**Fast microwave-assisted catalytic co-pyrolysis of corn stover and scum
for bio-oil production with CaO and HZSM-5 as the catalyst**

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ABSTRACT

This study investigated fast microwave-assisted catalytic co-pyrolysis of corn stover and scum for bio-oil production with CaO and HZSM-5 as the catalyst. Effects of reaction temperature, CaO/HZSM-5 ratio, and corn stover/scum ratio on co-pyrolysis product fractional yields and selectivity were investigated. Results showed that co-pyrolysis temperature was selected as 550 °C, which provides the maximum bio-oil and aromatic yields. Mixed CaO and HZSM-5 catalyst with the weight ratio of 1:4 increased the aromatic yield to 35.77 wt.% of feedstock, which was 17% higher than that with HZSM-5 alone. Scum as the hydrogen donor, had a significant synergistic effect with corn stover to promote the production of bio-oil and aromatic hydrocarbons when the H/C_{eff} value exceeded 1. The maximum yield of aromatic hydrocarbons (29.3 wt.%) were obtained when the optimal corn stover to scum ratio was 1:2.

Keywords:

Scum

Catalytic co-pyrolysis

Microwave-assisted system

CaO catalyst

Zeolite

1. Introduction

Fast pyrolysis is a promising technology, which converts the lignocellulosic biomass to liquid valuable fuels such as bio-oil. This technology has been extensively studied in

the past decades. As an alternative to conventional fuels, bio-oil still has limited use as a fuel due to its high water content, high viscosity, high oxygen content, chemical instability and corrosiveness (Bridgwater, 2012; Dickerson & Soria, 2013; Mohan et al., 2006). Some of these issues were addressed by using high heating rate in pyrolysis process (fast pyrolysis). One of the fast pyrolysis processes is fast microwave-assisted pyrolysis (fMAP) in which the biomass can be instantaneously heated to the desired temperature. Fast microwave-assisted catalytic pyrolysis technology has already been successfully used in bio-oil production (Borges et al., 2014; Xie et al., 2014). Microwave assisted heating has many advantages over other heating methods, including uniform internal heating for materials particles, ease of operation and maintenance, energy saving and cleaner products because there is no vigorous agitation and carrier gas.

In addition to increasing heating rate to facilitate fast pyrolysis, an increasing number of methods have been investigated and developed for upgrading bio-oil to higher quality and stability. Catalytic fast pyrolysis technology is one of the most prevailing methods for in-situ bio-oil upgrading. Of the hundreds of catalysts that have been tested and analyzed, HZSM-5 zeolite was found to be the most effective due to its deoxygenating capacity and shape-selectivity for aromatics (Czernik & Bridgwater, 2004). However, HZSM-5 can cause formation of coke due to the polymerization of large oxygenates on the surface of the catalyst resulting in its deactivation (Carlson et al., 2010; Vitolo et al., 2001). On the other hand, CaO is a catalyst used for cracking heavy compounds into several light oxygenated compounds (Lu et al., 2010b; Veses et al., 2014), which can in turn be converted to aromatics on HZSM-5 catalyst. Thus,

combining CaO and HZSM-5 is a potential way to improve the quality of bio-oil by reducing coke formation during pyrolysis.

Furthermore, to improve the quality of the bio-oil, co-pyrolysis of biomass and materials containing higher hydrogen contents can be considered. Zhang et al. (2015b) conducted catalytic pyrolysis of black-liquor by co-feeding with polystyrene in a fluidized bed reactor and obtained the maximum aromatic yield of 55.3%. In addition, previous studies by Martinez et al. (2014) and Cao et al. (2009) showed that co-pyrolysis of biomass and waste tires could increase the bio-oil yield and quality. In the present study, scum from municipal wastewater treatment plant was used as a hydrogen donor in the co-pyrolysis of corn stover and scum. Scum is the floatable solids skimmed off from the surface of the sedimentation process in wastewater treatment plants, and contains fats, oil, grease, and plastics (Spellman, 2014) which are high in hydrocarbons. Therefore, scum can serve as an excellent hydrogen donor in pyrolysis of lignocellulosics. Utilization of scum in co-pyrolysis is a potential solution to current scum disposal methods which are faced with many economic and environmental challenges (Anderson et al., 2015; Bi et al., 2015).

In this study, co-pyrolysis of corn stover and scum with CaO and HZSM-5 as the catalysts was investigated. The synergistic effect of scum and corn stover on bio-oil yield and selectivity was evaluated. The effects of temperature, CaO/HZSM-5 ratio, corn stover/scum ratio on the product fractional yields and chemical and physical properties were analyzed.

2. Methods

2.1 Materials

The feedstocks used were corn stover and scum. Corn stover (provided by Agricultural Utilization Research Institute, Waseca, Minnesota, USA) was air dried and mechanically pulverized and sieved to less than 2 mm. Scum was obtained from the Metropolitan Wastewater Treatment Plant, Saint Paul, Minnesota, USA. Prior to use, the solid scum samples were melted in water bath at 70 °C for 4 h and filtered through a 100-micron polyester mesh filter bag to remove large solid particles. The elemental compositions of corn stover and scum are listed in Table 1. The elemental analysis was performed with elemental analyzer (CE-440, Exeter Analytical Inc., MA).

2.2 Catalyst

CaO was purchased from Sigma-Aldrich Corporation. Ammonium form ZSM-5 (Si/Al=80, Surface Area= 425m²/g) was obtained from Zeolyst International (Conshohocken, PA, USA). Prior to use, the ZSM-5 was activated to its hydrogen form HZSM-5 in a muffle furnace at 500 °C in air for 5 h.

2.3 Experimental procedure

The schematic diagram of microwave-assisted catalytic co-pyrolysis system is shown in Fig. 1. Microwave oven (MAX, CEM Corporation) was used with a constant power input of 750W at a frequency of 2,450 MHz. The system has been described elsewhere (Xie et al., 2014). In this study, experiments were carried out in three sections.

The aim of the first section was to determine the effect of reaction temperature on co-pyrolysis product fractional yields and selectivity. Co-pyrolysis was conducted at temperatures of 450 °C, 500 °C, 550 °C, 600 °C and 650 °C, respectively. After the optimal temperature was determined, the effects of CaO to HZSM-5 ratio and corn stover to scum ratio on product fractional yields and selectivity were studied at the optimal temperature in section 2 and 3, respectively. A blank pyrolysis test without using CaO/HZSM-5 was conducted. Prior to the pyrolysis, the system was vacuumed at 100 mmHg for 15 min to eliminate the influence of air. The vacuum was maintained during the entire experiment.

For a typical run, 500 g SiC particles (30 grit) were used as the microwave adsorbent. SiC was used due to its unique absorptive capacity of the microwave. Because of the thermal conduction from heated SiC particles, the desired temperature was reached instantaneously. The sample was prepared by physically mixing corn stover, scum and catalyst according to a certain ratio. The ratio of biomass (corn stover + scum) to catalyst (CaO + HZSM-5) was constant at 1:1, with the total weight of 30 g for each run. When the temperature reached the set point, the well-mixed sample was introduced onto the heated SiC in the microwave reactor. The microwave oven was turned on or off manually to maintain a stable temperature of the SiC bed. When the pyrolysis vapor traveled to the condensers, the condensable volatiles were converted to liquid form and collected as bio-oil fraction. The solid residue was cooled to room temperature and collected after each experiment as biochar fraction. The char and SiC can be separated easily using the sieve because of different particle sizes. The weight of char can be calculated by weight difference of quartz reactor with and without char. The bio-oil and biochar yields were

calculated using their actual weight, while the gas fraction yield was calculated by difference based on the mass balance. For safety purpose, a microwave detector (MD-2000, Digital Readout) was used to monitor microwave leakage. The experiments were repeated twice.

2.4 Pyrolysis products characterization

Chemical composition of bio-oil was analyzed using Agilent 7890-5975C gas chromatography/mass spectrometer (GC/MS). The column used was a HP-5 MS at 30 m x 0.32 mm and 0.25 μ m thickness. The oven temperature was programmed to be held at 50 $^{\circ}$ C for 2 min and then increased to 260 $^{\circ}$ C at a rate of 5 $^{\circ}$ C/ min, and held at 260 $^{\circ}$ C for 5 min. The injector temperature was 290 $^{\circ}$ C, and the injector size was 1 μ L with a split ratio of 1:10. Helium was used as the carrier gas at a flow rate of 1.2 mL/min. The compounds were identified by comparing their mass spectra with those from the National Institute of Standards and Technology (NIST) mass spectral data library. Calibration was not carried out due to the large number of compounds in the pyrolysis bio-oil. A semi-quantitative method was used to determine the relative proportion of each compound in the bio-oil by calculating the chromatographic area percentage. The volatile compounds that were detected by GC-MS were the main components of the bio-oil.

2.5 Evaluation method

In our work, the overall yields of different chemical groups were analyzed and discussed. The overall yield of relative content was defined and calculated as follows:

$$Y_E = Y_{\text{Bio-oil}} \times Y_{\text{chemical group}} \quad (1)$$

where Y_E is the overall yield of different chemical groups (experimental value); $Y_{\text{Bio-oil}}$ is the bio-oil yield; $Y_{\text{chemical group}}$ is the proportions of different chemical groups in the bio-oil.

3. Results and discussion

3.1 Effect of reaction temperature on co-pyrolysis product fractional yields and selectivity

Fig. 2 shows the effect of reaction temperature on co-pyrolysis product fractional yields and selectivity. Constant ratio of corn stover: scum: CaO: HZSM-5= 1:1:1:1 was used in this experiment. Fig. 2(a) shows that reaction temperature had a great influence on the product fractional yields at different temperatures ranging from 450 °C to 650 °C. The bio-oil yield increased from 17.4 wt.% at 450 °C to 29.22 wt.% at 550°C and then slightly decreased to 24.72 wt.% at 650 °C, and the maximum bio-oil yield was obtained at 550 °C. Therefore, 550 °C was considered as the optimum temperature. The devolatilization reactions are favored by increasing temperature (Ioannidou et al., 2009), which is the main reason for the increase in the bio-oil yield at lower temperatures. However, the decrease in bio-oil yield when the temperature was higher than 550 °C was due to the secondary thermal cracking reaction of the volatile compounds (Xie et al., 2014). When temperature was too high, the pyrolysis vapor was converted to lower molecular weight organic products with lower molecular weight or other **non-condensable** gases. It was also the main cause for the significant increase in the gas yield from 11.46 wt.% (450 °C) to 48.02 wt.% (600 °C). In addition, the biochar yield decreased from 71.14 wt.% (450 °C) to 25.87 wt.% (600 °C).

In addition to the bio-oil yield, the composition of the bio-oil was also investigated at the temperatures ranging from 450 °C to 650 °C. The major components of bio-oil could be classified into several groups as aliphatic hydrocarbons, aromatic hydrocarbons, oxygen-cont. aliphatic compounds, oxygen-cont. aromatic compounds, nitrogen-cont. compounds and polycyclic aromatic hydrocarbons (PAHs). It can be seen from Fig. 2(b) that the maximum yield of aromatics (aromatic hydrocarbons and PAHs) was 83.68 wt.% at the temperature of 550 °C. It is noted that there were almost no aliphatic hydrocarbons, aromatic hydrocarbons, or polycyclic aromatic hydrocarbons at 450 °C and 650 °C. The proportions of aliphatic hydrocarbons decreased from 6.64 wt.% (500 °C) to 1.45 wt.% (650 °C). As can be seen from Fig. 2(b), the relative contents of oxygen-cont. aliphatic compounds, oxygen-cont. aromatic compounds and nitrogen-cont. compounds first decreased to the minimum values of 5.95 wt.% (500 °C), 2.52 wt.% (550 °C), 1.24 wt.% (500 °C), respectively, and then increased with the increasing temperature. In the contrary, the proportion of polycyclic aromatic hydrocarbons (mainly naphthalene) decreased from 33.53 wt.% (500 °C) to 25.48 wt. % (600 °C), and there were almost no polycyclic aromatic hydrocarbons at 450 °C or 650 °C. The polymerization reaction could lead to formation of aromatic compounds, many of which contained oxygen. This is the reason why there is a pretty high yield of oxygenates. Carlson et al. (2009) indicated that naphthalene was produced from monocyclic aromatics (benzene, toluene, and xylene) with oxygenated fragments over HZSM-5 as the catalyst. From the above results, higher selectivity to aromatics was observed at the co-pyrolysis temperatures from 500 °C to 600 °C. According to the yield and composition of bio-oil, the optimal temperature for co-pyrolysis of corn stover and scum with CaO and HZSM-5 as the catalysts was 550 °C at

which the highest yield (29.22 wt.%) of bio-oil and maximum proportion of aromatics (83.68 wt.%) were achieved. The main aromatic compounds included benzene, toluene, xylene, indene and naphthalene which are all important chemical intermediates to other useful chemicals. The optimal temperature of 550 °C was used in the following experiments.

3.2 Effect of CaO/HZSM-5 ratio on co-pyrolysis product fractional yields and selectivity

The objective of this section was to study the synergistic effect of CaO and HZSM-5 as the catalysts in microwave-assisted catalytic co-pyrolysis system. To achieve this aim, the effect of CaO/HZSM-5 ratio on co-pyrolysis product fractional yields and selectivity at the temperature of 550 °C was investigated. During experiments, the total amount of corn stover and scum was constant. The ratio of (corn stover + scum) to (CaO + HZSM-5) was kept at 1:1. In addition, the ratio of corn stover to scum was 1:1, and CaO and HZSM-5 were used at various ratios (No catalyst, CaO only, 4:1, 2:1, 1:1, 1:2, 1:4 and HZSM-5 only in mass). Fig. 3 shows the effect of CaO/HZSM-5 ratio on co-pyrolysis product fractional yields and selectivity. As can be seen from Fig. 3(a), the use of catalyst in the pyrolysis resulted in a decrease in bio-oil yield. This is because the pyrolysis vapors had to pass through the catalyst particles, which increases the gas residence time. Besides, with an increasing amount of HZSM-5 catalyst, the bio-oil yield increased from 10.74 wt.% (CaO only) to the maximum value of 38.34 wt.% (CaO: HZSM-5=1:4), and then slightly decreased to 35.21 wt.% (HZSM-5 only). This indicates that CaO catalyst reduced the yield of the bio-oil. The result was different from the previous studies. Lin et al. (2010) studied the effect of CaO as the catalyst on bio-oil

production from biomass pyrolysis in a fluidized-bed reactor, and observed an increased bio-oil yield with the addition of CaO catalyst. One possible reason is that with the addition of CaO catalyst, more time was needed for the volatiles to be released and hence the gas residence time was increased, which promoted the secondary thermal cracking and reduced the bio-oil yield. By comparison, it is easier for the pyrolysis vapor to go through HZSM-5 due to its three-dimensional porous structure (Dickerson & Soria, 2013).

The overall yields of different chemical groups over different catalyst combinations are shown in Fig. 3(b). The proportion of aliphatic hydrocarbons did not change too much **with catalyst**. However, the proportion of aromatic hydrocarbons increased with the increasing addition of HZSM-5, and reached the maximum value of 35.77 wt.% when the ratio of CaO to HZSM-5 was 1:4, which was 17% higher than that with HZSM-5 alone. More aromatics were produced over the mixture of the two catalysts compared to either catalyst. The results indicated a synergistic effect between these two catalysts. With the addition of CaO catalyst, the yield of oxygen-containing products decreased to the minimum of 1.54 wt.% when the ratio of CaO to HZSM-5 was 1:2. Fig. 3(c) shows the proportions of different chemical groups in the bio-oil during catalytic co-pyrolysis of corn stover and scum with different CaO to HZSM-5 ratios. The aromatic proportion in the bio-oil significantly increased as the CaO to HZSM-5 ratio was lower than 2:1, and reached the maximum value of 93.30 wt.% when the CaO to HZSM-5 ratio was 1:4. In addition, the proportion of oxygen-containing compounds decreased with the addition of CaO catalyst and reached the minimum value of 4.98 wt.% when the CaO to HZSM-5

ratio was 1:2. Furthermore, there was almost no nitrogenated compounds in the bio-oil when the ratio of CaO to HZSM-5 was lower than 1:2.

From the above results, the CaO catalyst also has a significant effect on deoxygenation of bio-oil (Li et al., 2012; Lin et al., 2010). The production of light phenols was improved at the expense of large oxygen-containing compounds on CaO catalyst, which was different from other catalysts reported to be selective to phenolic compounds (Lu et al., 2010a). On the other hand, HZSM-5 catalyst has been widely used in the catalytic fast pyrolysis of biomass (Dickerson & Soria, 2013) due to its attractive performance in removing the oxygenated organic compounds and favoring hydrocarbon production in bio-oil through the catalytic cracking reaction. Reduction of oxygen-containing compounds was positive to the quality of the bio-oil since oxygen-containing compounds in the bio-oil would cause the thermal instability and increase the viscosity and corrosiveness. The possible reaction mechanism can be surmised as follows: when pyrolysis vapor passed through the mesoporous CaO catalyst, the heavy compounds such as large phenols and anhydrosugars were cracked into light compounds, followed by conversion of the light compounds into hydrocarbons over the microporous HZSM-5 catalyst (Dickerson & Soria, 2013; Lu et al., 2010a).

3.3 Effect of corn stover/scum ratio on co-pyrolysis product fractional yields and selectivity

In this section, the effect of corn stover/ scum ratio on the co-pyrolysis product fractional yields and selectivity was studied at the temperature of 550 °C with a constant (corn stover + scum)/(CaO + HZSM-5) ratio of 1:1, and the ratio of CaO to HZSM-5 was kept at 1:1 with the total weight of 15g for each run. During the experiments, corn stover and scum were mixed in various ratios (corn stover only, 4:1, 2:1, 1:1, 1:2, 1:4, and scum only in mass).

In order to have a comprehensive understanding of the synergistic effect between corn stover and scum, a parameter called effective hydrogen index (H/C_{eff}) was used in this study to indicate the relative amount of hydrogen available in various feedstocks and assess the economic possibilities for biomass catalytic fast pyrolysis with zeolites. Previous studies (Chen et al., 1988) showed that the feedstocks with H/C_{eff} lower than 1 were difficult to be converted to hydrocarbons over HZSM-5 catalyst due to the rapid deactivation of the catalyst. The H/C_{eff} is defined as:

$$H/C_{\text{eff}} = (H - 2O - 3N - 2S)/C \quad (2)$$

where H, C, O, N and S are the moles of hydrogen, carbon, oxygen, nitrogen and sulfur in the feedstock, respectively. Synergistic effects obtained for the bio-oil and aromatic yields in the co-pyrolysis of corn stover and scum under different corn stover to scum ratios are shown in Table 2. The H/C_{eff} value of scum was 1.65, whereas the corn stover had a H/C_{eff} of only 0.04. This result indicated that the corn stover was a hydrogen-deficient feedstock for catalytic fast pyrolysis (CFP) conversion, whereas scum was much more hydrogen-rich.

Fig. 4 shows effect of corn stover/scum ratio on co-pyrolysis product fractional yields and selectivity. As seen in Fig. 4(a), the bio-oil yield was between 17.12 wt.% and 31.44 wt.% and the maximum value reached 31.44 wt.% when corn stover to scum ratio was 1:2. With the decreasing ratio of corn stover to scum, the gas yield increased and the char yield decreased.

The selectivity of different chemical groups was also influenced by corn stover to scum ratio. In Fig. 4(b), the overall yields of aromatic and aliphatic hydrocarbons gradually increased with the increasing addition of scum and then decreased. When corn stover to scum ratio was 1:2, the aromatic yield reached the maximum of approximately 29.33 wt.%. In addition, the yields of oxygen- and nitrogen-containing compounds decreased with an increasing scum in the mixture. As shown in Fig. 4(c), aromatic proportion in the bio-oil significantly increased as the corn stover to scum ratio was lower than 1:1 and reached the maximum value of 93.00 wt.% when the corn stover to scum ratio was 1:4. It can be also observed that the addition of scum in the feedstock mixture significantly reduced the amount of oxygen-containing compounds such as phenols and aldehydes compounds, which contributed to the improvement in bio-oil quality. It can be explained by the fact that fatty materials in scum could be pyrolyzed into alkanes and olefins, which were beneficial to the production of aromatics in the catalytic pyrolysis process (Ooi et al., 2005).

To obtain comprehensive insight of how synergistic effect influenced the fractional yields and selectivity of bio-oil with the addition of scum, the predicted value (Y_p) of bio-

oil and extent of synergistic effect were calculated using the Eq. (3) and Eq. (4), respectively.

$$Y_p = M_{\text{corn stover}} \times Y_{\text{corn stover}} + M_{\text{scum}} \times Y_{\text{scum}} \quad (3)$$

$$\text{Synergistic effect (\%)} = (Y_E - Y_p) / Y_p \times 100\% \quad (4)$$

where predicted value (Y_p) is calculated based on pyrolysis of corn stover and scum alone ;

$Y_{\text{corn stover}}$ and Y_{scum} are the experimental yields of bio-oil or aromatics in the bio-oil from fast microwave-assisted catalytic pyrolysis of corn stover and scum, respectively; $M_{\text{corn stover}}$ and M_{scum} are the weight percentage of mixture corn stover and scum, respectively.

In addition, the synergistic effect (%) can be obtained through the predicted value (Y_p) and experimental value (Y_E). Furthermore, the H/C_{eff} values at different corn stover to scum ratios were also calculated and presented in Table 2. **When the corn stover/scum is 4:1 or 2:1, the experimental value (Y_E) is smaller than the predicted value (Y_p), so there is no synergistic effect at these points.** A significant synergistic effect was observed when the corn stover to scum ratio was lower than 1:1, or the H/C_{eff} value exceeded 1. The extent of synergistic effect in the production of bio-oil increased with the addition of scum, and reached the maximum value of 27.3% when the corn stover to scum ratio was 1:2 and then decreased. Additionally, it is noticed that the synergistic effect dramatically enhanced the production of aromatics. When the corn stover to scum ratio was 1:1, the predicted value of aromatic yield was 11.5 wt.%, and the experimental value was 24.5 wt.% with an increase of 112.8%. The extent of synergistic effect in the production of aromatics reached the maximum value of 112.8% at the corn stover to scum ratio of 1:1. Considering both the bio-oil yield and the proportion of aromatics in the bio-oil, corn

stover to scum ratio of 1:2 was selected as the optimal mixed ratio. In addition, synergistic effect became significant when the corn stover to scum ratio was lower than 1:1, whereas the H/C_{eff} ratio exceeded 1. Similar results were reported by Zhang et al. (2015a) and Xie et al. (2015). Also, Asadieraghi and Daud (2015) indicated that in in-situ catalytic upgrading of palm kernel shell and methanol on HZSM-5 catalyst in a multi-zone fixed bed reactor, the maximum aromatic yield (50.02 wt.%) was obtained when H/C_{eff} was 1.35. This was due to the rapid HZSM-5 deactivation by coke deposits, while feedstocks with low H/C_{eff} (e.g., <1) (Chen et al., 1988; French & Czernik, 2010).

Microwave pyrolysis has already been successfully scaled up to pilot scale. More future research is needed to achieve the commercial scale. We believe that microwave pyrolysis can be scaled up to commercial scale because non-condensable gases and some bio-oil can be used to generate electricity to provide power for microwave in future.

4. Conclusions

Co-pyrolysis of corn stover and scum was conducted in a microwave-assisted pyrolysis system for bio-oil production with CaO and HZSM-5 as the catalyst. The addition of CaO catalyst increased both the bio-oil yields and aromatic yields. When CaO to HZSM-5 ratio was 1:4, 35.77 wt.% of feedstock was converted into aromatics. Scum showed a significant synergistic effect with corn stover to maximize the production of bio-oil and aromatic hydrocarbons when the H/C_{eff} value exceeded 1. The optimal co-

pyrolysis temperature, CaO to HZSM-5 ratio, and corn stover to scum ratio were 550 °C, 1:4, and 1:2, respectively.

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Figure captions

Fig. 1. Schematic diagram of microwave-assisted catalytic co-pyrolysis system.

Fig. 2. Effect of reaction temperature on co-pyrolysis product fractional yields and selectivity. (a) Product fractional yields **based on feedstock**. (b) Overall yields of different chemical groups **based on feedstock**.

Fig. 3. Effect of CaO/HZSM-5 ratio on co-pyrolysis product fractional yields and selectivity. (a) Product fractional yields **based on feedstock**. (b) Overall yields of different chemical groups over different catalysts combinations **based on feedstock**. (c) The proportions of different chemical groups in the bio-oil.

Fig. 4. Effect of corn stover/scum ratio on co-pyrolysis product fractional yields and selectivity. (a) Product fractional yields **based on feedstock**. (b) Overall yields of different chemical groups over different feedstocks combinations **based on feedstock**. (c) The proportions of different chemical groups in the bio-oil.

Fig. 1. Schematic diagram of microwave-assisted catalytic co-pyrolysis system. (1) semi-continuous biomass feeder; (2) inlet and outlet connector; (3) microwave oven; (4) quartz reactor; (5) microwave absorbent (SiC) bed; (6) thermocouple to measure the temperature of cavity; (7) thermocouple to measure the temperature of SiC bed; (8) quartz connector; (9) bio-oil collector; (10) condenser; (11) connection for vacuum pump.

(a)

(b)

Fig. 2. Effect of reaction temperature on co-pyrolysis product fractional yields and selectivity. (a) Product fractional yields **based on feedstock**. (b) Overall yields of different chemical groups **based on feedstock**.

(a)

(b)

(c)

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(a)

(b)

(c)

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(a) Product fractional yields **based on feedstock**. (b) Overall yields of different chemical groups over different feedstocks combinations **based on feedstock**. (c) The proportions of different chemical groups in the bio-oil.

Tables

Table1. Elemental compositions of corn stover and scum

Compound	Elemental analysis (wt.% dry basis)				
	C	H	N	O ^a	Ash
Corn stover	44.91	6.00	1.58	44.07	3.45
Scum	65.77	11.50	1.05	17.77	3.91

^a Calculated by difference, O(%)= 100-C-H-N-Ash

Table 2. Synergistic effects obtained for the bio-oil and aromatic yields in the co-pyrolysis of corn stover and scum under different corn stover to scum ratios.

Corn stover/scum ratio	Bio-oil yield		Aromatics yield		Synergetic		H/C _{eff} ^b
(w/w)	(wt%)		(wt%)		effect (%) ^a		
	Y _p	Y _E	Y _p	Y _E	SE _b	SE _a	
Corn stover	26.4	26.4	0.0	0.0	—	—	0.04
4:1	25.9	23.5	4.6	0.0	—	—	0.47
2:1	25.5	17.1	7.7	0.2	—	—	0.73
1:1	25.1	29.2	11.5	24.5	16.3	112.8	1.00
1:2	24.7	31.4	15.3	29.3	27.3	91.5	1.25
1:4	24.4	27.5	18.4	25.4	12.7	38.2	1.42
Scum	23.9	23.9	23.0	23.0	—	—	1.65

^a SE_b, SE_a : Synergetic effects of bio-oil and aromatic yields, respectively

^b Calculated using the equation ((Chen et al., 1988)) $H/C_{eff} = (H-2O-3N-2S)/C$

Note : – represents no synergistic effect.