during dry torrefaction. The CI of solid fuel first showed a slight increase at the treatment temperatures below 220 °C and then a decrease at higher treatment temperatures during wet torrefaction. The CI of solid fuel had no great change at the treatment temperature below 260 °C during dry torrefaction, but it showed a dramatic decrease at higher temperatures, due to the complete decomposition of cellulose and hemicellulose at these treatment temperatures.

CONCLUSIONS

1. The yields of solid fuels decreased with increasing treatment temperature in both torrefaction processes, reflecting the decomposition of cellulose and hemicellulose. Cellulose was much more reactive than hemicellulose in both bamboo and Japanese cedar during torrefaction, probably due to the interactions among biomass components. Aromatic-linked chars derived from the decomposition products of cellulose and/or hemicellulose were generated during dry torrefaction, which increased the weight of lignin in solid fuel.
2. The fuel properties of bamboo and Japanese cedar were elevated after wet and dry torrefaction, and the HHVs of some prepared solid fuels were comparable to those of commercial coal. Dry torrefaction was better than wet torrefaction to improve the fuel properties of solid fuels.
3. The crystalline structure of solid fuels had no great change at 260 °C in both torrefaction processes, although a majority of bamboo and Japanese cedar were decomposed at 260 °C. Moreover, the crystalline structure of solid fuel was almost utterly destroyed at 300 °C during dry torrefaction.

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