

Coal/biomass co-combustion investigation by thermogravimetric analysis

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Abstract. In this study, the thermal characteristics and kinetic parameters of coal/biomass blended fuels (75:25, 50:50 and 25:75 wt./wt.%) were investigated by using the thermogravimetric technique under atmospheric air. Three types of agricultural waste biomass including cassava root, palm kernel shell and rice husk were used as raw materials. The experiments were performed under different temperatures, ranging from 313-973 K with the heating rate of 5, 10, 20 and 40 K/min. The results show that the thermal decomposition of biomass exhibit three-four stages including moisture and some light volatile removal stage (up to 463 K), volatile oxidation stage (423-663 K), char combustion stage (663-823 K) and inorganic oxidation stage (803-953 K). Lignite on the other hand exhibits only two main peaks during the entire combustion process, corresponding to the moisture removal (up to 433 K) and the decomposition/oxidation (433-833 K), respectively. In addition, it was also found that the blending of biomass residues improved the ignition temperature of the blended fuels, indicating an improvement of devolatilization of coal. Kinetic studies show that the average apparent activation energies of the co-combustion of coal/cassava root, coal/palm kernel shell and coal/rice husk calculated from the Kissinger-Akahira-Sunose method are reported at ca. 105.25, 179.66 and 121.84 kJ/mol, respectively.

Keyword. Biomass, Coal, Co-combustion, Thermogravimetric analysis

1 Introduction

In Thailand, the domestic resource potentials of major biomass residues, namely cassava root, palm kernel shell and rice husk, are about 6.1, 0.5 and 8.2 million tons per year, respectively, according to the Department of Alternative Energy Development and Efficiency, Ministry of Energy. Most of these agricultural and agro-industrial residues are utilized for power generation. However, the electricity produced in the country is still based on fossil fuel power plants. In order to reduce the consumption of fossil fuels, the co-combustion or co-firing technology is one of the most promising options for applications with renewable fuels. Co-combustion of solid fossil fuel with biomass benefits in terms of cost and emission reductions. In addition, co-combustion of biomass with coal in conventional coal-fired boilers can provide a reasonably attractive option for utilization of biomass for power generation in which using the infrastructure that is associated with the existing fossil fuel-based power system and requires some capital investment [1].

Thermo-analytical methods, such as thermogravimetric analysis (TGA or TG), differential thermogravimetry (DTG), differential thermal analysis (DTA) and differential scanning calorimetry (DSC), have been used to evaluate the measurements of mass and energy variations which cover a wide range of

applications in research and development. For example, the DTG thermograms were employed to determine the decomposition temperatures of biopolymer templates for photocatalyst preparation [2], the TGA/DTA thermograms were used to obtain the thermal stability information of antibacterial filler prepared from leather industrial waste [3], the TGA and DSC data were applied to analyze the reaction areas, characteristic temperatures and heat flow rates of pellets derived from blends of animal manure and lignocellulosic biomass [4], and so on. Among these techniques, TGA, along with DTG, is one of the most approved techniques to provide a rapid assessment of the thermal characteristics during the combustion of solid fuels. Besides decomposition behavior, quantitative methods can be applied to TGA profiles in order to obtain kinetic parameters as reported in the cases of co-combustion of coal with pine sawdust [5], coconut fibers and eucalyptus leaves [6], lignocellulosic and animal wastes [7] and wood waste and rice straw [8], etc. Thermal decomposition characteristics and kinetic parameters of biomass, coal, as well as their blends provide pivotal information to evaluate energy potential of renewable feedstocks. Up to date, numerous TGA experiments in the field of biomass/coal co-combustion have been studied continually. For instance, F. Guo *et al.* [9] investigated the co-combustion of biomass pellets and the two kinds of coal using a thermogravimetric analyzer. They found

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that by increasing biomass pellet ratio, the maximum combustion rate and combustion index increased, while the burnout temperature decreased, indicating that the combustion performance of coal can be improved. S. Qi *et al.* [10] evaluated the ignition and combustion characteristics of single particles of two biomass residues (corn straw and wheat straw) and three coals (lignite, bituminous and anthracite coals) in N₂/O₂ and CO₂/O₂ environments. They reported that the biomass and lignite particles ignited homogeneously, while the bituminous coal and anthracite particles ignited heterogeneously. Moreover, the biomass particles ignited earlier than the coal particles. For the three coals, the ignition delay time decreased almost linearly with the increase in their volatiles contents.

Due to the combustion characteristics and reaction of biomass, composed of hemicellulose, cellulose and lignin, are quite different. Therefore, the purpose of this research is to investigate the combustion characteristics of the three abundant biomass wastes in Thailand, i.e., cassava root, palm kernel shell and rice husk, as well as the influence of these residues when co-combusted with lignite coal. The experimental results of the co-combustion between lignite coal and such three biomass wastes discussed in this article would be helpful to promote the utilization of coal/biomass co-combustion for energy production and also to reduce the coal consumption (partially substitute for coal) in any coal-based thermal power plants in Thailand.

2 Materials and methods

2.1 Sample preparation and characterisation

Lignite and palm kernel shell samples were provided by an industry, while cassava root and rice husk are obtained from the local agricultural areas of Mabkha City, Rayong Province, Thailand. The biomass samples were washed with water, cut into small pieces and naturally dried for 3-5 days. Using a grinding machine, the sample was ground and was sieved to collect the fraction with particle size smaller than 250 μm for further study. The individual raw materials were named C100 (lignite coal), CR100 (cassava root), PKS100 (palm kernel shell) and RH100 (rice husk). Different mixtures of lignite coal and biomass residues were prepared by physical mixing and were denoted by CXCXY, CXPKSY and CXRHXY, where X = 75, 50 and 25; Y = 25, 50 and 75 wt.%/wt.% for coal/cassava root, coal/palm kernel shell and coal/rick husk blends, respectively. The proximate analyses including moisture content (M), volatile matter (VM), and ash content (A) were determined according to ASTM E870–82, while the fixed carbon (FC) was calculated by subtracting the percentages of moisture content, volatile matter and ash content from 100%. In addition, the calorific value or higher heating value (HHV) of samples was calculated by the data obtained from the oxygen bomb calorimeter (Parr 1341).

2.2 Thermogravimetric experiments

The combustion behavior of solid fuel samples was carried out with TA Instrument Q50 analyser under an air atmosphere. Prior to the TGA experiments, the fine sample powder, ca. 5-10 mg, was placed in a small platinum crucible and thermally purged under a nitrogen stream at 313 K for 10 min. Thermogravimetry (TG) and derivative thermogravimetric (DTG) profiles were attained by heating the sample from 313 to 973 K using an air flow of 60 ml/min, with the heating rate of 20 K/min. Analysis of each sample was repeated at least twice and the repeatability of experiments was more than 99%. In an attempt to obtain the kinetic parameters of coal/biomass co-combustion, the heating rates of 5, 10, 20 and 40 K/min were used for kinetic analysis.

2.3 Kinetic procedure

The reaction rate (r) of co-combustion of coal-biomass blends may be expressed by the following equation:

$$r = \frac{d\alpha}{dt} = k(T)f(\alpha) = Ae^{(-E_a/RT)}f(\alpha) \quad (1)$$

where $k(T)$ is the reaction rate constant, T is the absolute temperature, $f(\alpha)$ is the function of reaction mechanism, A is the frequency factor, E_a is the activation energy, R is the universal gas constant and α is the fractional change in solid mass due to thermal decomposition at any time t or conversion, given by the equation:

$$\alpha = \frac{m_0 - m_t}{m_0 - m_f} \quad (2)$$

where m_0 , m_t and m_f are the initial mass, the instantaneous mass and the final mass of the solid sample, respectively. Under constant heating rate, $\beta = dT/dt$, and integrating both sides of equation (1) give:

$$g(\alpha) = \int_0^\alpha \frac{d\alpha}{f(\alpha)} = \frac{A}{\beta} \int_{T_0}^T e^{(-E_a/RT)} dT = \frac{AE_a}{\beta R} p\left(\frac{E_a}{RT}\right) \quad (3)$$

$$= \frac{AE_a}{\beta R} p(u)$$

where $g(\alpha)$ is the integral form of the conversion dependence function and $p(u)$ is the temperature integral function which is no analytical solution.

The most common solution used to determine the kinetic parameters is the isoconversional method or model-free method. Isoconversional method has been proven effective particularly for kinetic analysis and has recently been strongly recommended by the Kinetics Committee of the International Confederation for Thermal Analysis and Calorimetry (ICTAC) [11]. By

applying the Kissinger-Akahira-Sunose (KAS) method, one of the isoconversional method, in Equation (3), the KAS equation can be expressed as:

$$\ln\left(\frac{\beta}{T^2}\right) = \ln\left[\frac{AR}{E_a g(\alpha)}\right] - \frac{E_a}{RT} \quad (4)$$

Plotting $\ln(\beta/T^2)$ against $(1/T)$, the activation energy was determined from the slope of the resulting straight line. In order to find the frequency factor, the general thermal decomposition reaction represented by $f(\alpha) = (1-\alpha)$ was used in this study.

3 Results and discussion

3.1 Physical properties of sample

The basic characteristics, including M, VM, FC, A and calorific value, of lignite and biomass wastes are presented in Table 1. It was observed that C100 is dominated by fixed carbon content (32.04 wt.%), whereas the biomass wastes, CR100, PKS100 and RH100, are prevailed by volatile matter (54.96-75.25 wt.%) and relatively low ash content except rice husk. High amount of ash in the case of RH100 can be explained by high silica content [12]. Considering the key elements involved in the initiation of ignition, some research studies [13, 14] reveal that biomass contain higher volatile matter and volatile fuel ratio $[VM/(VM+FC)]$ than coal. In this work, the values of volatile fuel ratio for biomass residues are in the range of 0.74-0.89 higher than that of lignite coal (0.63). This indicates that biomass residues have a higher reactivity and are easier to achieve ignition. Therefore, it can be expected that the blending of biomass waste and coal would enhance the ignition property of fuel.

Table 1. Characteristics of coal and biomass wastes.

Sample	Proximate analysis (wt.%)				HHV (MJ/kg)
	M	VM	FC	A	
C100	8.97	53.54	32.04	5.45	23.77
CR100	9.05	75.07	8.94	6.94	16.94
PKS100	7.62	72.25	13.52	6.61	21.25
RH100	7.98	54.96	19.29	17.78	14.29

Based on data obtained from the oxygen bomb calorimeter, the higher heating value of C100 is 23.77 MJ/kg, while the calorific values of biomass wastes are 16.94, 21.25, and 14.29 MJ/kg for CR100, PKS100, and RH100, respectively, which are located at the normal HHV range (i.e., 14-20 MJ/kg) of biomass [15].

3.2 Combustion behavior of individual fuels

Figure 1 and Table 2 show the typical TG curve, DTG curve and decomposition temperature intervals of lignite coal and biomass wastes decomposed under atmospheric air. According to the derivative weight loss, agricultural and agro-industrial residues exhibit 3-4 degradation stages reflecting the existence of structures of different reactivity. Whereas lignite coal shows only two characteristic peaks indicating more homogeneous material.

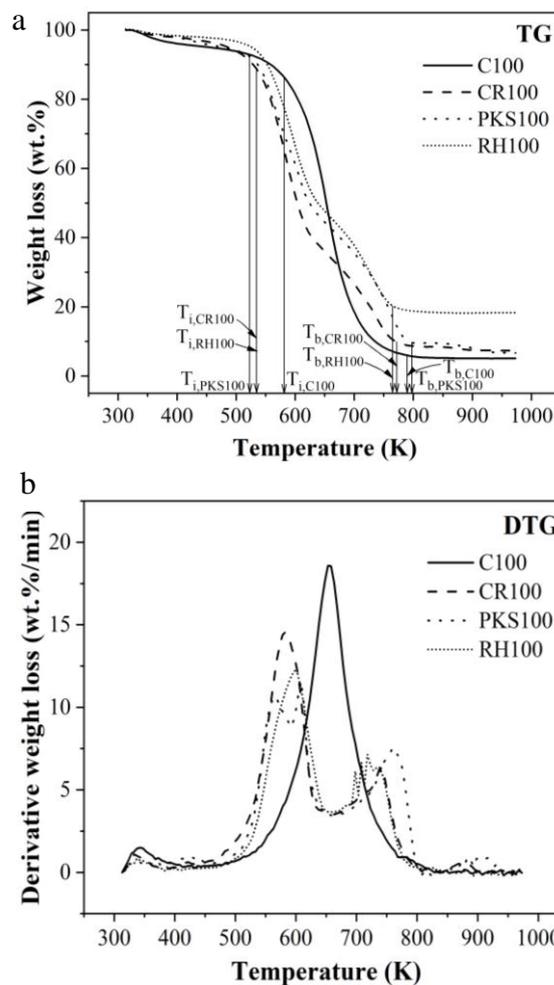


Fig. 1. a) TG and b) DTG profiles of coal and biomass wastes combustions with the heating rate of 20 K/min.

Table 2. Temperature intervals for different mass loss regions.

Sample	Temperature range (K)			
	Stage 1	Stage 2	Stage 3	Stage 4
C100	300-433	433-833	-	-
CR100	300-433	433-663	663-803	803-933
PKS100	300-463	463-663	663-823	823-953
RH100	300-423	423-663	663-823	-

The mass loss during the first stage of both the lignite coal and biomass wastes are normally due to the evaporation of free moisture, inherent moisture as well as low-boiling volatile release occurred at the temperature up to 463 K. For C100 sample, the main peak occurs in the second stage between 433 and 833 K with the maximum weight loss rate (R_{max}) of 18.67 wt.%/min, which was caused by the simultaneous combustion of volatile and solid carbon. In contrary to coal, biomass residues, CR100, PKS100 and RH100, exhibit 2-3 more decomposition stages after evaporation stage with the maximum weight loss rates between 11.29 and 14.57 wt.%/min. Stage 2 occurs between 423 and 663 K and stage 3 occurs in the temperature range of 663-823 K, which are ascribed as the volatilization of three main constituents (hemicellulose, cellulose and lignin) of biomass and the combustion of char residue, respectively. Nevertheless, some researchers [9, 16] claimed that the mass loss during the second stage is attributed to the total decomposition of hemicellulose and cellulose and the partial decomposition of lignin and during the third stage by the decomposition of remaining lignin and combustion of char residue. Another thermal decomposition stage (stage 4) in the temperature range of 803-953 K can be observed in the cases of CR100 and PKS100, which is attributed to the inorganic material decomposition [14]. It is noteworthy that the maximum weight loss rate of C100 is highest. Moreover, all biomass wastes lost their mass rapidly in the temperature below 650 K, while lignite coal sample decomposed rapidly at the temperature above 650 K. These circumstances imply that the incorporation of biomass wastes into lignite coal might not be totally benefit in terms of combustion performance.

Ignition temperature (T_i) and burnout temperature (T_b) are important properties of solid fuels for their industrial application. A number of methods have been developed to figure out the ignition and burnout temperatures of fuels, i.e., intersection method, derivation method, and conversion method. In this study, the ignition and burnout temperatures were determined following the intersection method as described by Lu and Chen [17]. Figure 2 illustrates the schematic of the ignition and burnout temperature determinations for CR100 sample by using the intersection method. Two points, A and B, on a TG curve are first identified. Point A is the point at which a vertical line from the highest value in the DTG curve crosses the TG curve. Point B is the point at which devolatilization begins (about 378-383 K). A tangent at point A on the TG curve and the horizontal line through point B are drawn. The corresponding temperature at the intersection of two lines is identified as the ignition temperature. In order to determine the burnout temperature of fuel sample, points C and D are located. Point C is the position on the TG curve at which a vertical line from the second peak of the DTG curve crosses the TG curve, while point D is the location at which the TG curve becomes steady. A temperature corresponding to the intersection of the tangent on the TG curve at C and the horizontal line through D is defined as the burnout temperature.

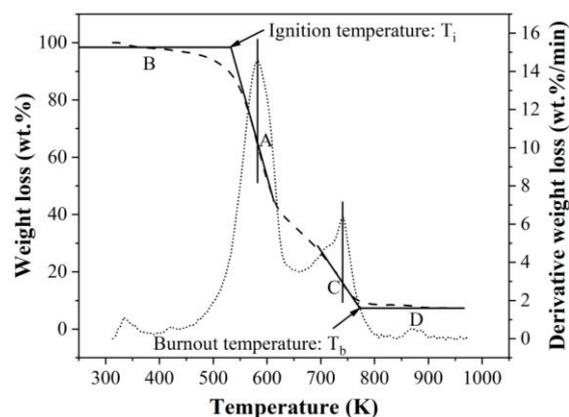


Fig 2. Schematic of the ignition and burnout temperature determinations.

The result of combustion characteristic parameters of individual sample is given in Table 3. It is noted that in the cases of cassava root and palm kernel shell the weight loss occurred above 800 K, due to the inorganic substance decompositions, were not considered for burnout temperature determination. It was found that the ignition temperatures of biomass residues are lower by 45-57 K than that of lignite coal. This could be enhanced the ignition performance of blended fuels caused by the blending of biomass wastes into coal. In terms of the burnout temperature, however, palm kernel shell shows higher value than lignite (796 K > 790 K). This implies that some volatiles released during the early combustion of PSK100 inhibit the char or heavy volatile combustion and thereby caused a longer complete combustion. The total burnout of C100, CR100, PKS100 and RH100 are about 94.85, 92.64, 93.32, and 81.70 wt.%, respectively.

Table 3. Characteristic parameters of coal and biomass wastes.

Sample	T_i (K)	T_b (K)	R_{max} (wt.%/min)	Total burn out (wt.%)
C100	580	790	18.67	94.85
CR100	535	772	14.57	92.64
PKS100	523	796	11.29	93.32
RH100	535	764	12.16	81.70

Note: T_i , ignition temperature; T_b , burnout temperature; R_{max} , maximum mass loss rate.

3.3 Co-combustion of fuels

The TG and DTG profiles of co-combustion of coal/biomass blended fuels with different percentages are shown in Figure 3-5. A similar trend can be seen for all biomass blended where the combustion of samples takes place with combined weight loss lied between that of the individual fuel. Similar phenomena were also found in the case of other blending samples [13, 14]. With considering the example of coal/biomass co-combustion in present study, C50CR50 (equally

C25CR75) decomposes rapidly and more reactive than C100 at the temperature below 660 K. However, C75CR25 exhibits the most reactivity at the temperature above 660 K but it still lower than that of C100. In addition, the maximum weight loss rate of the combustion of coal component shifts to higher temperature (from 654 K to 678 K) with increasing of biomass portions. For coal-palm kernel shell blended fuels, C50PKS50 losses its weight abruptly at the temperature below 650 K, but at the temperature above 650 K C75PSK25 shows the most reactive for combustion. The maximum weight loss rate of the combustion of coal component, in addition, shifts to higher temperature from 655 K to 670 K with increasing of palm kernel shell portions. In the case of coal-rice husk blended fuels, C50RH50 exhibits the most reactivity at the temperature below 644 K, while C75RH25 shows the most reactivity at the temperature above 644 K. Moreover, the maximum combustion weight loss rate of coal component shifts to higher temperature from 656 K to 686 K with increasing of rice husk portions. These phenomena indicate that the combustion processes of the blended fuels are complex, which could be attributed to the interaction combustion behavior between biomass residues and lignite coal.

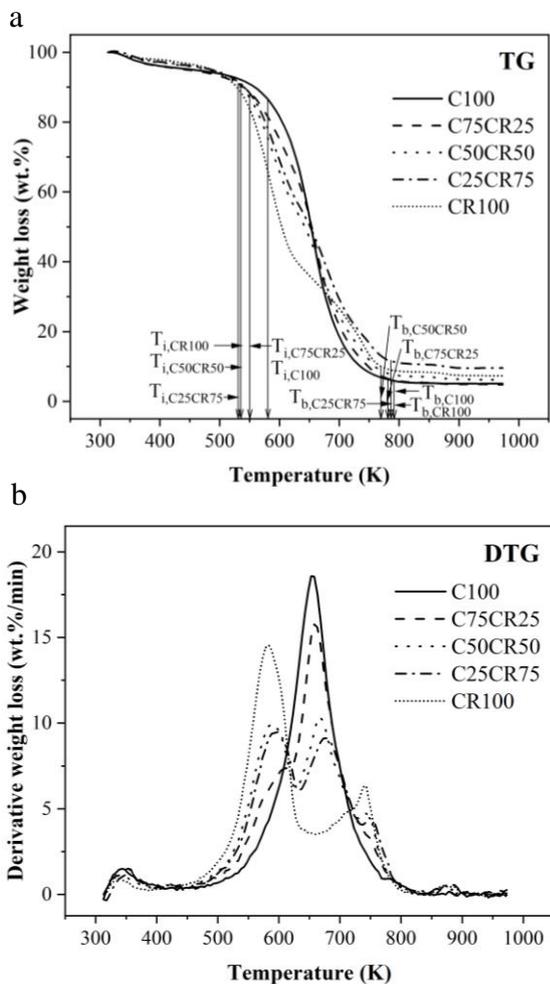


Fig. 3. a) TG and b) DTG profiles of coal/cassava root co-combustion.

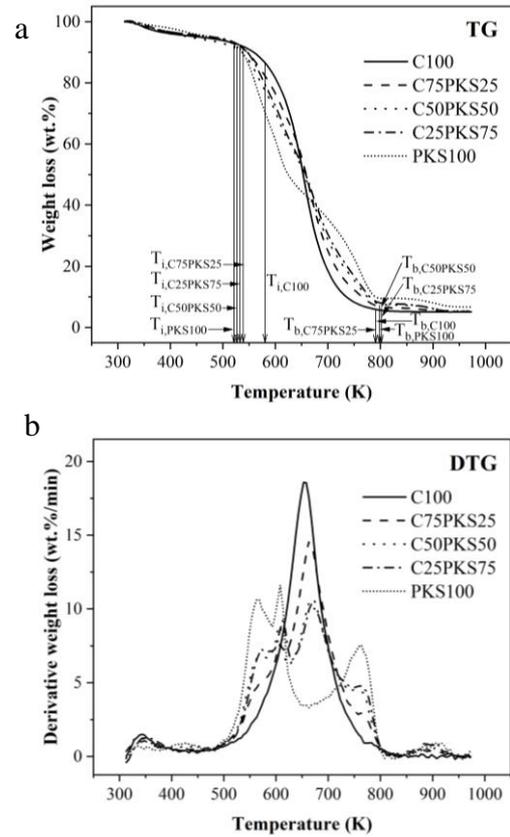


Fig. 4. a) TG and b) DTG profiles of coal/palm kernel shell co-combustion.

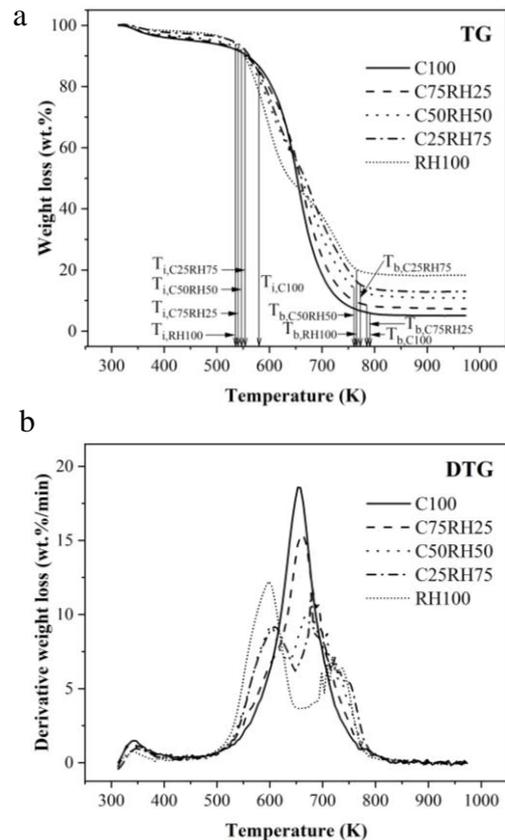


Fig. 5. a) TG and b) DTG profiles of coal/rice husk co-combustion.

It can be briefly suggested as: (i) biomass residues have high content of volatile matters which easily decompose and ignite. Therefore, they could combust rapidly and release the energy preheating coal at the low temperature region, e.g., < 660 K for C25CR75. In addition, the volatile compounds released abundantly consume a great amount of oxygen and thus hindered the oxygen molecules to reach the lignite coal surface, resulting in a lower reactivity of coal decomposition. So, this stage is dominated by the volatilization and volatile matter combustion (ii) when the temperature is higher (> 660 K), most of volatile compounds released in the early stage are combust completely, accompanied with coal has enough energy to ignite and combust, the rapidly mass loss due to coal combustion could be observed beyond 660 K. At this stage the fixed carbon combustion of coal is dominated.

In order to evaluate the combustion performance of coal/biomass co-combustion, two parameters, i.e., ignition index (D_i) and combustion index (S_i), have been used for various fuel systems [16, 18-20]. The ignition and combustion index can be determined by the following equations:

$$D_i = \frac{R_{\max}}{t_i t_m} \quad (5)$$

$$S_i = \frac{R_{\max} R_{\text{mean}}}{T_i^2 T_b} \quad (6)$$

where R_{\max} and R_{mean} are maximum and average mass loss rates, respectively. T_i and T_b stand for the ignition and burnout temperatures, respectively. t_i and t_m are the ignition time and the time which corresponds to maximum mass loss rate, respectively.

The result of characteristic combustion parameters calculated from the thermal decomposition profiles is shown in Table 4. It was unexpectedly found that although biomass residues improve the ignition temperature of the blended fuels (528-553 K) compared to coal (580 K), the ignition index of all blended (7.08×10^{-4} - 12.28×10^{-4}) are lower than that of C100 (12.81×10^{-4}). Furthermore, the combustion index of the blended fuels are also lower than pure lignite coal, i.e., 27.42×10^{-8} - 47.48×10^{-8} are lower than that of 53.95×10^{-8} . This might be because the maximum weight loss rates of the blended fuels are lower than that of coal. In fact, it can be remarked that most of research works [5, 9, 13-14, 21-23] studied on the low-grade coals, which have the lower maximum combustion rate than the studied biomass and less thermal decomposition reactivity.

Although, both of ignition and combustion index of coal/biomass-blended fuels in present study are lower than lignite coal, the utilization of biomass wastes approximately 25 wt.% instead of coal could be recommended in which the combustion performances are lower than coal in the range of 11.45-19.35%. The application in equal parts, however, the combustion index would be diminished by almost 50%.

3.4 Kinetic analysis

The TG and DTG profiles of the C75CR25, C75PKS25 and C75RH25 samples at different heating rates are shown in Fig. 6-8. It can be seen that the TG curves shift to high temperatures without a significant change in their shapes while the heating rate increases, suggested that the entire combustion process slows down with the increase of heating rate. Additionally, the increasing in heating rate made the maximum mass loss rate shift toward higher values, suggesting an improvement of combustion intensity. Similar phenomena were also found in the cases of other biomass residues [8, 13, 16]. Figures 9-11 show the KAS plots for kinetic parameter calculations and Table 5 summarises the kinetic parameters for coal/biomass co-combustion. It was found that the activation energies of coal/biomass co-combustion are in the range of 91.92-113.20, 141.05-230.60 and 98.42-129.63 kJ/mol, which the average values are about 105.25, 179.66 and 121.84 kJ/mol for C75CR25, C75PKS25 and C75RH25, respectively. It should be noticed that the activation energy of C75PKS25 is larger than those of C75CR25 and C75RH25, suggesting more energy requirement for coal/palm kernel sell co-combustion system. The variation of activation energy with respect to conversion, furthermore, can be observed, implying the complex reactions took place during the coal/biomass co-combustion process. The values of calculated frequency factors also show in the wide range: 6.62×10^5 – 6.26×10^7 , 1.62×10^8 – 6.49×10^{16} , 4.13×10^6 – 9.60×10^8 s⁻¹, for C75CR25, C75PKS25 and C75RH25, respectively.

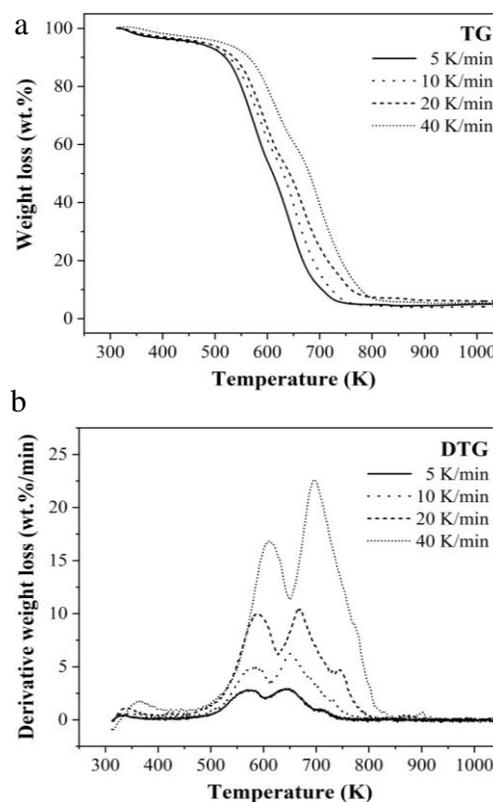


Fig. 6. a) TG and b) DTG profiles of C75CR25 co-combustion with different of heating rates.

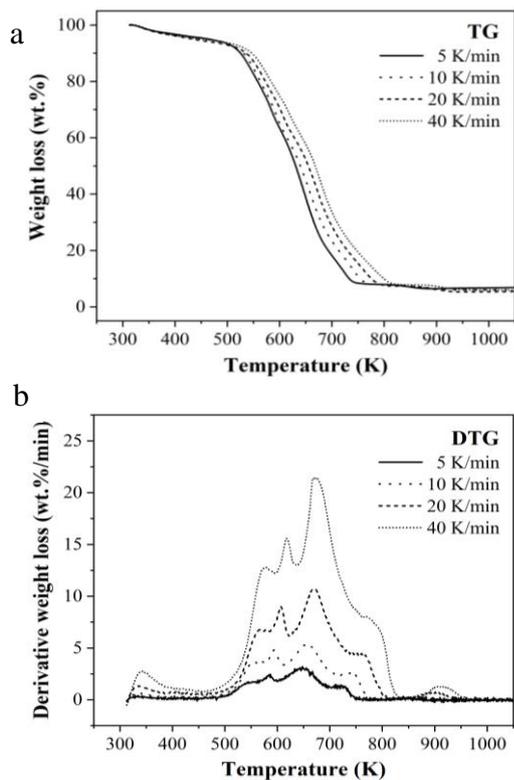


Fig. 7. a) TG and b) DTG profiles of C75PKS25 co-combustion with different of heating rates.

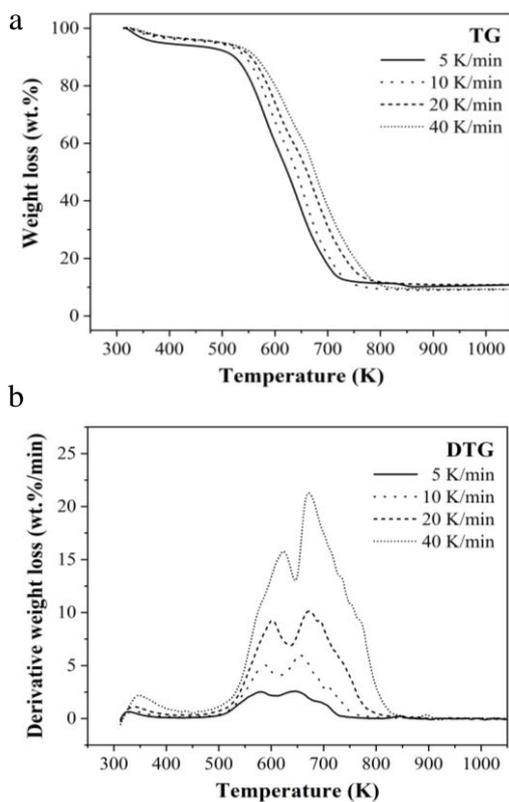


Fig. 8. a) TG and b) DTG profiles of C75RH25 co-combustion with different of heating rates.

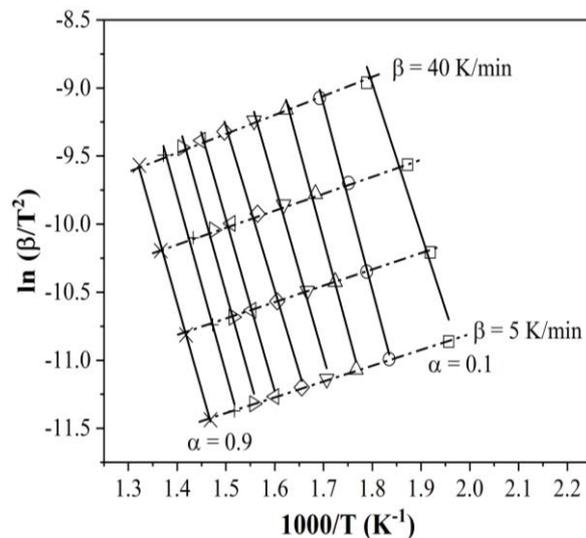


Fig. 9. KAS plot for C75CR25 co-combustion.

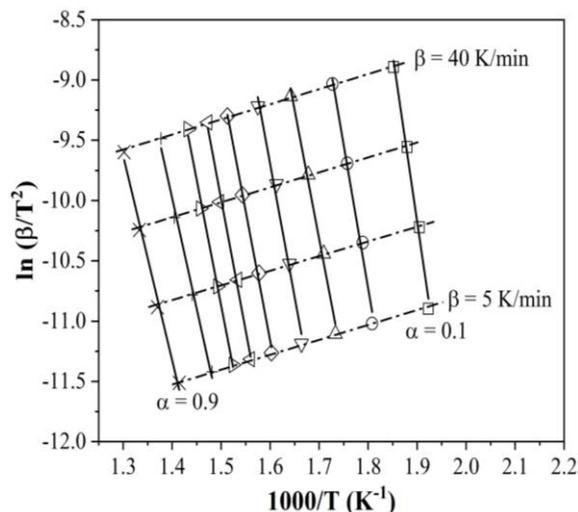


Fig. 10. KAS plot for C75PKS25 co-combustion.

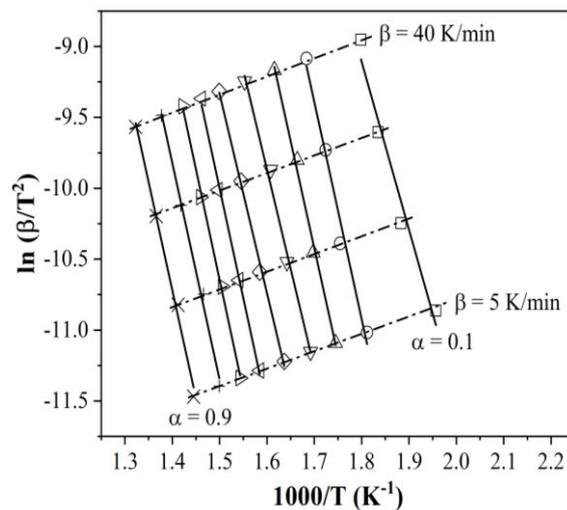


Fig. 11. KAS plot for C75RH25 co-combustion.

Table 4. Characteristic parameters of co-combustion.

Sample	T _i (K)	T _b (K)	R _{max} (wt. %/min)	t _i (min)	t _b (min)	t _m (min)	Total Burnout (wt.%)	D _i (×10 ⁻⁴)	S _i (×10 ⁻⁸)
C100	580	790	18.67	13.84	24.35	17.55	94.85	12.81	53.95
C75CR25	550	780	15.81	12.31	23.83	17.75	95.04	12.06	47.78
C50CR50	536	769	10.58	11.55	24.55	18.05	93.75	8.46	30.41
C25CR75	532	781	9.484	11.43	23.88	14.35	90.16	9.64	27.42
CR100	535	790	14.57	11.55	23.42	13.95	92.64	15.07	43.91
C75PKS25	536	789	14.81	12.03	24.67	18.45	94.66	11.12	43.51
C50PKS50	528	798	10.75	11.23	24.78	18.35	94.41	8.69	29.81
C25PKS75	530	801	10.42	11.35	24.91	18.15	94.74	8.43	28.90
PKS100	523	796	11.29	10.87	24.54	15.15	93.32	11.43	31.42
C75RH25	540	788	11.83	11.83	24.21	17.80	92.39	12.28	45.46
C50RH50	549	762	12.29	12.29	22.93	18.45	88.96	7.47	31.98
C25RH75	553	773	12.52	12.52	23.49	18.75	86.80	7.08	29.49
RH100	535	764	11.65	11.65	23.10	14.75	81.70	11.79	35.76

Note: T_i, ignition temperature; T_b, burnout temperature; R_{max}, maximum mass loss rate; t_i, time at T_i; t_b, time at T_b; t_m, time at R_{max}; D_i, ignition index; S_i, combustion index.

Table 5. Kinetic parameters for coal/bio mass co-combustion by KAS method.

α	C75CR25		C75PKS25		C75RH25	
	E _a (kJ/mol)	A (s ⁻¹)	E _a (kJ/mol)	A (s ⁻¹)	E _a (kJ/mol)	A (s ⁻¹)
0.1	91.92	1.09 × 10 ⁶	230.60	6.49 × 10 ¹⁶	98.42	4.13 × 10 ⁶
0.2	113.20	6.26 × 10 ⁷	198.01	8.04 × 10 ¹⁵	127.30	9.60 × 10 ⁸
0.3	111.48	2.56 × 10 ⁷	177.74	2.55 × 10 ¹³	125.75	3.93 × 10 ⁸
0.4	105.19	4.04 × 10 ⁶	183.66	2.59 × 10 ¹³	116.33	3.26 × 10 ⁷
0.5	99.87	8.63 × 10 ⁵	178.80	3.11 × 10 ¹²	116.71	2.01 × 10 ⁷
0.6	104.90	1.50 × 10 ⁶	180.81	2.24 × 10 ¹²	128.49	1.25 × 10 ⁸
0.7	106.79	1.65 × 10 ⁶	173.90	3.37 × 10 ¹¹	129.63	1.07 × 10 ⁸
0.8	108.20	1.59 × 10 ⁶	152.40	3.18 × 10 ⁹	127.20	4.47 × 10 ⁷
0.9	105.67	6.62 × 10 ⁵	141.05	1.62 × 10 ⁸	126.71	2.39 × 10 ⁷
Average	105.25		179.66		121.84	

Note: R² are between 0.96 and 0.99.

4 Conclusions

It can be concluded that lignite coal mainly decomposes only two stages, i.e., evaporation and the simultaneous volatile and char combustions. Biomass residues, namely cassava root, palm kernel shell and rice husk, decompose three to four stages which are corresponding to the evaporation, volatilization, volatile and char combustions and inorganic decomposition, respectively. Moreover, the coal/biomass blended fuels show the combined weight loss decomposition behaviors. Even though the incorporation of biomass wastes into lignite coal improved the ignition temperature of the blended fuels, the ignition and combustion index are worsened. This might be because biomass wastes, used in this present work, possess a lower values of maximum combustion rate and the less combustion reactivity in high temperature region, compared to lignite coal. From the kinetic studies, the average apparent activation energies of C75CR25, C75PKS25 and C75RH25 co-combustion calculated from KAS method are reported at 105.25, 179.66 and 121.84 kJ/mol, respectively. In order to maintain the combustion performance with regarding to the concerned environmental issues, it would be recommended that the co-combustion of coal/biomass, 75/25 wt.%/wt.% in particular, can be utilized for energy production.

From the present experimental data, the outcome of this research would be useful for biomass waste utilization in terms of energy production and environmental concerns. In practical, the next step should be to evaluate all costs involved in the entire logistics chain, e.g., collecting, milling, storage, and transportation, in order to obtain the information for an economic point of view. It is also recommended that, moreover, the investigation of other biomass wastes as well as the solid products obtained from the biomass thermochemical conversion processes, e.g., torrefied biomass and biochar, should be accounted for coal/biomass waste co-combustion system.

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