Consequences of sludge composition on combustion performance derived from thermogravimetry analysis

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ABSTRACT

Wastewater treatment plants produce millions of tons of sewage sludge. Sewage sludge is recognized as a promising feedstock for power generation via combustion and can be used for energy crisis adaption. We aimed to investigate the quantitative effects of various sludge characteristics on the overall sludge combustion process performance. Different types of sewage sludge were derived from numerous wastewater treatment plants in Beijing for further thermogravimetric analysis. Thermogravimetric–differential thermogravimetric curves were used to compare the performance of the studied samples. Proximate analytical data, organic compositions, elementary composition, and calorific value of the samples were determined. The relationship between combustion performance and sludge composition was also investigated. Results showed that the performance of sludge combustion was significantly affected by the concentration of protein, which is the main component of volatiles. Carbohydrates and lipids were not correlated with combustion performance, unlike protein. Overall, combustion performance varied with different sludge organic composition. The combustion rate of carbohydrates was higher than those of protein and lipid, and carbohydrate weight loss mainly occurred during the second stage (175–300 °C). Carbohydrates have a substantial effect on the rate of system combustion during the second stage considering the specific combustion feature. Additionally, the combustion performance of digested sewage sludge is more negative than the others.

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1. Introduction

Sewage sludge produced in wastewater treatment plants (WWTPs) is currently a problem because elevated amounts of sludge are generated with increasingly stringent wastewater treatment requirements (Wang et al., 2012b). European statistics indicated that the dry weight of sewage sludge production is nearly 90 g per capita per day (Davis, 1996), and the implementation of wastewater management regulations has caused approximately 10 million tons of additional sewage sludge generated yearly since 2005 (Werle and Wilk, 2010). About 30 million tons of sewage sludge is produced in China (Khan et al., 2013). Sewage sludge that is not properly disposed will lead to other environmental issues, such as greenhouse gas emissions (Wang et al., 2012a).

Dried sewage sludge contains a high quantity of organic matter and has a substantial calorific value. Sewage sludge is recognized as an alternative feedstock for power generation via combustion and can be used for energy crisis mitigation (Garcia et al., 2013; Werther and Ogada, 1999). This emerging practice can facilitate

the substantial reduction of for-disposal sewage sludge amount because detrimental substances are removed when sewage sludge is used for power generation. Thus, energy recovery through sludge combustion is no longer a possibility, but rather an obvious reality. The sludge combustion process (SCP) has been extensively studied. However, information is still lacking on the combustion performance of sewage sludge and its connection with sludge composition. Sewage sludge contains a variety of complex components, and each constituent shows specific burning features unlike single-solid fuels, such as coal (Viet et al., 2013). Previous studies on SCPs have only addressed small components of a comprehensive technical scheme (Ogada and Werther, 1996); (Francisca Gómez-Rico et al., 2005). Designing and operating an industrial-scale SCP still requires reliable information on feedstock characteristics, which has been historically obtained from semi-empirical tests. This lack of data often presents a problem in the scale-up stage because the contributions of all complex constituents in real sewage sludge to SCP efficiency are not considered in experience-based models.

Thermogravimetry (TG) and differential thermogravimetric (DTG) analyses are widely applied in the comparative evaluation of varying thermal processes in the combustion system (Su et al.,

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2013). These methods can rapidly examine multiple combusting indices (e.g., maximum combustion rate, ignition temperature, and burnout temperature). In particular, TG can monitor the sample mass of substance as a function of temperature and/or time, whereas DTG is an approach performed by detecting the rate of mass loss. These two approaches have been used recently in thermal degradation of biomass samples (Eero, 1981; Jakab et al., 1997; Meszaros et al., 2007; Sebestyén et al., 2011; Shafizadeh, 1968; Varhegyi et al., 1988; Villanueva et al., 2011; Wilson et al., 2011), investigations of sewage sludge pyrolysis (Dumpelmann et al., 1991; Magdziarz and Werle, 2014), and combustion (Font et al., 2001; Magdziarz and Wilk, 2013), as well as co-combustion of sewage sludge and other substances (Otero et al., 2002; Park and Jang, 2011; Yu and Li, 2014). Operation parameters of SCPs, such as temperature and atmosphere conditions, were also evaluated using both TG and DTG approaches (Calvo et al., 2013; Manara and Zabanitoutou, 2012). The dynamic connection between sludge characteristics and SCP performance using TG and DTG techniques should be explored. However, little research has been conducted from this perspective at a comprehensive scale.

We aimed to investigate the relevant effects of sewage sludge composition on SCP performance and the consequences of such effects. The most significant constituent for SCP performance was also estimated to provide a reference basis for the future design and operation of SCPs.

2. Materials and methods

2.1. Brief description of sludge samples

All sludge samples were collected from 10 municipal WWTPs in Beijing, China, in June 2012. Table 1 presents a summary of these samples. Three kinds of sewage sludge derived from WWTPs were used: primary sludge (PS) from the primary clarifiers, waste activated sludge (WAS) from secondary clarifiers, and digested sludge (DS) from anaerobic digesters. Sludge samples were freeze-dried immediately after retrieval. After lyophilization, the sludge samples were ground to 100 mesh and stored at 4 °C before further tests.

2.2. Composition analysis of sludge samples

A standard method was used to determine the compositions based on proximate analysis, i.e., moisture, volatiles, ash, and fixed

Table 1
Description of sludge samples.

Sample no.	Sample source ^a	Capacity (×10 ⁴ m ³ /d)	Wastewater source	Treatment process ^b
1	WAS	7	Municipal	OD
2	WAS	7	Municipal	A ² /O
3	WAS	20	Municipal	OD
4	WAS	5	Industrial	CASS
5	WAS	5	Industrial	CASS
6	WAS	20	Municipal	Inverted A ² /O
7	WAS	20	Municipal	A ² /O
8	WAS	4	Municipal	UCT
9	PS	60	Municipal	A ² /O
10	WAS	60	Municipal	A ² /O
11	DS	60	Municipal	A ² /O
12	WAS	100	Municipal	General AS
13	WAS	8	Municipal	OD
14	WAS	8	Municipal	CASS

^a Sludge samples from the same sewage treatment plant are: sludge nos. 1 and 2; sludge nos. 6 and 7; sludge nos. 9, 10, and 11.

^b OD—oxidation ditch; A²/O: anaerobic–Anoxic–Oxic process; CASS—cyclic activated sludge system; UCT: a type of improved A²/O process, proposed by the University of Cape Town; AS—activated sludge process.

carbon (D5142-04, 2002). Proteins in various kinds of sludge originated from different sources. The PS protein was from a protein-containing substance in wastewater that settled in the primary sedimentation tank. The WAS and DS proteins were from microbial metabolism. Protein content was analyzed using a Kjeldahl instrument (UDK152). Carbohydrates and lipids were determined using a colorimetric method (Dubois et al., 1956) and an ether extraction method (Ferraz et al., 2004), respectively. The weight fractions of major elements (C, H, O, N, and S) were analyzed by two elemental analyzers (EAI CE-440 Element Analyzer and PE-2400 II Element Analyzer), and the net calorific value (NCV) was measured using an automatic oxygen bomb calorimeter (IKAC2000).

2.3. TGA approach of sludge samples and organic matter

TGA on real sludge samples and representative matter for sludge organics [i.e., bovine serum albumin (BSA), casein, glucose, starch, soybean oil, and lipids extracted from the sludge] were performed using a thermogravimetric analyzer (NETZSC STA-409PC). The weight of each sample was approximately 18 mg. The furnace temperature was increased from 40 °C to 850 °C at a rate of 10 °C/min with an air flux of 30 mL/min. The sample weight was monitored continuously as a function of temperature. Soybean oil and lipids extracted from the sludge were mixed with silicon dioxide to prevent splashing during combustion.

2.4. Determination of combustion characteristic index (CCI)

In this study, indicator CCI (mg² min^{−2} K^{−3}) represented the combined effect of four general combustion parameters (maximum combustion rate, average combustion rate, ignition temperature, and burnout temperature) and was used to evaluate the overall performance of SCP. Thus, CCI can be defined by the following equation according to a previous study (Wang et al., 2011):

$$CCI = \frac{(d_w/d_t)_{\max}(d_w/d_t)_{\text{mean}}}{T_i^2 T_h} \quad (1)$$

where $(d_w/d_t)_{\max}$ (mg/min) is the maximum combustion rate, $(d_w/d_t)_{\text{mean}}$ (mg/min) is the average combustion rate, T_i (K) is the ignition temperature, and T_h (K) is the burnout temperature. The combustion performance improved with increasing CCI (Wang et al., 2011).

2.5. Statistics approach for correction analysis

Statistics analysis was performed to identify the quantitative relationships of individual sludge characteristic and combustion performance, and a representative approach of univariate linear correlations was used (Ou et al., 2014; Yoshiyuki and Yutaka, 2003) with IBM SPSS Statistics 19.0 software (SPSS Inc., Chicago, IL). The Pearson's product momentum correlation coefficient was referred to as *R* value and was used for linear estimation. The value of *R* is in the range −1 to +1. A value of −1 indicates a perfect negative correlation, whereas a value of +1 represents a perfect positive correlation. A value of 0 indicates the absence of correlation.

3. Results and discussion

3.1. Sludge composition

Table 2 presents detailed data on sludge composition of the samples. Volatile compounds (50–74%) are the main components of sludge, and the amounts vary with the samples collected. The proportion of volatile compounds was lowest in sludge no. 5 (~50%) and was highest in sludge no. 8 (~74%). Volatiles of sludge

Table 2
Compositions analyses of sludge samples^a.

Sample no.	M ^b	A ^b	V ^b	FC ^b	Pro ^b	CHO ^b	L ^b	C ^b	H ^b	N ^b	S ^b	O ^b	NCV ^b
1	1.80	27.81	66.27	4.12	38.55	9.74	2.23	36.93	5.71	6.17	1.26	25.22	17.11
2	2.02	31.08	64.60	2.30	34.47	13.91	3.52	33.00	5.25	5.52	1.05	28.20	14.86
3	1.65	31.65	64.90	1.80	37.04	10.42	1.21	33.58	5.20	5.93	1.03	26.54	15.09
4	1.31	39.69	57.93	1.07	31.31	10.95	2.16	28.68	4.78	5.01	1.15	23.69	12.69
5	2.36	46.58	50.00	1.06	24.13	9.54	4.97	23.48	4.06	3.86	1.39	29.11	10.51
6	1.85	27.34	66.98	3.83	39.39	11.67	1.99	35.56	5.49	6.30	1.16	27.95	16.16
7	1.95	25.69	70.21	2.16	40.03	18.25	1.99	36.10	5.57	6.40	1.12	27.37	16.31
8	1.59	23.24	73.67	1.50	41.79	9.78	2.42	36.92	5.64	6.69	1.16	30.45	16.41
9	1.72	39.95	55.37	2.96	30.31	6.72	5.14	30.97	4.72	4.50	2.75	25.30	14.23
10	3.24	34.20	62.09	0.46	35.34	11.61	13.26	29.49	4.93	5.66	0.87	29.68	13.14
11	1.88	34.93	59.99	3.20	30.16	8.98	14.44	33.16	4.75	4.83	3.31	27.33	12.17
12	1.64	24.49	72.90	0.97	40.74	12.73	6.50	36.04	5.39	6.75	1.18	30.10	16.09
13	1.41	27.92	68.82	1.85	41.57	10.94	8.85	36.33	5.29	6.65	1.24	27.97	16.40
14	2.19	38.54	57.36	1.91	30.31	9.30	3.42	29.15	4.56	4.85	1.11	27.46	12.95

^a Unit: NCV MJ/Kg; others wt.%.

^b M—moisture; A—ash content; V—volatiles; FC—fixed carbon; Pro—protein; CHO—carbohydrates; L—lipid; NCV—net calorific value.

nos. 9, 10, and 11 varied even if they were derived from the same sewage treatment plant (55%, 62%, and 60%, respectively). Specifically, the volatile content of PS was lower than that of DS, and the volatile content of DS was lower than that of WAS. Ash is the second largest component in sludge. The ash contents of the sludge samples amounted to 23–47%. The fixed carbon and moisture contents of the sludge samples were very low (0.46–4.12% and 1.4–3.2%, respectively).

Organic matter was the main component of volatiles; and the main components, i.e., proteins, carbohydrates, and lipids, were analyzed (Table 2). Protein content was 24–44%, accounting for 47.5–60.4% of volatile compounds. The protein content of sludge no. 5 was the lowest, accounting for 24.13% of volatiles. The protein contents of all the other WAS samples were higher than in PS samples. Furthermore, the carbohydrates comprised 13.6–26.0% of all volatile compounds on average, and their contents were lower than those of proteins. The carbohydrate content of sludge no. 9 was the lowest (only 6.72%). Compared with other contents, the lipid contents of the sludge samples were low, with an average content of only 5.15%.

C, H, O, N, and S were the main elemental components of sludge, accounting for 62–81% of the total elements. Sludge also contained other elements, such as Ca, Si, K, P, Fe, Mn, Mo, B, Cr, Cu, Zn, Ni, and Pb. Obviously, C was the most abundant element in the 14 sludge samples, and element S was the least abundant. The highest C content reached 37% (in sludge nos. 1 and 8), and the lowest C content was 24% (in sludge no. 5).

The exhaust gases generated in SCPs mainly comprised oxides of carbon (CO_x), nitrogen (NO_x), and sulfur (SO_x), and H₂O, which is estimated to vary significantly with the sludge components (Magdziarz and Wilk, 2013). N content was highest in sludge nos. 8 and 12 among the investigated sludge samples; hence, a high NO_x emission could be expected considerably. The highest CO_x concentration was predicted during the combustion of sludge nos. 1 and 8, which had the highest C contents. The contents of S in PS (sludge no. 9) and DS (sludge no. 11) were approximately 2-fold to 3-fold higher than in WAS. Sludge with high S content may produce more sulfur dioxide (SO₂) during the combustion process, and SO₂ emissions will increase the difficulty and cost of subsequent processing for air pollution control.

The NCV of biomass is crucial for the conversion of biomass to energy and biofuels. Table 2 shows the variation of NCVs (10.51–17.12 MJ/kg) of various sludge samples. Sludge NCV was affected by moisture, ash, and oxygen contents, and the drying process (Magdziarz and Werle, 2014). Sludge no. 5, which had the highest ash content (46.58%), had the lowest NCV (10.51 MJ/kg).

3.2. TGA of sludge

The sludge samples were heated from 40 °C to 850 °C in the TGA process. Combustion of the samples took place with increasing temperature and with associated mass losses, which were observed in the TG and DTG curves (Fig. 1). The curves for sludge nos. 2 and 3 were similar to that of sludge no. 1, and the curve of sludge no. 6 was similar to that of sludge no. 7.

Fig. 1 shows the TG and DTG curves of sludge samples. The shapes of the TG and DTG curves varied for different sludge samples. The lowest weight loss was observed for sludge no. 5, which had the lowest volatile content. The DTG curves revealed the weight loss rate, i.e., the combustion rate. Fig. 1 shows that the weight loss rate of sludge no. 5, which had the lowest volatile and protein contents (50% and 24%, respectively), was significantly lower than those of the other sludge samples. The weight loss rate of sludge no. 8, which had the highest volatile and protein contents (74% and 42%, respectively), was the largest. The numbers of weight loss peak in the DTG curves of sludge samples are also different. No obvious peak appeared in the range 175–300 °C for sludge nos. 9, 11, and 14, but all other sludge samples showed obvious peaks. The different peak numbers were related to the airflow rate and composition of the sludge samples (Norton, 1993). However, the present test was conducted under the same airflow speed. Therefore, the phenomena of different peak numbers may be related to the sludge composition. If the content of a substance that combusted in the range 175–300 °C was insufficient, a peak may not appear in such a temperature range. Table 2 shows that the carbohydrates contents of sludge nos. 9, 11, and 14 were the lowest, i.e., 6.72%, 8.98%, and 9.30%, respectively. The low carbohydrate content may explain the absence of a peak at 175–300 °C in the DTG curve.

The TG curves of sludge samples showed continuous mass loss. This occurred in stages for all sludge samples in combustion. Sludge weight losses were divided into five stages based on temperature and according to the TG curves: 40–175 °C, 175–300 °C, 300–400 °C, 400–600 °C, and 600–850 °C. The first stage is often attributed to water volatilization (Werther et al., 1995; Zhao et al., 2013), and the weight losses in the first stage were 5.01–9.42% here. However, the moisture contents of the samples were only 1.4–3.2% (Table 2). The weight losses in the first stage were much higher than the moisture contents. Hence, some very light volatile compounds also evaporate at this stage, as mentioned in a previous study (Magdziarz and Wilk, 2013). The weight loss in the second and third stages represented the combustion of volatiles. The second stage involved the combustion of biodegradable

Fig. 1. TG and DTG curves of sludge samples.

small-molecule organic compounds, while the third stage represented the combustion of macromolecule organic matter (Barneto et al., 2009). The weight losses during the second and the third stages contributed approximately 77% of the total weight loss. In the fourth stage, the shoulder in the DTG curves was due to the combustion of fixed carbon. The mass loss in the fifth stage was mainly due to CaCO_3 decomposition (Folgueras et al., 2013).

Table 3 shows the TGA results, including maximum combustion rate, average combustion rate, ignition temperature, burnout temperature, and CCI. Sludge no. 5 had the lowest maximum combustion rate, the lowest average combustion rate, and the highest burnout temperature. The ignition temperature of PS sample (sludge no. 9) was lower than that of WAS and DS samples (except sludge no. 14), thereby showing that PS is easy to ignite. The CCIs of sludge nos. 6, 7, and 8 were high, thereby indicating that these sludge samples have good comprehensive combustion performances. The average WAS CCI of $4.3 \times 10^{-10} \text{ mg}^2 \text{ min}^{-2} \text{ K}^{-3}$ was higher than that of DS (sludge no. 11, $3.54 \times 10^{-10} \text{ mg}^2 \text{ min}^{-2} \text{ K}^{-3}$).

3.3. TGA of organic matter

As mentioned above, the most important components of sludge are the proteins, carbohydrates, and lipids, which account for

Table 3
Characteristic sludge combustion parameters.

Sludge no.	$(d_w/d_t)_{\max}$ (mg/min)	$(d_w/d_t)_{\text{mean}}$ (mg/min)	T_i (K)	T_h (K)	CCI ($10^{-10} \text{ mg}^2/(\text{min}^2 \text{ K}^3)$)
1	0.66	0.16	473.98	1031.48	4.51
2	0.72	0.17	483.98	1078.98	4.77
3	0.74	0.17	480.65	1047.32	5.25
4	0.54	0.14	477.32	1054.82	3.14
5	0.42	0.13	488.98	1081.48	2.14
6	0.73	0.19	502.32	1028.98	5.46
7	0.73	0.18	500.65	1024.83	5.24
8	0.78	0.19	513.15	1023.98	5.47
9	0.67	0.17	473.98	1064.82	4.90
10	0.69	0.18	503.15	1078.98	4.62
11	0.54	0.15	495.65	1053.15	3.54
12	0.62	0.16	499.82	1035.65	3.73
13	0.73	0.17	506.48	1080.65	4.90
14	0.49	0.13	463.98	1062.32	2.37

$((d_w)/(d_t))_{\max}$ is the maximum combustion rate, $((d_w)/(d_t))_{\text{mean}}$ is the average combustion rate, T_i is the ignition temperature, T_h is the burnout temperature.

76–97% of the sludge volatile contents. Therefore, the combustion characteristics of these organic materials were analyzed in detail in the following Section. BSA protein, casein, glucose, starch, soybean

oil, and lipid extracted from the sludge were investigated using TGA, and the relevant TG–DTG curves are shown in Fig. 2. The first stage was mainly associated with moisture vaporization, whereas in the second and third stages, the samples were subjected to organic matter combustion. The fourth and the fifth stages failed to occur because the organic materials were pure substances, except for fixed carbon and inorganic substances. Fig. 2 shows that all these organic compounds showed weight losses in the second and third stages. The weight losses in the second stage for BSA protein, casein, glucose, starch, soybean oil, and lipids extracted from sludge amounted to 0.8, 0.8, 2.2, 2.5, 2.3, and 3.2 times of those in the third stage, respectively. Therefore, the protein contents (BSA protein and casein) in the two main weight loss stages did not obviously differ. However, the weight losses for carbohydrates (glucose and starch) and lipids (soybean oil and lipid extracted from sludge) in the second stage were greater than those in the third stage.

The weight loss rate peaks in the second stage of the DTG curves of glucose and starch were higher than those in the third stage. The maximum combustion rates of glucose in the second and third stages were 0.38 and 0.14 mg/min, respectively. The maximum combustion rate of glucose in the second stage was 2.7 times that in the third stage. The peak values for starch in the second and third stages were 1.26 and 0.13 mg/min, respectively. The maximum combustion rate of starch in the second stage was approximately 10 times that in the third stage. The maximum

combustion rate of carbohydrates in the second stage was much higher than that in the third stage. The maximum combustion rates of glucose (0.37 mg min^{-1}) and starch (1.25 mg min^{-1}) were much higher than those of other organic substances (Fig. 2). Therefore, carbohydrate content had a significant effect on the sludge combustion rate in the second stage. Low carbohydrate content resulted in low combustion rate in the second stage. A sufficiently high third peak resulted in a non-obvious second peak. In this case, no obvious peak appeared in the second stage, as observed in the DTG curves of sludge nos. 9, 11, and 14.

The glucose ignition temperature (135°C) could be determined from the TG and DTG curves of glucose (Fig. 2). This finding also confirmed that small-molecule volatiles were released during the first stage ($40\text{--}175^\circ\text{C}$) of sludge combustion.

3.4. Effect of sludge components on combustion performance

A comparison of the volatile content and the CCI of the sludge samples showed that the highest CCI was found in sludge no. 8, which had the highest volatile content (74%). The lowest CCI was found in sludge no. 5, which had the lowest volatile content (50%). A comparison of the maximum combustion rates and the volatile content of these sludge samples showed that the CCI values of sludge nos. 5 and 8 were the lowest and highest, respectively. Thus, the maximum combustion rate of sludge was associated with volatile content. As studied previously (Ischia et al.,

Fig. 2. TG and DTG curves of organic components.

Table 4

Correlation coefficient of sludge compositions and combustion performance.

	M	A	V	FC	Pro	PS	L	C	H	N	S	O	NCV	CCI
M	1	–	–	–	–	–	–	–	–	–	–	–	–	–
A	0.29	1	–	–	–	–	–	–	–	–	–	–	–	–
V	–0.32	–0.99*	1	–	–	–	–	–	–	–	–	–	–	–
FC	–0.28	–0.20	0.06	1	–	–	–	–	–	–	–	–	–	–
Pro	–0.28	–0.96*	0.97*	0.02	1	–	–	–	–	–	–	–	–	–
PS	0.08	–0.49	0.51	–0.17	0.46	1	–	–	–	–	–	–	–	–
L	0.44	0.15	–0.15	–0.18	–0.18	–0.19	1	–	–	–	–	–	–	–
C	–0.46	–0.94*	0.91**	0.44	0.90**	0.33	–0.14	1	–	–	–	–	–	–
H	–0.34	–0.95*	0.92**	0.34	0.94**	0.46	–0.31	0.94*	1	–	–	–	–	–
N	–0.29	–0.96**	0.98**	0.06	0.99**	0.49	–0.17	0.88**	0.92**	1	–	–	–	–
S	–0.15	0.31	–0.36	0.42	–0.42	–0.50	0.48	–0.07	–0.34	–0.49	1	–	–	–
O	0.41	–0.34	0.38	–0.42	0.27	0.21	0.31	0.11	0.11	0.35	–0.25	1	–	–
NCV	–0.42	–0.90**	0.87**	0.37	0.93**	0.36	–0.38	0.92**	0.95**	0.86**	–0.32	0.07	1	–
CCI	–0.18	–0.71**	0.67**	0.32	0.75**	0.30	–0.18	0.73**	0.78**	0.62*	–0.13	0.08	0.77**	1

M moisture; A ash content; V volatiles; FC fixed carbon; Pro protein; CHO carbohydrates; L lipid; NCV net calorific value.

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

2007; Magdziarz and Wilk, 2013), the main components of ash generally include a variety of stable inorganic compounds, such as SiO₂, CaO, MgO, Fe₂O₃, and Al₂O₃, the combustion of which will require additional heat. Hence, relatively low CCI scores were observed with high ash contents among the samples.

The main components of volatile compounds were proteins, which accounted for 46–60% of the total volatile components. A comparison of CCI and protein content showed that sludge no. 8 had the highest protein content and CCI scores, whereas sludge no. 5 had the lowest values for these parameters. Thus, protein content was connected closely with sludge combustion performance.

To determine the key factors affecting combustion performance, Pearson correlation of CCIs and sludge characteristics were analyzed subsequently. Table 4 shows the *R* values among the CCIs and sludge characteristics. The *R* values of CCI and protein were higher than those of CCI and volatiles (0.75 vs. 0.67), thereby showing that a much higher correlation was observed between CCI and protein content. Unlike proteins, carbohydrates and lipids did not show a good correlation with CCI. Additionally, correlations between combustion performance and caloric value were also estimated in a previous literature (Sebestyén et al., 2011). The elements of C, H and N, which are important components of protein, were also estimated to be highly linked with CCI in the present work. Overall, the volatile compounds, particularly proteins, are the important factors that affect sludge combustion performance.

4. Conclusions

The combustion characteristics of numerous representative sludge samples were studied in this work. Differences were found between these samples, and these samples varied substantially in terms of sludge composition. Specifically, much higher correlations were found between combustion performance and the content of proteins. Unlike proteins, carbohydrates and lipids were negatively linked with combustion performance. Nevertheless, the combustion of carbohydrates was mainly found in the second stage, and the combustion rate was marked higher than those of other organic substances. Owing to the specific features of carbohydrates, sludge nos. 9, 11, and 14, which had the lowest carbohydrates content, showed no peak in the DTG curve in the second stage. In addition, the combustion performance of DS was observed to be more negative compared with other types of sewage sludge. Thus, DS is not recommended for direct combustion in this work. Further research is needed for clarity.

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