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Combustion Characteristics and Slagging during Co-Combustion of Rice Husk and Sewage Sludge Blends

Hao Rong [1,2], Teng Wang [1,2], Min Zhou [1,2], Hao Wang [4], Haobo Hou [1,2,*] and Yongjie Xue [3,*]

1 School of Resource and Environmental Science, Wuhan University, Wuhan 430079, China; ronghao2363568@sina.com (H.R.); 2014102050042@whu.edu.cn (T.W.); zhoumin@whu.edu.cn (M.Z.)
2 Hubei Environmental Remediation Material Engineering Technology Research Center, Wuhan 430079, China
3 State Key Laboratory of Silicate Materials for Architectures, Wuhan University of Technology, Wuhan 430070, China
4 Department of Civil and Environmental Engineering, Rutgers, The State University of New Jersey, New Brunswick, NJ 08901, USA; hwang.cee@rutgers.edu
* Correspondence: hhb-bhh@163.com (H.H.); xyjskl@whut.edu.cn (Y.X.); Tel.: +86-139-086-44407 (H.H.); +86-135-450-37042 (Y.X.)

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Abstract: In this work, the thermal behavior of rice husk, sewage sludge, and their blends during combustion processes was investigated by means of thermogravimetric analysis (TGA), and the slagging characteristics were studied through X-ray fluorescence (XRF) and melting temperature. The effects of the proportion of rice husk and sewage sludge blends on the combustion process, ignition and burnout characteristics were also studied. The blends had rice husk percentages of 30, 50, 70 and 100%. The results indicate that there are four main stages of the material burning processes: dehydration, volatile oxidation, and decomposition/oxidation. The reactivity of the blends improved with increasing amounts of rice husk and the results suggest synergistic interactions between rice husk and sewage sludge during the co-combustion process. All co-combustion ashes showed a lower slagging potential owing to their high amorphous SiO_2 content. On the basis of combustion properties and slagging characteristics of ash, the ratio of sewage sludge in the blends should not exceed 30%.

Keywords: rice husk; sewage sludge; co-combustion; thermogravimetric analysis (TGA); slagging

1. Introduction

Biomass has been used in industrial production activities as a source of renewable energy and a substitute for fossil fuels. The use of this kind of renewable fuel for power production is governed by legal and international regulations, and its utilization as bio-fuel is a critical component of sustainable growth for most countries [1]. Direct combustion is the simplest, most common and successful thermo-chemical process for converting biomass into energy and is considered an effective method for biomass energy recovery in the short term [2]. Among different types of biomass, rice husk is commonly used as bio-fuel for power plants owing to its low average heating value [3].

Sewage treatment plants generate solid wastes known as sewage sludge, which may contain toxic substances, including inorganic and organic compounds as well as pathogenic microorganisms [4]. With higher expected standards for the amount and quality of water, the amount of sludge is increasing rapidly, and therefore, waste management and reutilization of sludge are required. The main problems in treatment of sludge for thermal utilization arise from the large volume and high moisture content. These problems will eventually lead to environmental risks, inefficient land use, and wasting of resources.

It is believed that thermal processes, such as mono-combustion and co-combustion of sludge with other fuels, can be implemented for converting large quantities of sludge into useful energy [5] and construction materials. Co-combustion is an efficient and direct method to combust mixtures of different fossil fuels, bio-fuels, and other flammable materials [6]. Through this method, not only can the amount of sewage sludge be decreased, but energy can also be generated. Unlike mono-combustion, co-combustion facilitates reductions in the emission of hazardous substances to the atmosphere. Sludge is difficult to burn directly because of its low heating value (LHV). Co-combustion of sludge with biomass fuels can make burning easier. However, the chemical and physical properties of the fuel used affect the characteristics of the combustion process [7]. Consequently, the residue from co-combustion using different fuels also varies, and these properties are discussed herein.

Thermogravimetric analysis (TGA) has been commonly used to describe and characterize thermal processes and combustion of sewage sludge, biomass, coal and other materials [8,9]. It facilitates not only preliminary evaluation of fuel values in investigating initial and final temperatures in the process of combustion, but also other relevant experimental data such as ignition or burnout temperature, and combustion time at different stages. TGA provides important information for the prediction of combustion efficiency and helps in determining the optimal operating conditions for combustion in power plants. Once the optimum mix proportion and combustion parameters of different biomass fuel are determined, further investigation on the residue from the process of co-combustion can be conducted. Using TGA data, the characteristics of residue from the combustion of rice husk, which is defined by combustion conditions, can be analyzed [10]. Previous researchers have focused on TGA of sewage sludge and found that the production of sludge–straw pellets is not suitable in its current state because of the high ash slagging potential [11]. According to derivative thermogravimetric analysis (*DTG*) profiles of the fuels, coal can be beneficially burned with sewage sludge and biomass [12].

In addition to combustion characteristics, slagging is another crucial factor affecting the widespread application of co-combustion technology. Fouling and slagging, which are phenomena related to the boiler gas, are somehow correlated although they are not exactly the same. Fouling, also called ash deposition, is the deposition of non-melting ash on the heating surface [13]. The non-melting ash indicates that the temperature is below its melting point. Deposition often occurs on convection heating surfaces. Slagging is the deposition of melting ash or semi-melting ash on the heating surface and it often occurs on radiant heating surfaces. Fouling and slagging on the heating surface of boilers are relatively common problems in power plants in China. They negatively affect boilers, not only reducing slag removal and thermal efficiency, but also shortening the operating life. With the increasing unit capacity and frequent changes in coal quality, the problem becomes more serious. The implementation of massive projects showed that biomass involves more serious slagging and fouling problems than coal, because biomass has higher alkali metal and chlorine content [14]. Thus, the chemical characteristics of biomass have greatly limited its application.

In general, information about the co-combustion behavior of sewage sludge and rice husk is lacking, thereby leading to a lack of scientific evidence for evaluating engineering application feasibility and conducting cost comparison analyses. The main objective of this work is to study the combustion characteristics and slagging of rice husk, sewage sludge, and their blends with different weight ratios of sludge. Ignition and burnout properties of different samples, as well as their slagging characteristics and ash characteristics are obtained. The results obtained may be useful in understanding the characteristics of rice husk/sewage sludge co-combustion residues and offer important thoughts for further evaluation and application of rice husk/sewage sludge co-combustion residues in environmental impact assessments and studies on reutilization processes.

2. Materials and Methods

2.1. Materials

Rice husks were collected from a local rice mill plant located at Jiangxia (Wuhan, China). Sewage sludge was obtained from the Sha Lake waste water treatment unit in Wuhan. These two materials were selected owing to their high annual production rates in China. The experiments were initiated within the shortest possible time after obtaining the samples from the wastewater treatment units in order to avoid chemical transformations of sludge. Sewage sludge samples were first air-dried for 8 h and then dried in an oven at 105 °C for two days. Pre-treatment sludge was mixed with rice husk at 25 °C before thermal treatment. Five types of rice husk-sewage sludge blends were prepared with increasing sewage sludge weight percentages of 0, 30, 50, 70 and 100%. In this study, samples were named according to their rice husk content and sewage sludge content. For example, 7R3S describes a mixture with a rice husk content of 70% and a sewage sludge content of 30%.

2.2. Ultimate and Proximate Analysis

The prepared samples were analyzed to determine the major parameters affecting the thermal conversion process. Proximate analysis was carried out according to the Standard Practice for the Proximate Analysis of Coal and Coke (GB/T212-1991), while the hydrogen, carbon, sulfur and nitrogen contents were determined through the ultimate analysis, which was performed using VARIO EL cube instrument (Elementar, Langenselbold, Germany). The high heating value (HHV) of the blends was measured by Oxy-II oxygen bomb calorimeter (Yisheng, Wuhan, China).

2.3. Methods and Apparatus

The combustion characteristics of sewage sludge, rice husk, and their blends were determined using an STA-449c/3/G thermogravimetric analyzer (NETZSCH-Gerätebau GmbH, Selb, Germany). All combustion experiments were conducted under atmospheric pressure at temperatures varying from room temperature to 1000 °C with a heating rate of 25 °C/min and an air flux of 50 mL/min. To minimize the effects of mass and heat transfer limitations, about 10 mg of samples were loaded into an alumina crucible. Three replicates of each thermogravimetric experiment were conducted. The differential thermal gravity (*DTG*), thermal gravity (*TG*), and differential scanning calorimetry (*DSC*) were calculated and described as a function of time and temperature during the thermal process.

2.4. Characterizations of Ignition and Burnout

Ignition temperature T_i is not a physical characteristic of any kind of fuel [15,16]. T_i is applied to the evaluation of different specimens for the same combustion procedure or operational conditions in order to compare their reaction activity. T_i and burnout temperature T_f, from the *DTG* and TG curves, can be determined according to Figure 1 [17,18].

The burnout index D_f and the ignition index D_i are calculated by the following equations [19]:

$$D_i = \frac{DTG_{\max}}{t_p t_i} \tag{1}$$

$$D_f = \frac{DTG_{\max}}{\Delta t_{1/2} t_p t_f} \tag{2}$$

where $DTG_{\max}$ is the maximum combustion rate, t_p is the corresponding time of the maximum combustion rate, $\Delta t_{1/2}$ is the time zone of $DTG/DTG_{\max} = 1/2$, and t_f and t_i are the burnout time and ignition time, respectively.

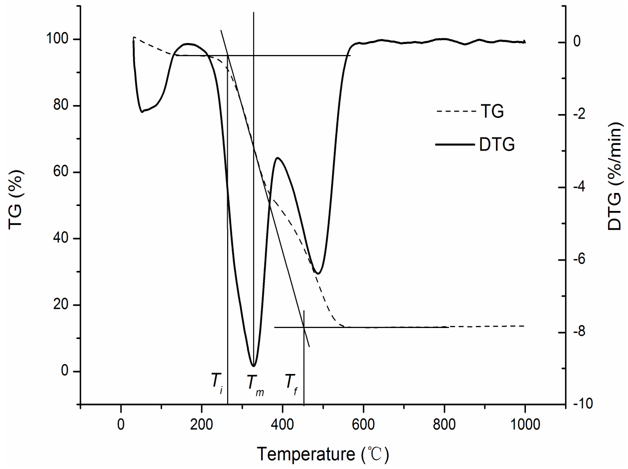

Figure 1. Determination of temperature of ignition (T_i), temperature of burnout (T_f) and temperature at the maximum weight loss rate (T_m).

2.5. Ash Elemental Analysis

The chemical composition of residue from the combustion of rice husk, sewage sludge, and their blends was analyzed using an Axios advanced X-ray fluorescence (XRF) spectrometer (PANalytical, Almelo, The Netherlands). In order to obtain the ash sample, a muffle furnace with ventilation was used to co-combust the rice husk and sludge blends at 815 ± 15 °C for the preparation of ash samples according to the GB/T 212-2008 method [20]. We named the ash sample according to its mixing ratio of sludge and rice husk, for example, 7R3S-A represents the residue of 7R3S after combustion. Oxide compositions of the residue, as well as the bed agglomeration index and base/acid ratio, were investigated in this study.

2.6. Characteristics of Ash Melting

Ash melting characteristics including deformation temperature (DT), softening temperature (ST), hemispherical temperature (HT), and fluidization temperature (FT) were determined using an ash melting point tester (SDAF2000d, Sande, Changsha, China). During the experiment, the carbon reduction method was used to control the weak reducing atmosphere.

2.7. X-ray Diffraction (XRD) Quantitative Phase Analysis

X-ray Diffraction (XRD) (Bruker, Billerica, MA, USA) was used to study the mineralogical composition of the co-combustion ash samples. The ashes were mixed with CaF_2 (internal standard) on a 70:30 weight basis and subjected to XRD. CaF_2 was used to determine the amorphous content of the samples [21,22]. The XRD tests were conducted using a Bruker (Billerica, MA, USA) D8 Advance diffractometer with Cu Ka1,2 radiation (1.5418 Å). The data for each sample were collected for the range of 10°–70° (2θ) for 2 h. Qualitative and quantitative measurements of the samples were conducted using the JADE (Jade 6.0, Telecom Italia, Milan, Italy) and MAUD (Maud 2.55, University of Trento, Trento, Italy) software.

3. Results and Discussion

3.1. Proximate and Ultimate Analysis of Rice Husk and Sewage Sludge

The ultimate and proximate analysis results of sewage sludge and rice husk are described in Table 1. Sewage sludge has higher ash and lower volatile matter compared with rice husk. The content of fixed carbon was nearly the same in both materials. Further, the LHV of sewage sludge materials was lower than that of rice husk. The high volatility of rice husk was advantageous for combustion. The LHV is calculated by Equation (3) [23].

Figure 2 shows the LHV and HHV of different mixtures. Without the addition of fuel, the blends required an LHV of >3 MJ/kg for incineration; an LHV of >4 MJ/kg was required for waste-heat utilization. In order to ensure auto-thermal combustion, an LHV of higher than 4 MJ/kg is recommended [24]. The LHV of rice husk and sewage sludge blends indicates that waste sludge is suitable for co-combustion with other fuels, such as rice husk, to minimize its high ash content risk and potential environmental problems. The element analysis showed that rice husk has higher hydrogen content than sewage sludge. The combustibility of a fuel increases with higher hydrogen content. Therefore, it is expected that the blending of higher hydrogen and volatile content rice husk with sewage sludge will result in the enhancement of ignition.

Table 1. Properties of raw rice husk and sewage sludge.

Analysis	Ultimate Analysis (wt %)					Proximate Analysis (wt %)			
	C	H	O	S	N	M_{ad}	V_{ad}	FC_{ad}	A_{ad}
Rice husk	42.72	6.60	40.71	0.11	0.26	4.7	80.1	10.3	4.9
Sewage sludge	12.89	1.53	13.67	0.67	2.24	4.5	25	6	64.5

Notes: A_{ad}, ash (air-dried basis); V_{ad}, volatile matter (air-dried basis); FC_{ad}, fixed-carbon (air-dried basis); M_{ad}, moisture content (air-dried basis).

$$Q_{net,ad} = Q_{gr,ad} - 206H_{ad} - 203M_{ad} \quad (3)$$

where $Q_{net,ad}$ is the LHV of air-dried basis, $Q_{gr,ad}$ is HHV of air-dried basis, and H_{ad} is the hydrogen content of air-dried basis.

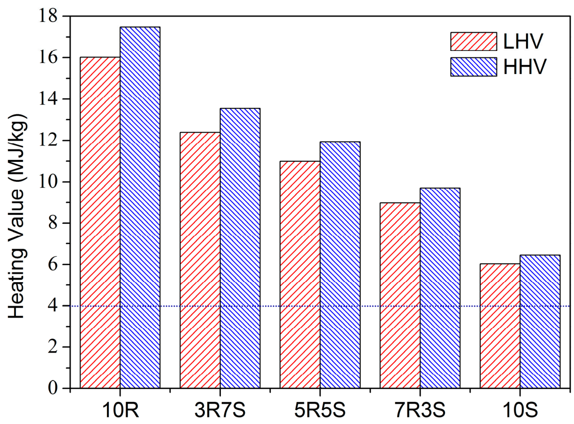

Figure 2. Low heating value (LHV) and high heating value (HHV) of fuel blends.

3.2. Mono-Combustion Behavior of Rice Husk and Sewage Sludge

TG, *DTG* and *DSC* profiles of rice husk and sewage sludge blends with different sludge to rice husk ratios are shown in Figures 3–5, respectively. The characteristic temperatures, reaction time, and peak points in the curve of the combustion process are listed in Table 2.

The ignition temperature is estimated from the *DTG* and *TG* curves in previous reports [25]. The final combustion temperature is the temperature at which more than 99% of flammable materials have been burnt out [26]. For rice husk, the *TG* and *DTG* curves in Figures 3 and 4 show that there are three main peaks during the combustion process and each has a clear burnout temperature. The first peak at the temperature of 100 °C is attributed to the evaporation of moisture and volatilization of small organic molecules deposited onto the surface of the rice husk. The second peak with a maximum weight loss rate of 12.56%/min at a temperature of 296 °C is attributed to continuous evaporation of moisture and loss of volatiles contained in the rice husk. The third peak occurs between 420 °C and 590 °C, with a maximum weight loss rate at 505 °C. The results indicate the occurrence of char gasification, loss of volatiles and fixed carbon, and combustion of hydrocarbons. These peaks likely occurred because rice husk is made of various hydrocarbon species with a wide range of boiling points. There are large differences in the *TG* and *DTG* curves of sewage sludge and rice husk. The peaks in the *DTG* profiles of sewage sludge are not sharp because weight loss of sewage sludge is a slow process. The first peak near 100 °C is due to the evaporation of moisture. The second peak with a maximum weight loss rate of 2.24%/min at a temperature of 281 °C develops from the continuous evaporation of moisture and loss of volatiles in sewage sludge. The third peak occurs between 400 °C and 520 °C, with a maximum weight loss rate at 490 °C. In the last stage of sewage sludge combustion, inorganic materials are decomposed and then burnt quickly at around 700 °C, with a continuous weight loss beyond 720 °C. As shown in Table 2, sewage sludge has the highest burnout temperature (721 °C) and the lowest total burnout (33.76%). The *DSC* curves of rice husk and sewage sludge are shown in Figure 5. The exothermic range and heat release of rice husk are higher than those of sewage sludge.

Consequently, the combustion of rice husk is easier than that of sewage sludge. This is mainly due to the combustion and emission of volatile matter in rice husk. Sewage sludge has higher moisture and ash, and lower volatile matter content; therefore, it is recommended that sewage sludge is recommended be burnt with materials having higher volatile matter.

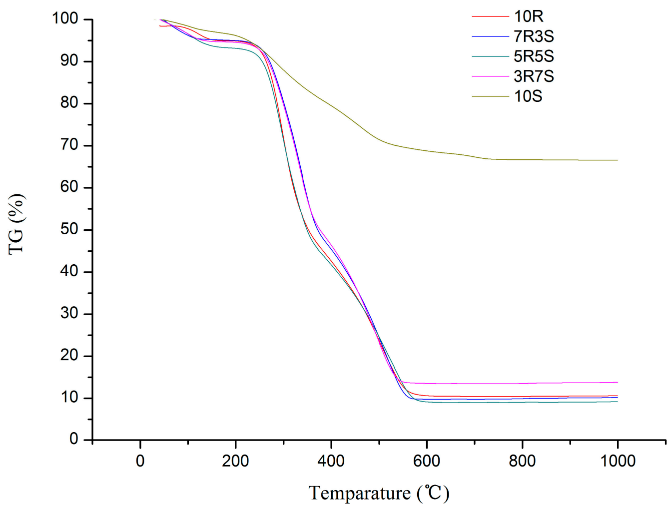

Figure 3. Combustion thermal gravity (*TG*) profiles of rice husk–sewage sludge with different sludge ratios.

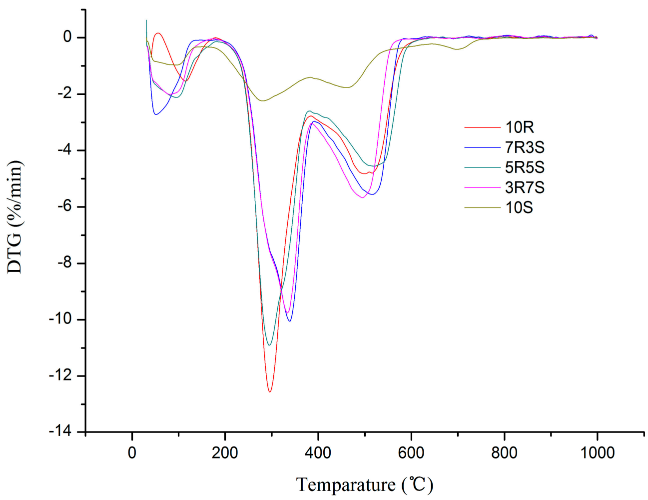

Figure 4. Combustion differential thermal gravity (*DTG*) profiles of rice husk–sewage sludge with different sludge ratios.

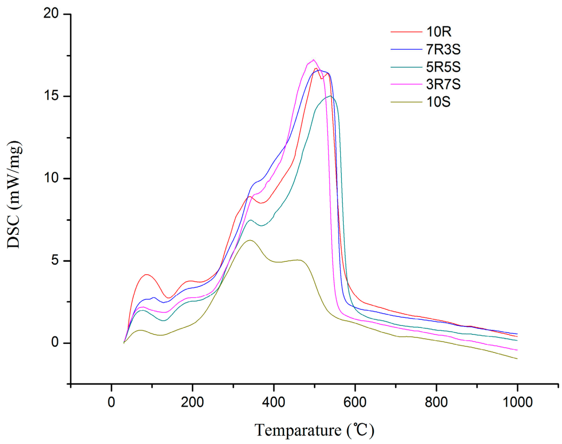

Figure 5. Combustion differential scanning calorimetry (*DSC*) profiles of rice husk–sewage sludge with different sludge ratios.

Table 2. Properties of raw rice husk and sewage sludge.

Sample	10R	7R3S	5R5S	3R7S	10S
DTG_{max} (%/min)	12.56	10.05	10.90	9.75	2.24
t_i (min)	14.8	16.1	15.2	16.1	12.7
t_p (min)	16.9	20.3	17.6	20.2	16.7
t_f (min)	26.2	25.9	26.5	25.2	34.7
$\Delta t_{1/2}$ (min)	9.6	10.7	10.1	10.6	7.5
D_i	5.02×10^{-2}	3.08×10^{-2}	4.07×10^{-2}	3.00×10^{-2}	1.06×10^{-2}
D_f	2.95×10^{-3}	1.78×10^{-3}	2.31×10^{-3}	1.80×10^{-3}	5.13×10^{-4}
T_i (°C)	263.6	264.8	269.1	272.1	291.3
T_f (°C)	553.5	547.5	559.6	532.5	721
T_{max} (°C)	295.9	338.5	295.1	333.8	281.1
R_m (%/min °C)	0.042	0.03	0.037	0.029	0.008
Total Burnout (%)	88.06	91.45	91.01	86.87	33.76

Notes: DTG_{max}, maximum combustion rate; t_p, corresponding time of maximum combustion rate; t_i, ignition time; t_f, burnout time; $\Delta t_{1/2}$ is the time zone of $DTG/DTG_{max} = 1/2$; T_i, ignition temperature; T_f, burnout temperature; D_i, ignition index; D_f, burnout index; R_m, mean reactivity.

3.3. Co-Combustion Behavior of Rice Husk and Sewage Sludge Blends

Figures 3–5 also show the *TG*, *DTG*, and *DSC* curves of the thermal processes for rice husk and sewage sludge co-combustion. For the *TG* curves, with increasing temperature after combustion of samples, moisture decreases, accompanied by associated weight losses. The profiles of blend samples contain several peaks that change mainly depending on the characteristics of the content of rice husk. Within most of the temperature ranges, the *TG* curves of the blends locate between those of rice husk and sewage sludge used to prepare the blends. For all *TG* curves, clear and rapid weight loss is observed. This is mainly because of early emission of volatile matter, which distinguishes the burning behavior of rice husk from that of sewage sludge. With increasing amounts of sewage sludge, the total weight loss of the blends decreases (from 88.06% to 33.76%). In the meantime, TG curves are upward and the temperature required increases, with the weight loss stages of the blends transforming from two to four, and the stages of volatile matter become more obvious. In particular, the total burnout with 30% and 50% of sewage sludge (91.45% and 91.01%) are higher than that for either rice husk (88.06%) or sewage sludge (33.76%). In this study, the co-combustion burnout is improved and enhanced by blending. This result may suggest synergistic interactions between rice husk and sewage sludge during the co-combustion process.

For the *DTG* curves, two or four peaks were associated with fixed carbon, combustion of volatile matter, and dehydration, which could dominate the combustion of rice husk, sewage sludge, and their blends. With decreasing content of sewage sludge in the blends, the combustion performance became more similar to that of rice husk. The maximum weight loss rate ($DTG_{\max}$) of the blends was higher than that of sewage sludge. The peak weight loss rate of the blends decreased initially, and then increased with increasing amounts of rice husk. However, the changing rules of other combustion characteristics such as corresponding ignition time (t_i), maximum combustion rate (t_p), burnout time (t_f) and $\Delta t_{1/2}$ in the blends were not obvious. This might show that the combustion processes of the blends are more complicated, which could be primarily due to the interaction of combustion between rice husk and sewage sludge. Therefore, when sewage sludge is used to partially replace rice husk in the blends, the appropriate content should be optimized according to the integrative characteristics of both materials. In order to evaluate the reaction activity of rice husk and sewage sludge blends, mean reactivity (R_m), which is defined as inversely proportional to peak temperature ($T_{\max}$) and directly proportional to the $DTG_{\max}$, is introduced [27] and applied in this work. As shown in Table 2, the value of R_m decreased with increasing proportions of sewage sludge. As expected, the ignition temperature (T_i) of the sample decreased gradually with the increase of rice husk. Generally, the lower value of the final temperature (T_p) indicated that it was more difficult to burn and required higher temperature and longer residence time for complete combustion [26]. Consequently, it was verified that the final temperature and residence time of the blends increased with increasing sewage sludge ratio. Compared with the ignition index (D_i) of all of the samples, D_i of the blends decreased from 5.02×10^{-2} to 1.06×10^{-2} with the increase of sewage sludge content, while the burnout index (D_f) decreased from 2.95×10^{-3} to 0.513×10^{-3} with the increase in sewage sludge content. Combined with the results of the ignition and burnout temperatures, the ignition and burnout characteristics of sewage sludge were improved by the combined effects of rice husk and sewage sludge. It is clear that volatile components were released from rice husk at lower temperatures and combusted to release enough energy for the combustion of sewage sludge. This effect was enhanced when the rice husk ratio in the blends was increased.

For the *DSC* curves, the exothermic regions and peaks both shift to lower temperature regions with an increase in sewage sludge percentage. The effect of sewage sludge materials on accelerating rice husk oxidation was verified. In addition, rice husk and sewage sludge blends showed few responses to *DSC* tests at the second and third stage with low heat release compared with that of the test on rice husk alone. Based on the above observations, it should be noted that the different physical/chemical properties among different raw biomass materials may lead to different handling and combustion behaviors.

3.4. Slagging Characteristics and Evaluation

3.4.1. Slagging Index Evaluation of Ash from Co-Combustion

The compositions of ash generated from combustion of rice husk, sewage sludge and their blends are presented in Table 3. With an increase of sewage sludge, the content of SiO_2 dramatically decreased while the content of Al_2O_3 increased. CaO, Na_2O, P_2O_5, and Fe_2O_3 contents were much lower and showed an increasing trend with an increase in sewage sludge:

$$B/A = (Fe_2O_3 + CaO + MgO + Na_2O + K_2O)/(SiO_2 + Al_2O_3 + TiO_2) \quad (4)$$

$$BAI = Fe_2O_3/(K_2O + Na_2O) \quad (5)$$

Slagging predictions such as the bed agglomeration index (*BAI*) and base/acid ratio (*B*/*A*) which are based on chemical composition analysis of the ashes are provided in Table 3. The test results characterize the combustion and ash forms when rice husk-sewage sludge was used as fuel in a boiler, such as a fluidized-bed reactor. The *BAI* and base/acid ratio (*B*/*A*) are calculated by Equations (4) and (5) [28]. Slagging is possible when base/acid ratio (*B*/*A*) values vary from 0.206 to 0.4, while it certainly occurs when these values are greater than 0.4. Bed agglomeration probably occurs when the BAI values are lower than 0.15 [29]. According to *BAI* in Table 3, there is no slagging tendency in the blended fuel, but according to B/A, slagging potential of the blends increased with increasing sewage sludge content. Co-combustion of rice husk and sewage sludge is appropriate as an alternative bio-fuel in the present situation due to their lower slagging potential. Temperature control and addition of mineral materials could be taken into account during the co-combustion of rice husk and sewage sludge to further improve the co-combustion and slagging characteristics.

Table 3. Chemical compositions, slagging indices in combustion ash of rice husk-sewage sludge blends with different ratios.

Sample	Chemical Composition (%)										*B/A*	*BAI*
	SiO_2	MgO	Fe_2O_3	Na_2O	CaO	Al_2O_3	K_2O	P_2O_5	Cl	TiO_2		
7R3S-A	66.23	2.00	5.57	0.71	3.96	11.58	4.26	3.74	0.09	0.48	0.21	1.12
5R5S-A	61.80	2.31	6.73	0.78	4.52	13.30	3.99	4.33	0.04	0.84	0.24	1.41
3R7S-A	55.46	2.35	8.28	0.83	5.98	14.33	3.58	4.34	0.06	0.88	0.30	1.88

3.4.2. Melting Characteristics of Ash from Co-Combustion

Among the characteristics of biomass, the relationship between ash melting point and slag is the most direct. Melting characteristics of biomass are key indexes of thermochemical treatment. Macroscopically, melting characteristics can be used to determine the hazardous level of ash deposition and slagging in the process of biomass combustion. Therefore, it is very important to investigate the melting characteristics of biomass, especially blended biomass. The melting characteristics of the mixtures of rice husk and sewage sludge are presented in Figure 6.

DT, ST, HT and FT clearly decreased with increasing sewage sludge content. In Table 4, ash slagging usually occurs when DT and ST are lower than 1289 °C and 1390 °C, respectively. Obviously, when the content of sewage sludge is more than 30%, the possibility of slagging is relatively high due to DT and ST being lower than the temperature limit. This conclusion agrees with the predicted results from chemical composition in Section 3.4.1. In addition, with increases in sewage sludge content, the possibility of slagging also increased. Therefore, *BAI* and *B*/*A* are suitable for predicting the slagging characteristics of rice husk and sewage sludge blends.

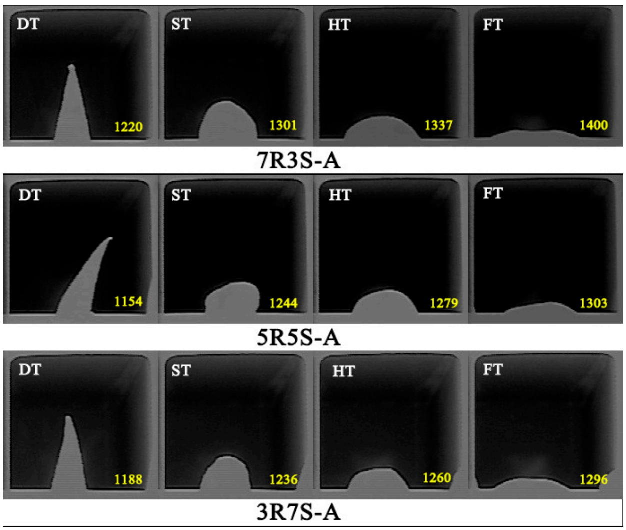

Figure 6. Temperatures showing different melting characteristics of rice husk-sewage sludge blends (°C).

Table 4. Index of slagging level.

Index	Slagging Level		
	Low	Medium	High
ST (°C)	>1390	1390–1260	<1260
DT (°C)	>1289	1108–1288	<1107

3.5. Influencing Factors of Slagging Characteristics

According to Section 3.4.1, the slagging deposition of these sludge-biomass mixtures during the process of combustion was very different. The slagging deposition was much more easily influenced by melting inorganic minerals (CaO, Al_2O_3, MgO, Fe_2O_3, SiO_2, K_2O and Na_2O) which could be liquidation. This liquid phase, slag-melt, might cause serious ash deposition problems. Meanwhile, alkali earth and alkali metals (K, Mg, Ca and Na) are likely to condense on the cooler zones of the boiler [30]. The total content of SiO_2 and Al_2O_3 decreased with an increase in sewage sludge content, indicating that the ash generated from co-combustion would weaken hydration activity when used in the preparation of cementious materials. However, due to the higher content of SiO_2 and Al_2O_3, the ash may be used as cementious materials or replacement material for cement. Furthermore, sulfur and chlorine contents were very different for these ashes and it is known that chlorine, as chloride that evaporates easily and acts as an intermediate medium for Na and K, usually exists in biomass fuels. In general, the higher the chlorine content, the more serious ash-related problems are [31].

Slagging characteristics are not only closely related to chemical composition, but are also affected by the mineral phase of ash. According to quantitative analysis by XRD, the main component of co-combustion ash was glassy state matter, which is generated from amorphous SiO_2 of rice husk during the low-temperature combustion process. The main crystal mineral phases were quartz and gismondite. The XRD results are presented in Table 5 and Figure 7.

Table 5. X-ray Diffraction (XRD) results at different ratios of rice husk and sludge sewage.

Mineral Phase	Content of Sludge Sewage		
	30%	50%	70%
Quartz	18.62	31.27	34.92
Gismondite	1.09	6.54	9.34
Amorphous	80.28	62.19	55.73

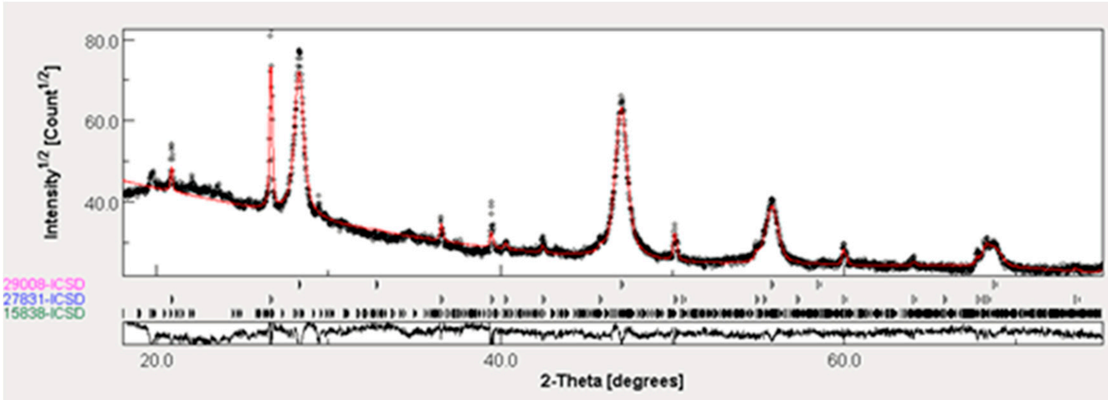

Figure 7. XRD quantitative analysis of ash from co-combustion of rice husk and sewage sludge.

Based on previous research, quartz minerals are typical refractory minerals and the higher content of quartz results in a higher melting point. In this study, the opposite was observed. This might be attributed to the higher content of residual amorphous SiO_2 in co-combustion ash. According to Table 5 and Figure 6, during the combustion process amorphous SiO_2 was transferred to quartz by consuming a quantity of energy. As a result, the effect of amorphous content on the melting point was better than that of quartz. That is to say, with an increase in amorphous content, an obvious decrease in melting point can be obtained. In addition, gismondite in co-combustion ash is a feldspar mineral. Alkaline earth metals in these kind of minerals are connected with unsaturated O^{2-}. Further, the structure of SiO_2 was broken. This facilitated the role of SiO_2 in melting. The three main phases affect the melting characteristics of co-combustion ash, in which the amorphous phase mainly determines the melting characteristics.

4. Conclusions

Co-combustion behaviors were investigated according to TGA experimental data, and slagging characteristics were studied through XRF and melting temperature. The obtained experimental and analytical results led to the following conclusions:

(1) The blends of rice husk and sewage sludge had high volatile matter content, low ash content. In addition, they had high hydrogen content and low contents of sulfur and nitrogen. These advantages mean that the blended fuel can provide clean and efficient energy.

(2) There are four main stages of the material burning processes: dehydration, volatile oxidation, and decomposition/oxidation.

(3) D_i, D_f, R_m of the blends increased with increasing rice husk ratio. The results not only show that the reactivity of the blends was improved by increasing the amount of rice husk, but also suggest synergistic interactions between rice husk and sewage sludge during the co-combustion process.

(4) According to *BAI*, there was no slagging tendency in the blended fuel, but according to B/A, ST, and DT, the slagging potential of the blends increased with increasing sewage sludge content. Hence, the ratio of sewage sludge in the blends should not exceed 30%.

(5) Thus far, experimental studies have been conducted at the laboratory scale. Future studies are aimed at investigating combustion characteristics and slagging during co-combustion of the blends in a pilot scale fluidized bed incinerator, as well as fly ash proposal and pollutant emission (SO_x and NO_x).

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