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Original Paper

Co-combustion of sewage sludge and Trakya lignite: the effect of blending on combustion characteristics

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ABSTRACT

Dried municipal sewage sludge, which is an unwanted by-product of wastewater treatment, has high organic content and relatively high calorific value. These characteristics make it a potential biomass energy source. Co-combustion of coal and sludge provides advantages such as waste reduction, energy recovery and destruction of organic pollutants and pathogens. This work investigated the combustion characteristics and gas emission profiles of Trakya lignite, sewage sludge, and their blends (70 and 85 wt%). Ignition temperatures and the temperatures where maximum mass loss observed were shifted to lower temperatures with the addition of sludge to coal. The predicted and measured TG/DTG profiles of blends were compared to investigate the interactions between sewage sludge and coal during co-combustion. A synergistic effect was observed during co-combustion for both blends. The synergistic effect increased with the increase in the sludge/coal ratio in the blend.

I. INTRODUCTION

Sewage sludge is an unwanted by-product of municipal wastewater treatment processes but could also be a source of energy, nutrient, and material recovery. Although sewage sludge composition varies by location, influent wastewater composition, the wastewater treatment method used, and season, the composition of sludge comprises organic matter, microorganisms, nutrients such as N and P, minerals besides hazardous contaminants such as heavy metals, pesticides, organic contaminants such as endocrine disrupters, pharmaceuticals residues, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and pathogens like viruses, bacteria, and parasites [1-3]. Therefore, sewage sludge must be treated and disposed of properly in order to reduce its adverse effects on the environment and human health. The investment and operating costs of municipal sewage sludge processing and disposal comprise up to 50% of the total expenditures of a typical wastewater treatment plant [2-4].

The use of traditional sewage sludge disposal methods such as composting, landfill, and ocean discharge is losing its popularity due to more stringent restrictions by governments, increasing public concern for the environment and human health, and increased interest in energy and material recovery. Consequently, thermal treatment methods such as combustion, pyrolysis, and gasification become prominent as promising treatment and utilization technologies for municipal sewage sludge [5-8]. The advantages of thermal treatments include waste reduction, energy recovery, and the destruction of organic pollutants and pathogens.

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Dried sewage sludge's high organic content and relatively high calorific values comparable to brown coal (lignite) make it a potential biomass energy source. Global energy demand decreased by 4% in 2020 because of the effects of the COVID-19 pandemic [9]. However, the increasing trend of energy demand is expected to rebound as a result of an increase in the human population, technological developments, and developing economies. The increase in the share of renewable resources such as biomass in energy production can make a significant contribution to reducing the environmental impacts of fossil resources. Combustion of sewage sludge can not only ensure the stabilization of a hazardous waste but also contribute significantly to the circular economy and reduce the dependence on fossil fuels by recovering energy [10, 11].

Thermo-analytical methods have been extensively used to determine combustion characteristics of sewage sludge and co-combustion of sewage sludge with other fuels [10, 12-16]. Thermogravimetric techniques enable us to study combustion characteristics such as T_i (ignition temperature), T_{max} (the temperature where the maximum mass loss occurred), T_b (burnout temperature) and to conduct proximate analysis to determine the volatile matter, fix carbon and ash content. A thermogravimetric analyzer can be combined with a Fourier transform infrared spectrometer (FT-IR) or a mass spectrometer (MS) to further study evolved gas emissions during combustion.

This study aimed to determine the combustion characteristics of a local wastewater treatment sludge and Trakya lignite, the blend of two fuels, and the effect of co-combustion on combustion characteristics using a thermogravimetric analyzer. A Thermogravimetric analyzer coupled with an FT-IR is also used to study the gas emission profiles during combustion.

II. EXPERIMENTAL METHOD

2.1 Materials

Sewage sludge samples were supplied by Bursa East Wastewater Treatment Plant. Trakya lignite samples were obtained from Uzunkopru coal mines located in Turkey's Northwest region. All samples were dried in an oven at 105 °C for 24 hours. Dried samples were grounded using a grinder and sieved (250 µm-60 mesh). In order to study the co-combustion of Trakya lignite and sewage sludge, 4 samples were prepared for analysis such as Trakya lignite, sewage sludge, 70% Trakya lignite and 30% sewage sludge blend, and 85% Trakya lignite and 15% sewage sludge blend. Table 1 summarizes the sample abbreviations used in the study.

Table 1. Sample abbreviations and mixing rates

Sample abbreviations	TL (wt%,db)	SS (wt%, db)
TL	100	0
SS	0	100
70TL-30SS	70	30
85TL-15SS	85	15

2.2 Analyses

A LECO elemental analyzer (CHNS-932) was used for the ultimate analysis of fuel samples. The thermogravimetry method [17] was used for the proximate analyses of the fuel samples. The calorific values of fuel samples were determined using an IKA bomb calorimeter (C5003) based on American Society for Testing and Materials (ASTM) D240 standards [18]. Moisture content of the samples were determined based on ASTM E871-82 method [19].

Combustion characteristics of fuels were analyzed using a Seiko thermogravimetric analyzer (TG/DTA 6300). Fuels were first heated with a heating rate of 10°C/min up to 105°C and held for 10 minutes. Later, samples were heated with a heating rate of 40°C/min up to 900°C and held for 7 minutes.

T_i and T_b were determined by using intersection and conversion methods described by Lu and Chen [20], respectively.

Gas emissions during combustion were examined using a Perkin Elmer thermogravimetric analyzer coupled with fourier transform infrared spectrometer (FT-IR) (Pyris STA 6000). The samples were heated from 30 °C to 950 °C with a heating rate of 15 °C/min.

To investigate the effect of co-combustion of coal and SS, the blend's predicted TG and DTG curves were obtained using equations 1 and 2 based on the assumption of no interaction between TL and SS during co-combustion. In equation 1, A, $TG_{A\%\,SS}$, TG_{SS} and TG_{TL} represent the percentage of SS in the blend, the predicted mass loss of the blend which contains A% SS and the measured mass loss of individual SS and TL respectively. In equation 2, $DTG_{A\%\,SS}$, DTG_{SS} and DTG_{TL} represent the predicted mass loss rate of the blend which contains A% SS, and the measured mass loss rate of individual SS and TL respectively. The predicted curves are then compared with curves obtained from actual experiments to better evaluate the effect of co-combustion.

$$TG_{A\%\,SS} = TG_{SS} \times \%A + TG_{TL} \times (1 - \%A) \tag{1}$$

$$DTG_{A\%\,SS} = DTG_{SS} \times \%A + DTG_{TL} \times (1 - \%A) \tag{2}$$

III. RESULTS AND DISCUSSIONS

3.1 Characterization of TL, SS and TL-SS blends

Table 2 shows the calorific value, proximate and ultimate analyses (wt%) of TL, SS, and TL-SS blends. Moisture content of the dry basis TL, SS, 70TL-30SS, and 85TL-15SS were 13.6%, 5%, 9.8% and 11.6%, respectively. When the elemental composition of the fuels is compared, SS has a lower C% and a higher N% with respect to TL which is expected considering its protein-rich composition. A similar sewage sludge elemental composition is reported by Xu and Wu [21]. H% and S% did not vary significantly between the two fuels. SS used in our study is characterized by its high volatile matter and ash, and low fixed carbon content which are 68.72%, 23.19%, and 8.09%, respectively. TL is characterized by a much higher fixed carbon (43.30%) and a lower volatile matter (41.31%) and ash content (15.39%).

VM/FC ratios can be used to compare the ignition characteristics of different fuels. A higher VM/FC ratio means that the fuel will have lower ignition temperature and it will burn relatively easier when compared to the fuel with lower VM/FC ratio [22]. When VM/FC ratios of the SS and TL are compared, SS has a remarkably higher ratio

(8.49) than TL (0.95) which is an indicator of better ignition characteristics. Calorific values of TL, SS, 70TL-30SS, and 85TL-15SS were 19.70, 16.05, 18.25 and 18.65 MJ/kg, respectively.

Table 2. Proximate and ultimate analyses and calorific values of TL and SS

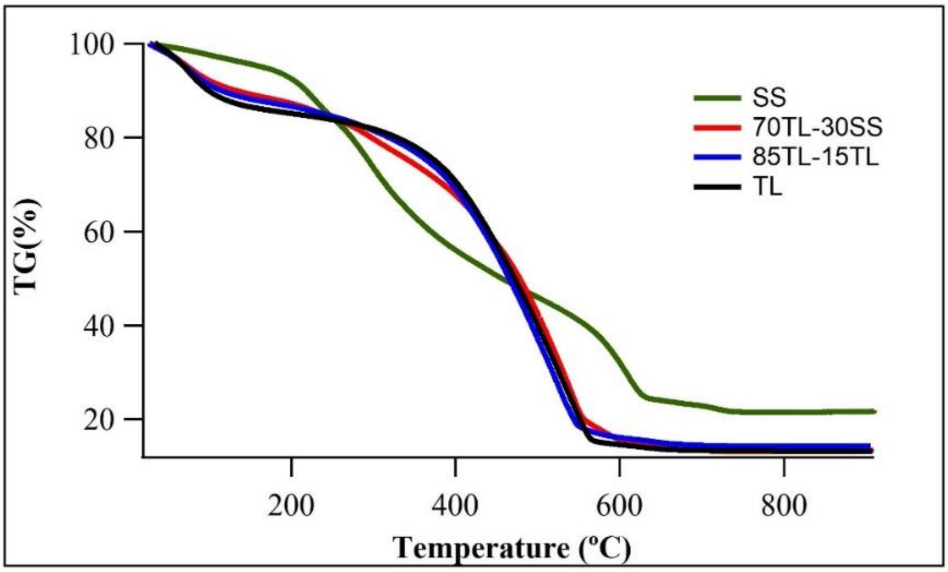
	TL	**SS**
VM(wt%, dba)	41.31	68.72
FC (wt%, db)	43.30	8.09
Ash (wt%, db)	15.39	23.19
C%	52.20	37.30
H%	4.36	5.41
N%	1.32	6.53
S%	0.16	0.21
Calorific Value (MJ/kg)	19.70	16.05

3.2. Combustion Characteristics of TL, SS and TL-SS blends

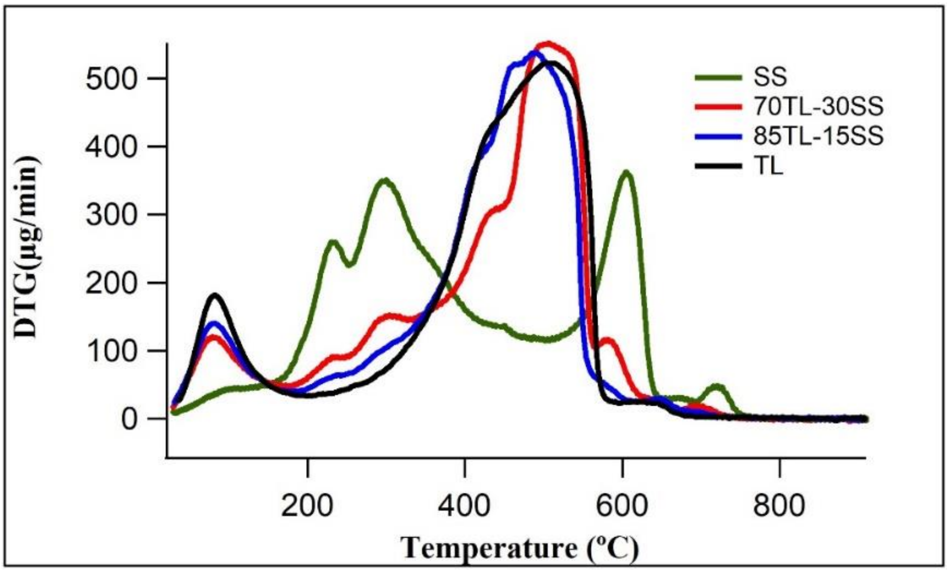
Combustion profiles of TL, SS, 70TL-30SS, and 85TL-15SS are represented in Figures 1 and 2. The TG/DTG plots (Figure 1 (a) and (b)) show that TL and SS have completely different combustion profiles. The combustion process of all four samples can be divided into four stages namely, dehydration, devolatilization and combustion of volatile matter, combustion of char, and burnout. During the dehydration stage, the initial mass loss was observed for all samples within temperature ranges up to 150 °C which resulted from the release of the inherent water content of fuels. TL and SS lost 13.6% and 5% of their initial mass in the dehydration stage, respectively which shows that TL has more inherent water than SS. T_i for SS was 206 °C which reflects its high volatile content. The devolatilization and combustion of the volatile matter and decomposition of biodegradable organic matter of SS occurred between 150 °C and 415 °C while the combustion of macromolecular organic compounds and fixed carbon occurred between 500 °C and 645°C. Although the combustion of fixed carbon is complete at this stage, a very distinct peak is observed after 690 °C which corresponds to the decomposition of inorganics such as carbonates [15]. Maximum weight loss for SS occurred at 605.2 °C with 11.92 wt%/min. T_b of SS was 716.45 °C. Wang, et al. [15] observed similar TG trends for sewage sludge with two combustion steps however higher heating rate in our study pushed the curve to the right to a higher temperature zone. This is expected since a higher heating rate will require a longer time for the sample to respond to the change in temperature.

The combustion profile of coal shows a one-step mass loss within the temperature range of 215 °C to 630 °C which corresponds to both devolatilization and combustion of the volatile matter and combustion of fixed carbon. T_i of coal was 392°C and the maximum weight loss occurred at 512 °C with 16.69 wt%/min. T_b of TL was 629.84 °C.

TG/DTG profiles of the mixtures 70TL-30SS, and 85TL-15SS mostly fall between the TG/DTG profile of individual fuels as expected. T_i of 70TL-30SS and 85TL-15SS were 374 °C and 380 °C and the maximum weight loss occurred at 507.1°C and 491.4 °C with 18.34 wt%/min and 17.67 wt%/min, respectively. Figure 2 shows that maximum mass loss intensified and T_{max} shifted left for the mixtures when compared to coal-only combustion. Additionally, as seen in Table 3, T_i decreased with the addition of sludge to coal because the volatile content in SS promotes the ignition characteristics of the blend. Both findings suggest that blending coal with sludge enhances the combustion properties of coal.



(a)



(b)

Figure 1. (a)TG and (b)DTG plots of TL, SS, 70TL-30SS and 85TL-15SS

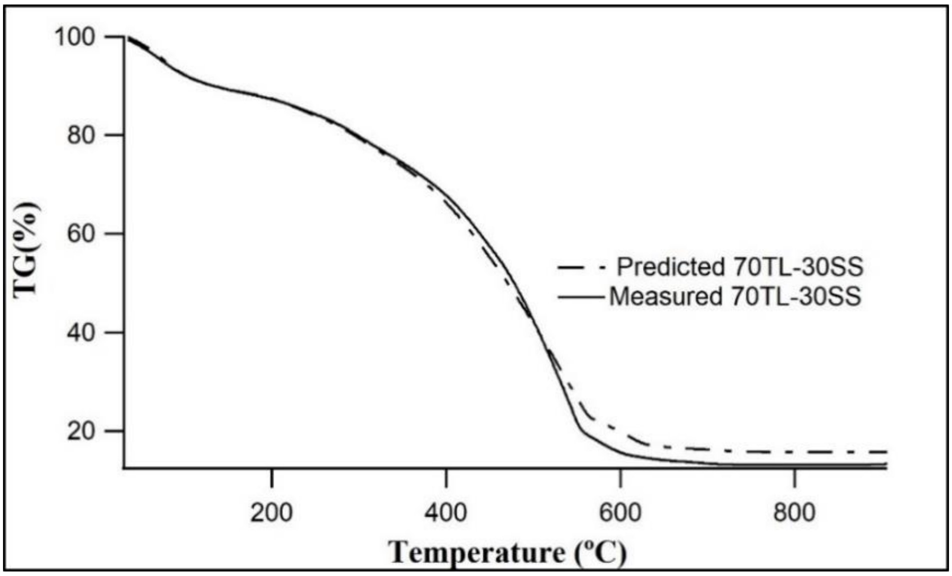
Table 3. Combustion characteristics of TL, SS and their blends

	TL	**SS**	**70TL-30SS**	**85TL-15SS**
T_i (°C)	392	206	374	380
T_{max} (°C)	512	605.2	507.1	491.4
T_b (°C)	629.84	716.45	660.15	650.47

3.3. Analysis of Synergistic Effect of Blending

To investigate the interactions between SS and TL during co-combustion, the predicted (calculated as the weighted average of SS and TL blends) and measured TG/DTG profiles of 70TL-30SS, and 85TL-15SS are plotted as shown in Figure 2 (a), (b) and Figure 3 (a), (b), respectively. Additionally, deviations between the two TG curves (Δw, %) which are calculated by the difference between predicted and measured TG values are shown in Figure 2c and Figure 3c to further illustrate the difference. Δw values greater than 0 represent a synergistic effect whereas Δw values less than 0 represent an antagonistic effect.

For both blends, predicted and measured TG values showed better agreement during the dehydration stage. As the temperatures increase above approximately 200 °C which is near T_i of SS, deviations from the predicted values started to occur.



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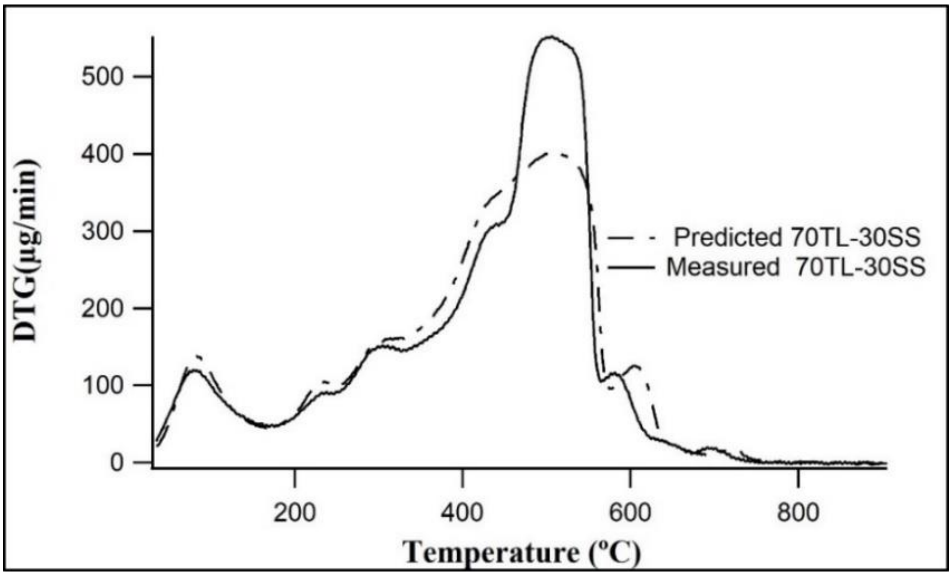

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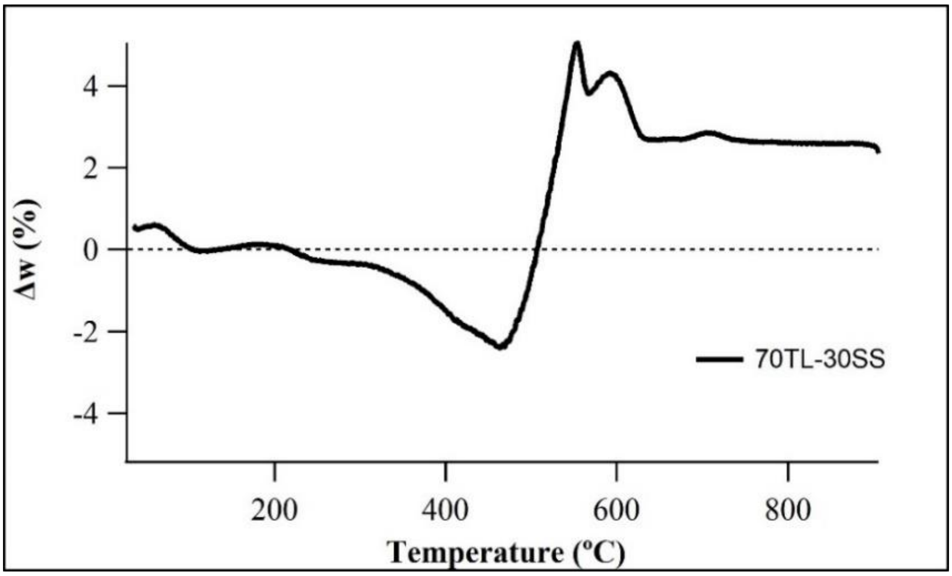
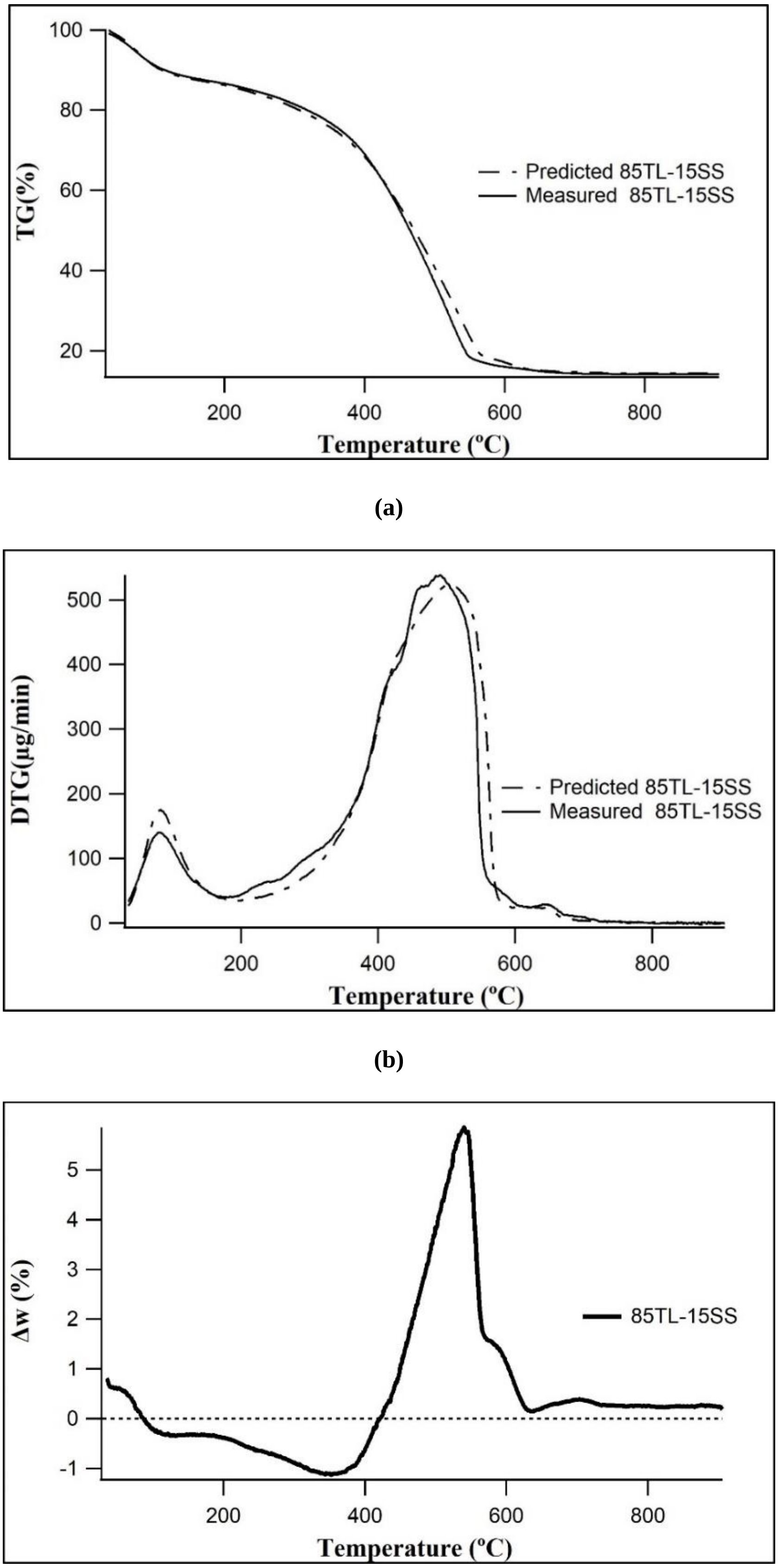


(c)

Figure 2. Comparison of experimental and predicted (a)TG and (b)DTG and (c) deviation of measured and predicted TG values of 70TL-30SS and 85TL-15SS

For the 70TL-30SS blend, Δw falls below zero after 220°C, and the negative deviation was more profound after 330 °C. For 85TL-15SS, a similar but slighter negative deviation was observed however the negative peak has shifted to a lower temperature range. This antagonistic effect could be explained by the coal particles that absorb the heat released from the combustion of sludge volatiles and suppress the devolatilization reaction of sludge. Similar results were observed for other fuel blends which consisted of two fuels with different volatile contents [23, 24]. This effect is more distinct for the 70TL-30SS blend due to its higher sludge content.

Δw become positive for the second step of combustion for both blends which mainly includes the combustion of the char. Δw value of 70TL-30SS blend became positive after 507 °C, reached its peak value around 550 °C, and stayed positive till the end of the combustion. For the 85TL-15SS blend Δw value became positive after 420 °C reached its peak value around 538 °C. However, the predicted and measured TG values showed a much better agreement around T_b. The maximum Δw 's observed for 70TL-30SS and 85TL-15SS were 5.04% and 5.86%, respectively. However, the overall synergistic effect was more dominant for the 70TL-30SS blend. The synergistic effect through the second stage of combustion resulted from the positive effect of inorganics in sludge on co-combustion and it is more profound for 70TL-30SS blend.



(a)

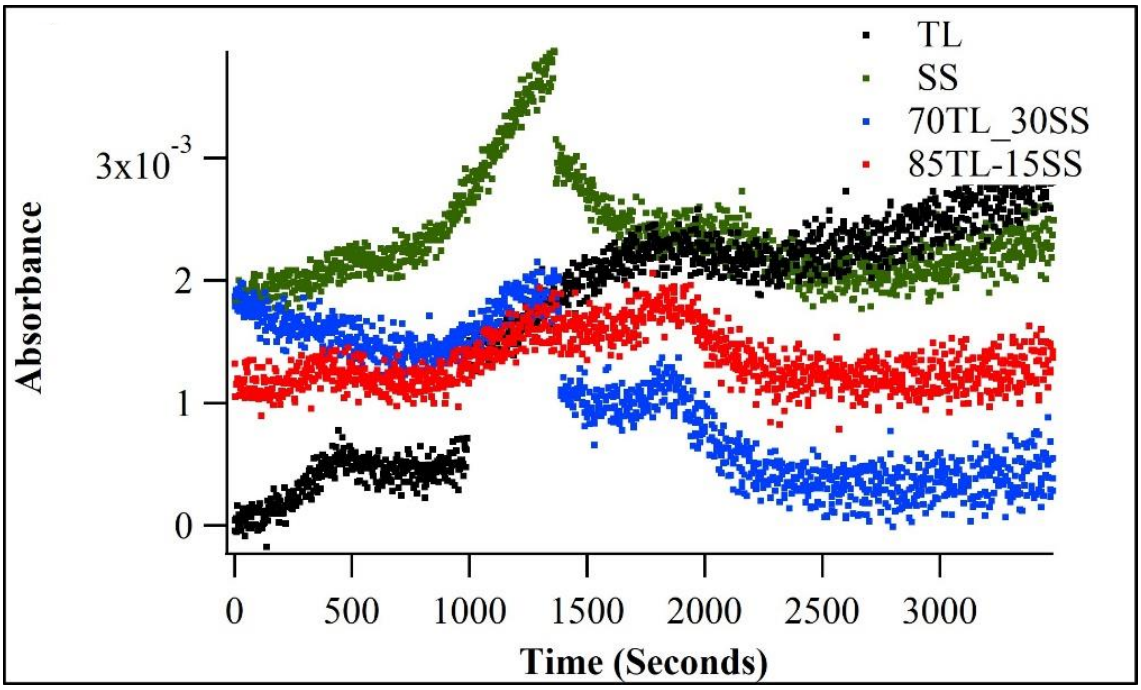
(b)

(c)

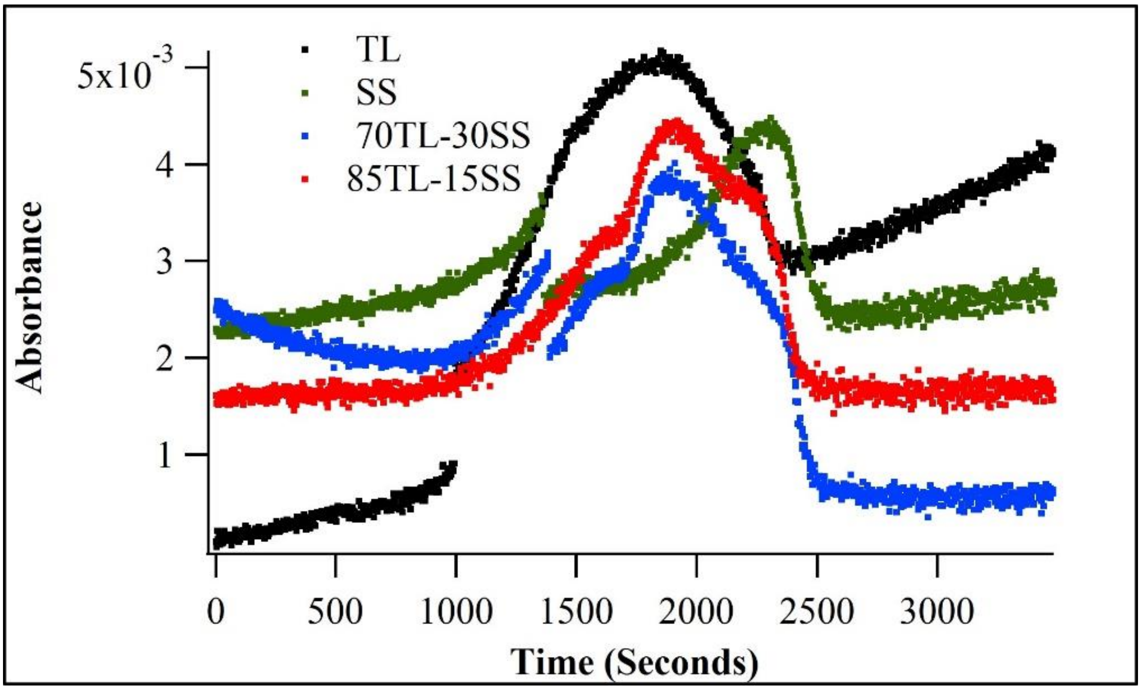
Figure 3. Comparison of experimental and predicted (a)TG and (b)DTG and (c) deviation of measured and predicted TG values of 85TL-15SS

3.4. Evolution of combustion gases of TL, SS and TL-SS blends

SO_2, CO and CO_2 emission curves against time were plotted in Figure 4 (a), (b) and (c). The IR radiation wavenumbers of SO_2, CO and CO_2 are 1340 cm^{-1}, 2112 cm^{-1} and 2360 cm^{-1}, respectively [25]. CO_2 was the most dominant evolved gas during combustion of all fuels since it has the highest absorbance intensity. All emission curves for TL match up to the one step combustion curve on DTG plot. For SS, a distinct SO_2 and a slight CO emission peak appeared at lower temperatures where combustion of the volatile matter and decomposition of biodegradable organic matter of SS occurred. The maximum SO_2 releases were observed around 380°C and 368°C, for TL and SS, respectively. CO and CO_2 emission curves of SS appeared later at the second step of combustion corresponding the combustion of char. While SO_2 emission peak was more profound for the combustion of SS, CO and CO_2 emission peaks were more profound for the combustion of TL. For the 70TL-30SS and 85TL-15SS blends, the first SO_2 emission peak decreased with the increase in coal content in the fuel while the second SO_2 emission peak increased. The maximum CO releases were observed around 505°C and 607 °C, for TL and SS. CO emission increased with the carbon content in fuel therefore the emission increased with the increase in coal content. The maximum CO_2 releases were observed around 515 °C and 615 °C for TL and SS, respectively. The CO_2 emission curves of blends fall between individual fuels. CO_2 peaks gets narrower and shifted to left with the addition of sludge when compared to CO_2 peak of TL.



(a)



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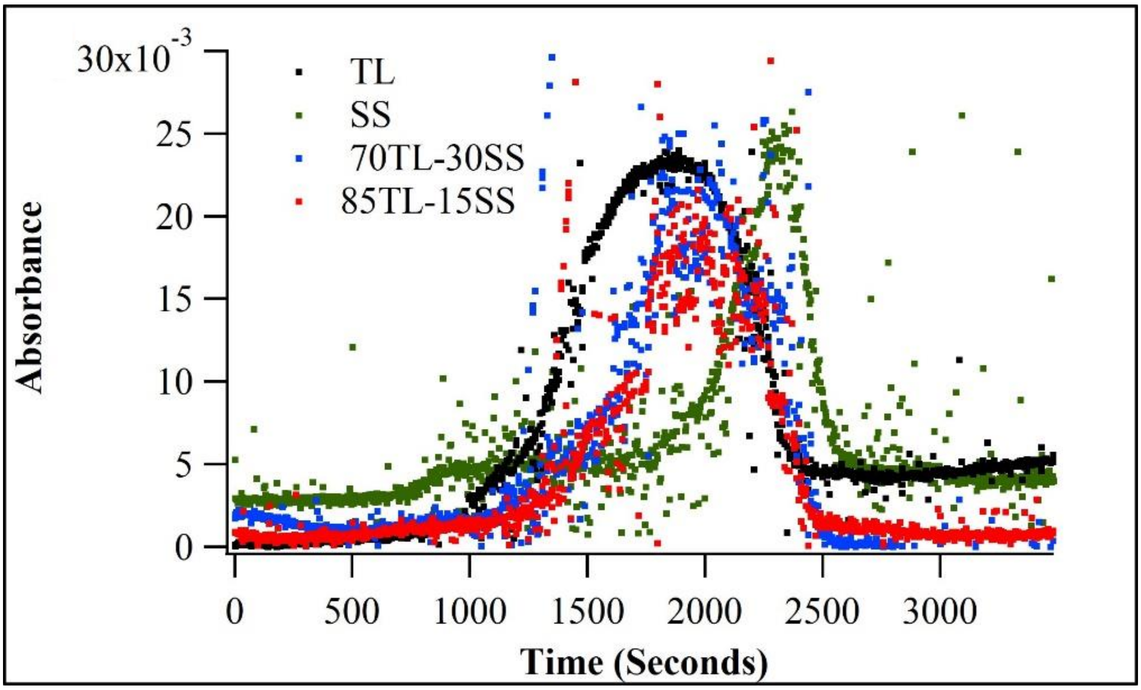

(c)

Figure 4. Emission profiles of (a) SO_2 and (b)CO and (c) CO_2 gasses for TL, SS, 70TL-30SS and 85TL-15SS

IV. CONCLUSIONS

Combustion characteristics and evolution of gas emissions of TL, SS and their blends were studied by thermogravimetric analysis. T_i and T_{max} occurred showed a decrease with the addition of sludge to coal which resulted from the positive effect of volatile content of sludge to the combustion process. Although both blends did not show a profound interaction for the first step of combustion, they showed a synergistic effect on the second step of combustion. Co-combusting of coal and sludge shows an overall synergistic effect on combustion which increases when the sludge content raise from 15% to 30% due to the positive effect of inorganics in sludge on combustion. The gas emissions of blends did not significantly differ from what is expected as gas emission curves of blends fall between the individual fuels.

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