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TECHNICAL ARTICLE

Characterization of Hydrochar Produced by Hydrothermal Carbonization of Organic Sludge

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Sludge is a serious problem due to the risks to environment. Therefore, an energy-efficient, economic-feasible and environmental sustainable measure for sludge management is urgently required, while hydrothermal carbonization (HTC) has been regarded as one promising method. In this study hydrothermal carbonization was utilized to convert organic sludge (OS) into solid carbonaceous product (hydrochar) under various reaction temperature (T = 180–240 °C) and residence time (t = 60–240 min), respectively. The reaction pressure ranged from 2.7 to 4.8MPa, depending on the reaction conditions. The obtained hydrochar was analyzed by elemental analysis, proximate analysis, SEM, FTIR, and BET, to investigate the effect of reaction parameters on the hydrochar properties, followed by discussions on potential applications of the obtained hydrochar. Obvious reduction of H/C and O/C ratio after HTC was observed, based on the Van Krevelen diagram and FTIR analysis, revealing that the dehydration and decarboxylation occurred during the HTC process. The reaction temperature was regarded as the dominant parameter affecting hydrochar characteristic, compared to residence time. The severity factor (log R_o) at the range from 4.13 to 5.90 showed good linear relationship with the ash content, volatile matter (VM), N content and H/C ratio of hydrochar, indicating that the severity factor could serve as a useful indicator for analyzing the hydrochar property. Although the surface area and porosity were improved by HTC, subsequent modification and activation should be needed to broaden the application field. Owing to the characteristic of high ash content, hydrochar derived from organic sludge might not be feasible for fuel use. Instead, the precursor of the activated carbon and low-cost adsorbent might be the potential applications, while further works should be needed to verify the feasibility.

Keywords: hydrothermal carbonization; organic sludge; hydrochar; severity factor

1. Introduction

As the environmental concerns and concepts of sustainable development increase, sludge management has gradually become an important issue discussed worldwide currently. Sludge is viewed as the residue derived from the wastewater treatment process and it mainly contains inorganic material and extracellular polymeric substances (EPS), wherein EPS primarily composed of proteins and polysaccharides. Because of large volume, high moisture content, poor dewaterability, fouling odor problems, and presence of pathogens, appropriate sludge management and utilization are needed not only to reduce cost and handling difficulty but also to avoid harmful effect on the environment and human being. The processes for sludge management typically include preliminary treatment, stabilization, conditioning, dewatering, followed by final treatments such as storage, landfilling, and agriculture use (Zhang et al. 2017). Traditionally landfilling, land application, and incineration are mainly used as a final treatment for sludge management, but these methods become unsuitable now owing to increasing environmental concerns and legislative forces. Thermal processes included pyrolysis, gasification, and combustion are regarded as alternative methods for sludge management recently due to the advantage of volume reduction and increasing dewaterability of treated sludge during the process. However, the pre-drying step is necessary for the processes mentioned above because of the restriction on feedstock moisture, which makes them become less energy efficient due to the intensive energy requirement of the pre-drying step.

Hydrothermal carbonization (HTC) with operating temperature 180–250 °C and pressure 2–10 MPa is regarded as a thermal process converting organic feedstock into the solid carbonaceous product (hydrochar). The process water, liquid byproduct of the HTC process, could also be utilized to synthesize chemicals, produce biogas, and recycle to HTC reactor for further reaction. Typically, the reaction mechanisms of hydrothermal carbonization mainly include hydrolysis, dehydration, decarboxylation, aromatization, and condensation polymerization (Funke and Ziegler, 2010). As water is used as reaction medium and acts as a catalyst during HTC process, the pre-drying step

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is unnecessary in HTC, indicating that HTC is more energy-efficient than other thermal processes such as pyrolysis, gasification, and combustion. Recently hydrothermal carbonization has received considerable attention and has been viewed as one promising method for treating feedstock with high moisture content such as sewage sludge or solid digestate (Libra et al. 2011). Additionally, hydrothermal carbonization has a higher yield of solid carbonaceous product (45–70%) than conventional thermal processes (with pyrolysis yield = 25–35% and gasification yield = 10%, respectively) because of milder reaction condition (Kambo and Dutta, 2015), suggesting that it has better efficiency toward carbon utilization as higher solid recovery.

Although a range of different solid wastes have been studied by hydrothermal carbonization, but the hydrochar property would be varied with the type of feedstock in use, further affecting the subsequent applications and the value of the obtained hydrochar. Currently, the applications of hydrochar mainly involve soil amelioration, solid fuel, adsorbents, and high added value product such as the capacitor. Restated, char characteristic dominantly determines the applications and added value of hydrochar, which would further influence the economic feasibility of HTC process for sludge management. This emphasizes the importance and necessity of fundamental characterization toward hydrochar property.

In this study, hydrothermal carbonization was carried out to convert organic sludge into hydrochar, and the obtained hydrochars under different HTC condition were examined. The schematic diagram illustrating the research process is shown in **Figure 1**. The main purpose of this work are: (1) to explore the physical and chemical properties of hydrochar derived from organic sludge; (2) to investigate the effect of reaction temperature and residence time on hydrochar properties; (3) to evaluate the potential applications of sludge-derived hydrochar based on the obtained results.

2. Material and Methods

2.1 Organic Sludge

Organic sludge (OS) with initial moisture of 90% was collected from the wastewater treatment plant of an optoelectronic factory located in Taiwan. The organic sludge was stored in a refrigerator at 4 °C until ready for use.

2.2 Hydrothermal Carbonization

All experiments were carried out in a 2L stirred pressure reactor (Model 4530; Parr Instrument Co., USA) with the material of CS Alloy 20Cb3. The effects of the reaction conditions on product characteristics and yields were examined by varying temperature over the range of 180–240 °C and varying reaction time over the range of 60–240 min. Approximately 300 g of raw organic sludge with premixed in water at 1:1 sludge/water ratio (w/w) was introduced into the reactor for hydrothermal carbonization reaction. Prior to reaction, residual air was removed from the sealed vessel by repeatedly purged with nitrogen thrice and then pressurized to 150 psi using nitrogen gas. The reactor was heated to the desired temperature at a stirring speed of 150 rpm and maintained at the desired temperature for a period of time. After the reaction was completed, the pressure inside the reactor was released and the reactor was quenched by cool water bath. The resulting mixtures were filtered, and the weight of obtained solid carbonaceous product was recorded. The hydrochar of each reaction was weighed independently to calculate the yield and stored in a sealed container for further characterization.

2.3 Analytical Methods

The hydrochar yield was calculated by the weight ratio of the recovery hydrochar to the dry sludge. The moisture of the sample was calculated by weight difference after oven-drying. Prior to analysis, the organic sludge and hydrochar products were dried at 105 °C for 24 h and ground into fine particles. The ultimate analysis of the hydrochar and raw sludge was determined by the elemental analyzer (Elementar Vario ELIII, Germany). For proximate analysis, the ash content (Ash) was evaluated by NREL/TP-510-42622 method, while the volatile matter (VM) content was determined based on Chinese National Standards method (GB/T 212-2008), where one gram of sample was burned at 900 °C for 7 min in a muffle furnace. The fixed carbon (FC) content was calculated as:

$$\text{Fixed carbon (FC) \%} = 100\% - \text{VM \%} - \text{Ash \%} \tag{1}$$

The higher heating value (HHV) was determined by the formula proposed by Channiwala and Parikh (Channiwala and Parikh, 2002):

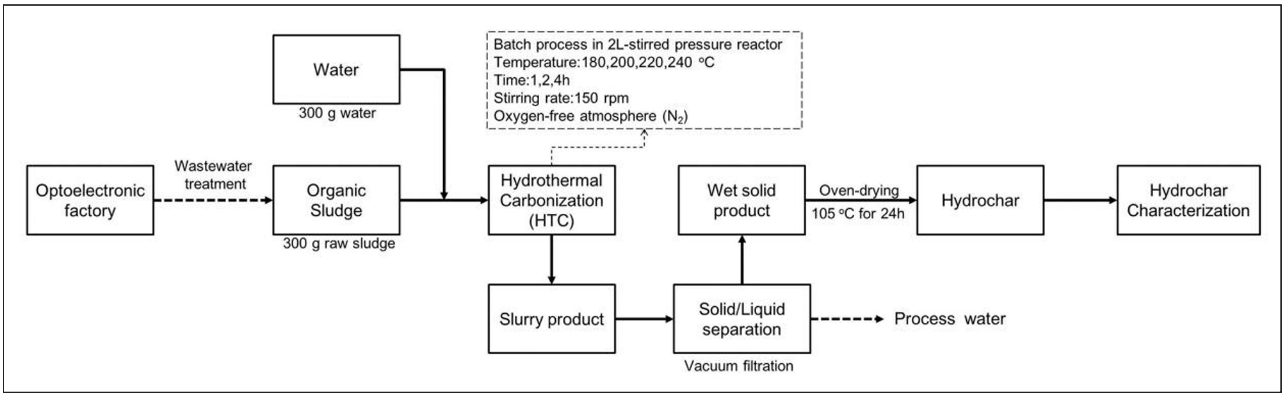

Figure 1: The schematic diagram of research process.

$$\text{HHV}\left(\text{MJ/kG}\right) = 0.3491\text{C} + 1.1783\text{H} + 0.1005\text{S} + 0.1034\text{O} - 0.015\text{N} - 0.021\text{A} \qquad (2)$$

where C, H, S, O, N, and A represent carbon, hydrogen, sulfur, oxygen, nitrogen, and ash content (wt.% dry basis), respectively (Channiwala and Parikh, 2002). The hydrochar morphology was analyzed by Scanning electron microscopy (SEM) microphotographs, obtained with a JSM-7100F. The surface functional groups of the sample were analyzed by the Fourier transform infrared (FTIR) spectroscopy recorded on a Spectrum 100 spectrometer (PerkinElmer Inc, USA), where the samples were scanned from 4000 cm^{-1} to 400 cm^{-1} with a resolution of 4 cm^{-1}. The porous structure, specific surface area, and total pore volume were determined by means of N_2 adsorption-desorption isotherms at 77 K using an ASAP 2020 instrument. Surface areas were calculated by Brunauer–Emmett–Teller (BET) method.

3. Results and Discussion

3.1 Ultimate and proximate analysis

The elemental analysis, proximate analysis, and yield were summarized in **Table 1**. For ultimate analysis, the percentages of C, H, N, and O initially in OS were 31.70%, 5.50%, 5.41%, and 24.42%, respectively. The H, N, O content in hydrochar decreased obviously after hydrothermal carbonization, which attributed to the loss of functional groups containing H, N, and O during the process. Generally, the mechanisms of hydrothermal carbonization include hydrolysis, dehydration, decarboxylation, aromatization, and condensation polymerization. The decrease of the H content herein was mainly attributed to the phenomenon of the dehydration during HTC. Besides, the H content decreased apparently as reaction temperature increased but changed insignificantly with increasing residence time, suggesting that reaction temperature is the dominant parameter for dehydration. On the other hand, the content of C decreased from 31.70% to 24.22~27.36% after HTC process unexpectedly and declined with increasing temperature. This result was not consistent with the finding in Areeprasert et al. (2014), where the C content increased after HTC and elevated with increasing temperature. One possible reason is that the feedstock in use for HTC is different and the variation in feedstock composition may affect the reaction pathways, further resulting in different hydrochar composition (Wang et al. 2018). The reduction in C content implies that some carbon may transfer into the liquid part or convert into the gas phase during HTC process. In addition, the C content in hydrochar increased slightly with increasing time but declined obviously with increasing temperature, suggesting that temperature is the dominant parameter affecting the carbonization process and longer reaction time may be needed for deeper carbonization.

For the proximate analysis, the variation of volatile matter (VM) and ash content were mainly discussed. Typically the volatile matter is composed of carbon, hydrogen and trace amount of nitrogen. As shown in the results the volatile matter (VM) declined obviously from 59.71% to 34.05~44.27% after HTC. The decrease of volatile matter (VM) could be supported by the result of elemental analysis above, where the C, H, N content decreased after the reaction. On the other hand, the ash content of organic sludge was high (31.95%) and elevated to 48.57%~57.88% with increasing reaction temperature and time after HTC

Table 1: Characteristics and properties of hydrochar and organic sludge.

sample	OS	180–60	200–60	220–60	240–60	200–120	200–240
Ultimate analysis							
C (%)	31.70	27.36	26.91	26.44	24.22	27.07	27.17
N (%)	5.41	2.91	2.61	2.21	1.89	2.44	2.35
S (%)	1.02	0.67	0.67	0.62	0.54	0.74	0.95
H (%)	5.50	4.02	3.75	3.55	3.19	3.71	3.73
O[a] (%)	24.42	16.47	14.85	12.57	12.28	12.89	11.85
Atomic H/C	2.08	1.76	1.67	1.61	1.58	1.64	1.65
Atomic O/C	0.58	0.45	0.41	0.36	0.38	0.36	0.33
Proximate analysis							
FC (%)	8.34	7.16	7.41	8.87	8.07	9.31	9.31
VM (%)	59.71	44.27	41.39	36.52	34.05	37.53	36.72
Ash (%)	31.95	48.57	51.20	54.61	57.88	53.16	53.97
HHV (MJ/kg)	14.37	11.59	11.23	11.00	9.75	11.41	11.58
Yield (%)	–	60.82	56.99	55.29	50.87	57.09	57.54

Abbreviation: OS, organic sludge; FC, fixed carbon; VM, volatile matter; HHV, higher heating value; 180–60, represents hydrochar obtained from 180 °C, 60 min.

[a] calculated by difference.

process. In general, the ash content of sludge and its derived hydrochar are expectedly high, which has been reported before (Tay et al. 2001). The phenomenon of ash enrichment in hydrochar after HTC suggests that organic components were transferred into the liquid phase, while dissolved inorganic salts precipitated on the hydrochar during HTC (Zhang et al. 2014).

The atomic ratio of H/C versus O/C for organic sludge and derived hydrochar were shown in the Van Krevelen Diagram (**Figure 2**). The Van Krevelen Diagram was used to investigate the coalition effect of hydrothermal carbonization. The initial ratios of H/C and O/C in organic sludge were 2.08 and 0.58 respectively. As shown in **Figure 2**, the obvious reduction in H/C and O/C ratio was observed after HTC process, where H/C declined to 1.58~1.76 and O/C decreased to 0.33~0.45, respectively. The H/C and O/C reduction indicates the phenomena of carbonization, attributing to the mechanism of dehydration and decarboxylation during hydrothermal carbonization (Funke and Ziegler, 2010). Generally, the lower value of H/C and O/C ratio suggest deeper carbonization effect toward hydrochar. In this study, the lowest value of the above ratio was still far away from the traditional coal such as sub-bitimious, bitimious and antheractie. This may imply that the degree of carbonization may not be enough for sludge derived hydrochar being used for fuel application.

3.2 Solid yield and Higher Heating Value (HHV)

To investigate the solid recovery of the HTC process, the hydrochar yield was determined. In the case of N-rich biomass such as sludge, the mechanism of hydrochar production during hydrothermal carbonization can be categorized into two parts: (1) Polymerization of dissolved compounds. The soluble compounds in biomass like carbohydrate and protein would be firstly dissolved and hydrolyzed into small molecules such as sugar and protein, subsequently converting to hydrochar by dehydration and polymerization. (2) Solid-solid conversion. Non-soluble parts in biomass would transfer into hydrochar by HTC reaction including decarboxylation and condensation (Wang et al. 2018). As shown in **Table 1**, the yield decreased from 60.8% to 50.9% as temperature elevated from 180 °C to 240 °C, but increased slightly (57.0%~57.5%) as the residence time became 4 times longer (60 min to 240 min) at 200 °C. Based on the above mechanisms, the results imply that reaction temperature is the dominant parameter affecting the hydrochar yield compared to residence time, and considerable amounts of soluble compounds in feedstock would dissolve to the liquid part rather than retain in the solid phase during the process. Besides, high temperature should not be favorable for getting good yield during HTC. In addition, because it possibly takes time for dissolved compounds converting into solid char by dehydration and polymerization, the longer residence time may be needed for further polymerization to achieve the higher hydrochar yield.

To explore the fuel characteristic of sludge-derived hydrochar, higher heating value (HHV) was evaluated. The HHV of hydrochar ranged from 9.75 MJ/kg to 11.59 MJ/kg, which were lower than the original sludge (14.37 MJ/kg) (**Table 1**). The low heating value of hydrochar attributes to high ash content and lower carbon content. Considering the result from the Van Krevelen diagram, and the potential problem of slagging and fouling during char combustion due to high ash content, using sludge-derived hydrochar for fuel application may not be economically feasible.

3.3 Relationship between hydrochar characteristic and severity factor

To further investigate the combined effect of reaction temperature and time on the properties of the sludge-derived hydrochar, the reaction ordinate, R_o was introduced here. The reaction ordinate (R_o) was defined by Overend

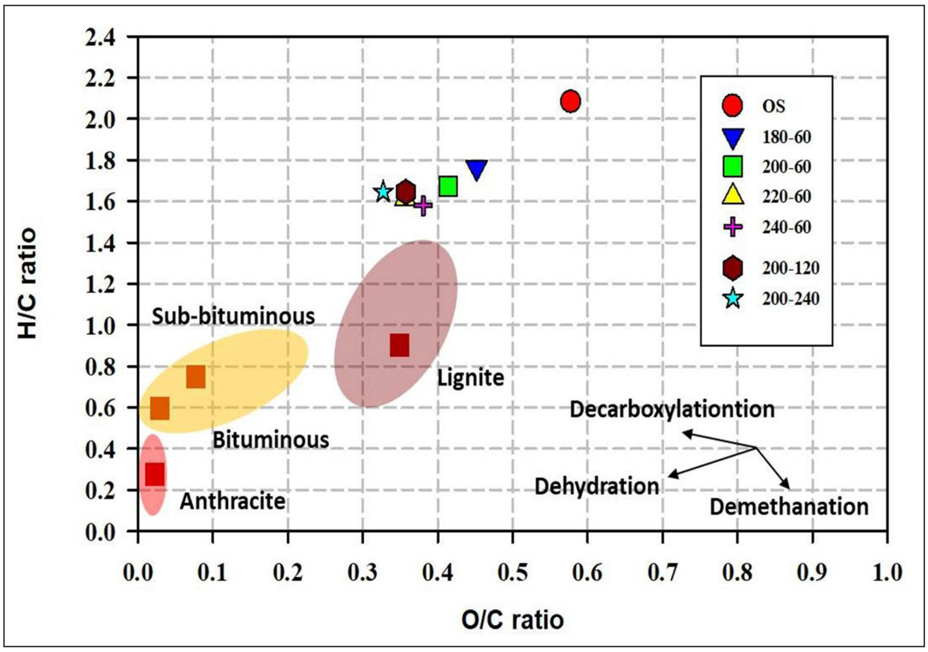

Figure 2: The Van Krevelen diagram.

et al. (1987) and was originally used to evaluate hydrolytic depolymerization processes (Overend and Chornet, 1987), while it was recently used to assess the condition toward hydrothermal reaction: The reaction ordinate (R_o) is defined as follow:

$$R_o = t \cdot \exp\left(T - 100 / 14.75\right) \tag{3}$$

where T is the reaction temperature in °C and t is the residence time in min. To illustrate the relation between reaction severity and selected experimental data, the severity factor (log R_o) was often used by many types of research. Besides, hydrochar characteristic correlated with the severity factor (log R_o) has also been reported, where the energy content of hydrochar was presented as a function of severity factor (Hoekman et al. 2017). In this work, the hydrochar properties were analyzed in term of log R_o by a linear regression method, and the properties with good regression results toward severity factor were shown in **Figure 3**. Obviously, the ash content increased with increasing severity factor, while the volatile matter (VM), N content and H/C ratio of hydrochar showed a converse trend. Additionally, there was a good linear relationship between log R_o and the above hydrochar properties when the log R_o was at range from 4.13 to 5.90. This may indicate that the severity factor (log R_o) could serve as a useful indicator to predict the hydrochar characteristics.

3.4 Surface morphology

The SEM images were used to analyze the surface morphology of organic sludge and sludge-derived hydrochar, which were shown in **Figure 4**. The surface morphol-

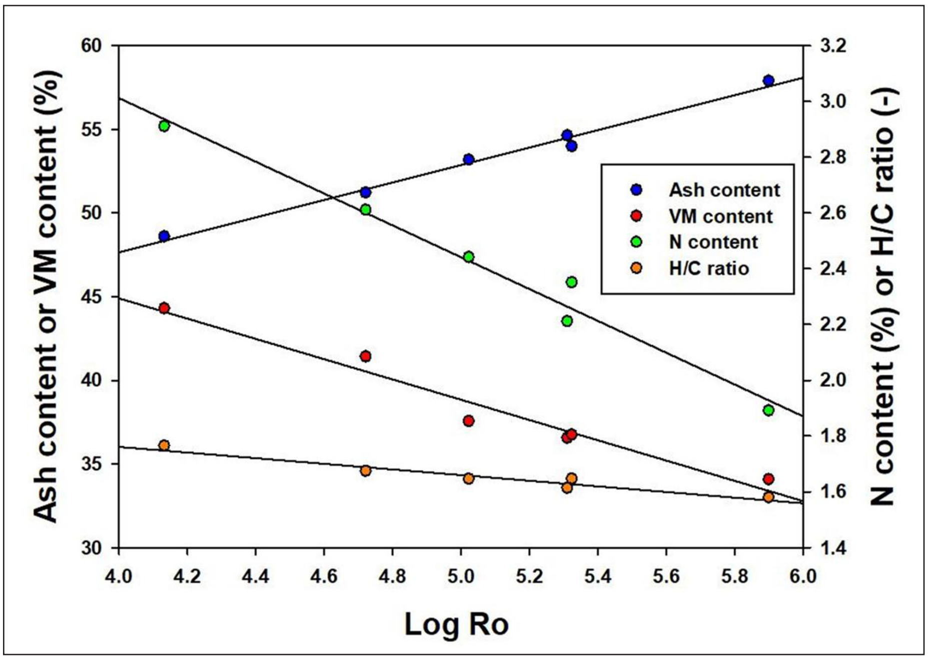

Figure 3: The relationship between hydrochar properties and HTC reaction severity (with ash content R^2 = 0.9882; volatile matter R^2 = 0.9598; N content R^2 = 0.9786; and H/C ratio R^2 = 0.9317, respectively).

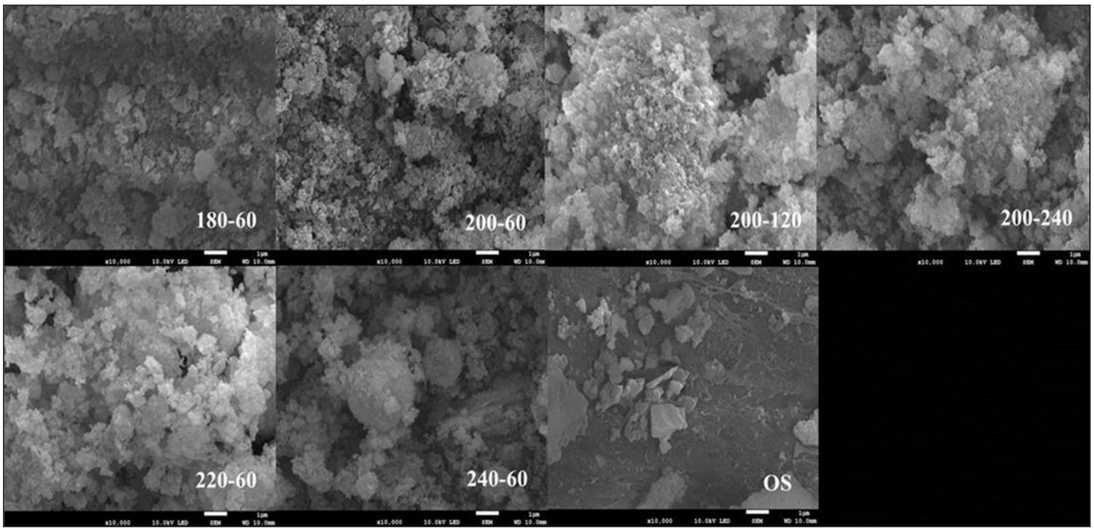

Figure 4: SEM images of organic sludge and hydrochar derived from different HTC conditions (OS: organic sludge; 180–60 represents hydrochar obtained from 180 °C, 60 min.).

ogy of sludge changed significantly after HTC process, and the fragmentation of hydrochar and the number of derived grains increased significantly as the reaction severity raised. This revealed that the flocs and cellular tissues in sludge were broken because of gas volatilization and chemical bond scission during the HTC process. The derived grains may result from the agglomeration of denatured protein in extracellular polymeric substances (EPS) or the sintering of the inorganic material because of thermal treatment. Furthermore, the sphere-like aggregates were observed at high reaction temperature (240 °C). Based on the finding of Sevilla et al. (2009), we speculate that these sphere-like aggregates consisting of hydrophobic aromatic structure and hydrophilic shell may attribute to the HTC reaction of polysaccharide in the organic sludge (Sevilla and Fuertes, 2009). This observation may suggest that the occurrence of aromatization and polymerization in HTC require high reaction temperature.

3.5 FTIR spectra

Figure 5 and **6** represented the FTIR spectra of organic sludge and hydrochar with different HTC operating parameters. The obvious difference was observed after HTC showing that the surface functional groups changed

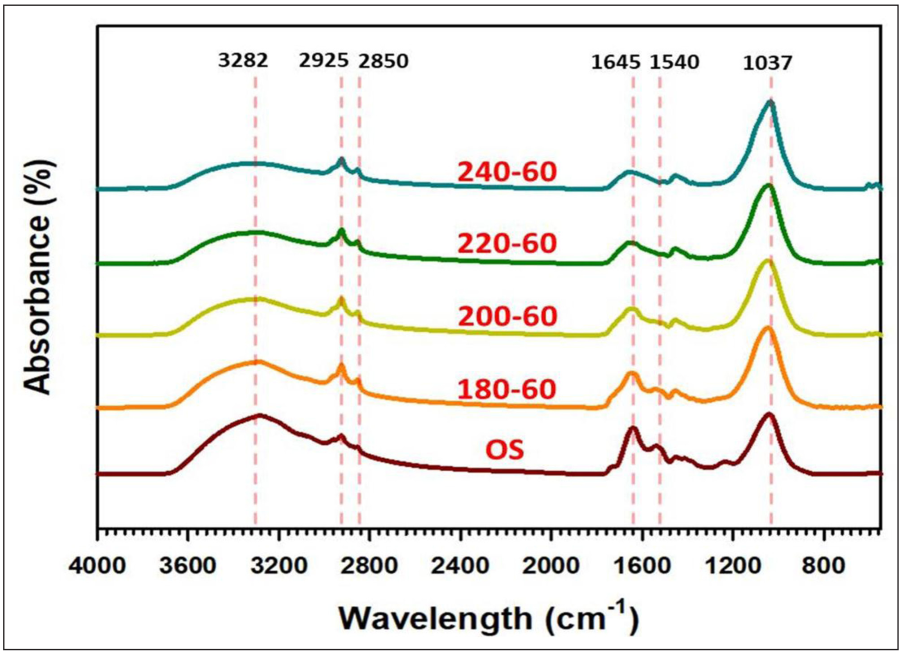

Figure 5: FT-IR spectra of organic sludge (OS) and hydrochar under various HTC conditions (T = 180,200,220,240 °C; t = 60 min).

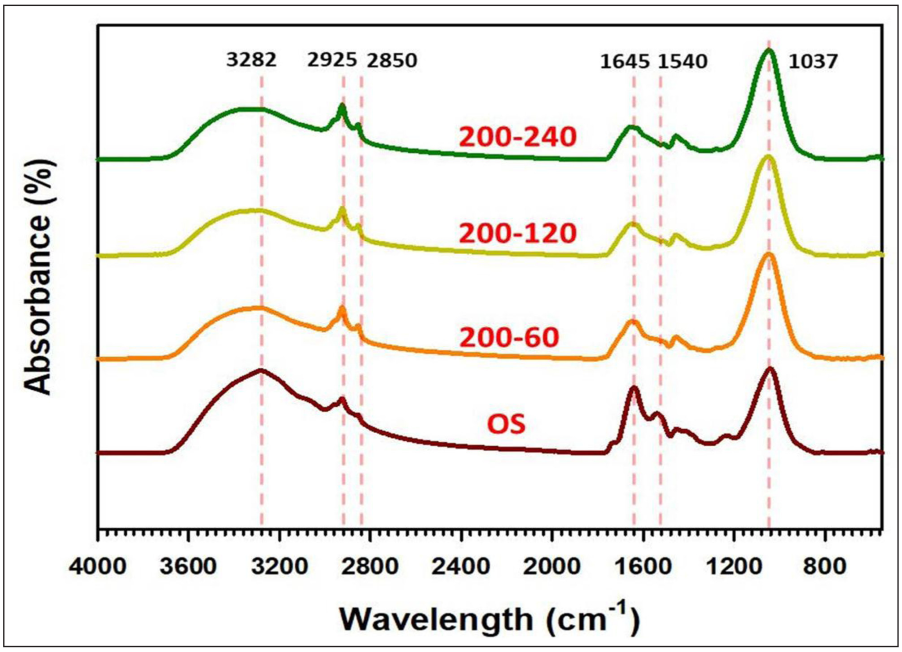

Figure 6: FT-IR spectra of organic sludge (OS) and hydrochar under various HTC conditions (T = 200 °C; t = 60,120,240 min).

during the process. Results and discussions were summarized as follow:

(1) The board band appearing at 3282 cm^{-1} was associated with OH vibration in the hydroxyl group. According to the results, the intensity of the peak for hydrochar was less than that of the organic sludge, revealing that dehydration occurred during HTC. Further, the intensity of the peak became less as the temperature increased while the time effect seemed not so obviously. This may imply that dehydration is mainly influenced by temperature rather than time, which is in line with the discussion for H content reduction in section 3.1 (Peng et al. 2016).

(2) The band at 2800–3000 cm^{-1} was attributed to aliphatic carbon -CH$_x$ stretching vibration corresponding to the alkyl aromatic structure. There was no obvious change at peak 2925 cm^{-1} and 2850 cm^{-1}, attributing to the asymmetric and symmetric -C-H stretching of the methylene groups, respectively (De Oliveira Silva et al. 2012).

(3) The band around 1645 cm^{-1} was originated by ketone and amide group while the band at 1540 cm^{-1} attributed to C=O asymmetric stretching in the carboxylic group (Lin, Wang & Wang, 2012). Evident attenuation in peak intensity was observed at 1645 cm^{-1} and 1540 cm^{-1}, implying that the decarboxylation occurred during HTC process. Still, the temperature effect seems so dominantly compared to that of the time.

(4) The peak around 1037 cm^{-1} referred to -Si-O stretching indicating the presence of SiO_2 (Yuan et al. 2011). Prominent growth of peak after HTC and steady increase of peak intensity with rising temperature was observed, suggesting that mineral compounds in sludge were retained in hydrochar during HTC. This result is consistent with the phenomena of ash enrichment after HTC, based on the proximate analysis in section 3.1. Still, the operating temperature seems to play an important role in determining ash content in hydrochar.

3.6 BET surface area and porosity

The adsorption isotherm plot was presented in **Figure 7** and **8**. The adsorption isotherm of organic sludge could be classified as Type IV isotherms generally provided by the mesoporous adsorbent. Besides, apparent hysteresis loops were observed for the sludge sample, while this type of hysteresis loops has been observed with certain silicas and it is associated with capillary condensation and pore blocking. This probably suggests that organic sludge may contain considerable amounts of silica, which may also be supported by the observation of high ash content in the sludge. On the other hand, the adsorption isotherm of hydrochar could be viewed as Type II isotherms. Typically macroporous or nonporous adsorbent provided Type II isotherms indicating unrestricted monolayer-multilayer adsorption (Thommes et al. 2015). Based on the results, these imply that the structure of organic sludge was changed after HTC because of a series of reaction including hydrolysis, dehydration, decarboxylation, polymerization, and aromatization. **Table 2** summarized the BET surface area (S_{BET}), total pore volume (V_t), and average pore size of sludge and hydrochar under various HTC conditions. The sludge-derived hydrochar had S_{BET} ranged from 26.48 to 35.43 m^2/g, V_t ranged from 0.24 to 0.30 cm^3/g, and average pore size ranged from 32.85 to 39.23 nm, respectively. Although the HTC enhanced the surface area by 2–3 times and improved the pore volume, the surface characteristic and porosity of hydrochar was still poor, implying that subsequent activation or modification should be needed for the further high added-value application.

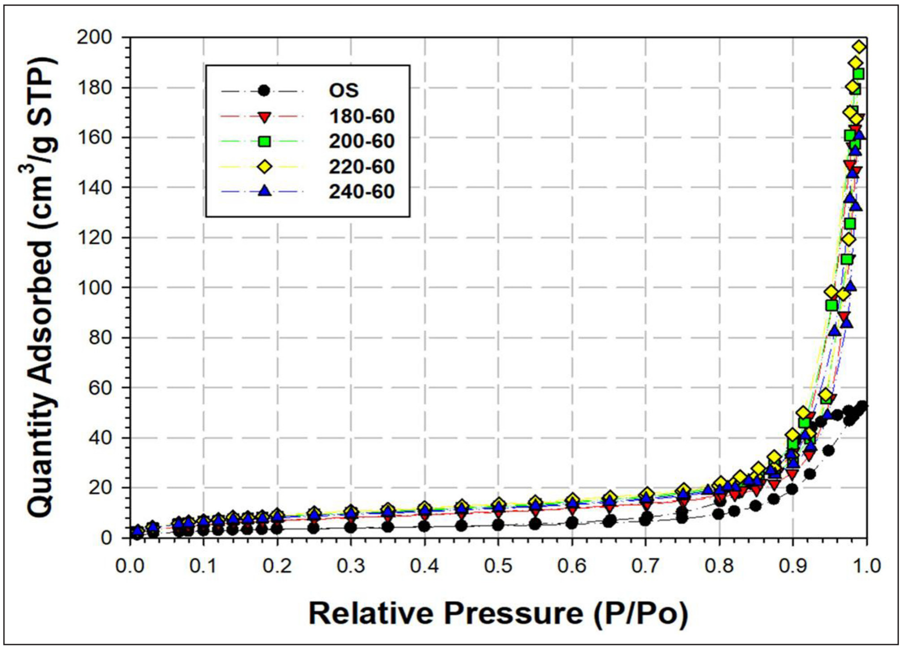

Figure 7: The adsorption isotherm of organic sludge (OS) and hydrochar under various HTC conditions (T = 180, 200, 220, 240 °C; t = 60 min).

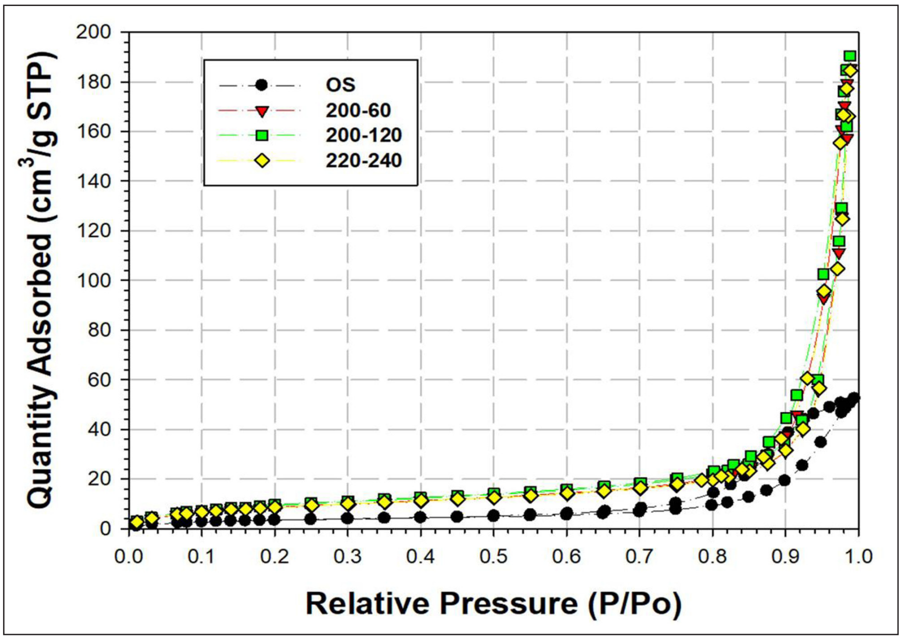

Figure 8: The adsorption isotherm of organic sludge (OS) and hydrochar under various HTC conditions (T = 200 °C; t = 60,120, 240 min).

Table 2: Surface area and porosity of hydrochar and organic sludge.

Sample	BET Surface Area (S_{BET}) (m^2/g)	Total Pore Volume (V_t) (cm^3/g)	Average Pore Size (nm)
OS	12.6126	0.0811	25.7269
180–60	26.4859	0.2598	39.2307
200–60	32.0941	0.2868	35.7432
220–60	33.5844	0.3035	36.1536
240–60	30.2606	0.2484	32.8476
200–120	35.4296	0.2953	33.2593
200–240	32.0872	0.2853	35.5687

Abbreviation: OS, organic sludge; 180–60, represents hydrochar obtained from 180 °C, 60 min.

3.7 Discussions on potential applications of sludge-derived hydrochar

The potential applications of hydrochar mainly include the capacitor, solid fuel, and low-cost adsorbent. Based on the results in this work, the sludge-derived hydrochars may not be feasible for solid fuel toward energy production, due to the low degree of carbonization and low heating value resulting from the high ash content and low carbon content of hydrochar. High ash content in hydochar is also not favorable for combustion because of slagging and fouling problems reducing the fuel efficiency. Typically, the ash content ranged from 5~10% and the heating value larger than 17~19 MJ/kg are required for hydrochar as a solid fuel.

On the other hand, attributing to low surface area and poor porosity, sludge-derived hydrochars are not suggested for direct use in the capacitor. Instead, further activation should be required. Recently there has been an increased interest in using hydrochar as precursors of activated carbon, owing to the low degree of condensation and high density of oxygen-containing functional group in hydrochar, which are beneficial for the following activation. The activated carbons with high surface area using hydrochar as precursors have been reported by many studies, showing that hydrochar has chance to become high-value-added products under appropriate activation. For instance, Correa et al. (2017) showed that the hydrochar derived from biogas digestate could serve as a useful precursor for producing activated carbon with good surface property. The surface areas were elevated from 8~14 m^2/g (hydrochar) to 930–1351 m^2/g (activated carbon) via KOH activation, although the surface areas were rather low compared to other KOH activated carbons due to the high ash content in hydrochar. One interesting result was that the ash content decreased from 25.6~38.7% (hydrochar) to 6.17~7.95% (activated carbon) after KOH activation and the following acid washing step. The phenomena of ash declination might attribute to the reaction between potassium (K) and clay material inside the hydrochar, which formed the potassium-containing compounds during activation. These compounds would be further removed by the subsequent washing step, resulting in the decrease of ash content (Correa et al. 2017). This may also suggest that KOH activation could be one potential method to reduce the ash content in hydrochar, elevating the potential of subsequent applications. In general, the market value of the hydrochar depends on its subsequent application. The hydrochar is typically between 130 and 200 €/ton. However; the market value could be increased up to 500~1,500 €/ton via appropriate activation and modification (De Mena Pardo et al. 2016).

Even though hydrochar has poor surface characteristic and porosity, some works reported that it could serve as low-cost adsorbent well such as heavy metal removal agent. For example, Alatalo et al. (2013) used sludge-derived hydrochar (S_{BET} = 9.1~18 m^2, V_t = 0.04–0.09 cm^3/g) as an adsorbent for heavy metal adsorption, which showed a good effect for Pb removal. Koottatep et al. (2017) found that sludge-derived hydrochar with KOH modification (S_{BET} = 4.41 m^2, V_t = 0.04–0.049 cm^3/g) had better performance toward Cu removal than commercial activated carbon. This suggests that the surface characteristic and porosity may not be the only factor affecting the efficiency of the heavy metal adsorption, whereas functional groups could play an important role during adsorption. In summary, because of high ash content, hydrochar derived from organic sludge might not be suitable for fuel use, whereas precursors of activated carbon and low-cost adsorbent could be the potential applications.

4. Conclusions

In summary, compared to the residence time, the reaction temperature was regarded as the dominant parameter affecting sludge-derived hydrochar characteristic. Obvious dehydration and decarboxylation were observed after HTC based on the Van Krevelen Diagram and FTIR analysis. Additionally, the severity factor (log R_o) could serve as an useful indicator in describing hydrochar properties. Because of high ash content and low heating value, the hydrochar obtained from organic sludge may not be suitable for fuel use. Besides, subsequent activation and modification should be needed for the application toward high added-value product such as capacitor owing to low surface area and poor porosity of the hydrochar. The precursor of the activated carbon and low-cost adsorbent might be the potential applications for the hydrochar derived from organic sludge. However, further work should be required to investigate the feasibility for applying sludge-derived hydrochar toward these potential applications. To further explore and elevate the potential value of sludge derived hydrochar, future works would mainly include: (1) Using sludge derived hydrochar as precursors to exploit suitable KOH activation process efficiently improving the surface properties. (2) Conducting Cu^{2+}, Pb^{2+}adsorption test to evaluate the feasibility of using sludge derived hydrochar as low-cost adsorbent toward heavy metal removal.

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Competing Interests

The authors have no competing interests to declare.

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