Research Article

Co-combustion Characteristics and Kinetics Behavior of Torrefied Sugarcane Bagasse and Lignite

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ABSTRACT. The co-combustion characteristics and kinetics of torrefied sugarcane bagasse (TB), lignite (L), and their blended samples were experimentally investigated using thermogravimetric analysis (TGA) and derivative thermogravimetry (DTG) based on the Coats-Redfern method for kinetic estimation. Their physicochemical properties were also investigated. Raw bagasse was thermally treated in a laboratory-scale torrefactor at 275 °C with a torrefaction time of 60 min under an inert nitrogen environment. Then, the torrefied bagasse was blended with Thai lignite as a co-fuel at ratios of 50:50 (TB50L50), 70;30 (TB70L30), and 90:10 (TB90L10), respectively. Torrefaction improved the fuel properties and heating value of the raw bagasse as well as reducing the O/C and H/C ratios. In addition, the blending of torrefied bagasse with lignite improved the combustion behavior. The TGA and DTG results indicated that the ignition and burnout temperatures stepped downwards with different increasing ratios of torrefied bagasse. The co-combustion behavior at the maximum burning rate showed that the burnout temperatures of TB50L50, TB70L30, and TB90L10 were 532, 529, and 528 °C, respectively, indicating a slight decrease with an increasing torrefied bagasse blending ratio. These results were sufficient to provide comprehensive guidelines in terms of the design and operation of the combustion system for adding torrefied bagasse into the co-firing process.

Keywords: Co-combustion; Co-fuels; Torrefaction; Lignite; Sugarcane bagasse; TGA

1. Introduction

In recent years, there has been a continuous increase in the demand for renewable energy resources with the expectation of replacing fossil fuels and as an option to reduce gaseous emissions and the greenhouse effect (Yin, Rosendahl, and Kær 2008; Elmay et al. 2013). This activity has arisen from the fact that biomass is a well-known choice for replacing fossil fuels. However, some properties and characteristics of biomass are different from those of traditional solid fuels and may lead to challenges if substituted for high quality coal. In fact, the lignocellulosic material in biomass has disadvantages regarding the energy potential such as low values for heating and grindability and high values for bulk volume, moisture content, and volatile matter. Thus, improvement by co-combusting biomass fuels with coal is one of the most promising options (Pang 2019; Gil et al. 2010). Thermal treatment via torrefaction or carbonization is considered to be one of the few viable replacement options to upgrade the drawbacks of biomass and to bring its properties closer to those of coal (Mundike, Collard, and Görgens 2018).

Torrefaction is a method for char production which increases the energy density, heating value, carbon content, and lowers the moisture content (Li et al. 2017; Sarkar et al. 2014; Manatura 2020). Torrefaction occurs under an inert atmosphere at temperature of 200-300 ℃ (Tran et al. 2013). It aims to improve other desirable aspects of biomass such as better ignition, reduced combustive limits of oxygen concentration, higher C/O and C/H ratios, and improved grindability and hydrophobic affinity in a homogenized material, while also partially addressing the improvement of devolatilization, depolymerization, and carbonization of biomass, with reduced microbial activity (Joshi et al. 2015; Manatura 2020). The torrefied biomass, called biochar, may be used for partial or complete substitution with coal in many thermochemical processes, especially in co-combustion process (Mundike, Collard, and Görgens 2018; Sarkar et al. 2014). Biochar blended with coal at suitable ratios plays an important role in increasing the interaction between the matrix of fuels during the co-combustion process (Gil et al. 2010). It can also enhance the burning performance of coal in terms of reducing the conversion temperature and the combustion period by mixing with coal (Liu et al. 2016; Liu, Chen, and Yu 2013; Toptas et al. 2015).

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Previous studies on co-combustion between torrefied biomass and coal have been reported in the state of the art literature. Atimtay and Yurdakul (2020) reported that blending of torrefied poultry litter with low-ranked Turkish lignite upgraded the fuel properties so that overall they were similar to higher-ranked Turkish lignite. Mundike, Collard, and Görgens (2018) explored the co-combustion behavior of torrefied biomass samples of Lantana camara and Mimosa pigra with coal samples from three coal mines in South Africa at Inyanda, Tshikondeni, and Phalanndwa. Their experimental results indicated that the addition of reactive biochars with coal led to decreases in the ignition and burnout temperatures and the co-combustion characteristics of fuels with added reactive biochar at 15% had similar characteristics as the original coal samples. The lowest combustion index in their study occurred with a higher biochar composition at a blending ratio of 30%. Wang *et al.* (2018) investigated the co-combustion characteristics of Yangquan anthracite and palm kernel shell biochar with different mass ratios. They found that the biochar supported the combustion reactivity, ignition temperature, and burnout temperature of the anthracite. Liu *et al.* (2016) reported the results of thermogravimetric analysis (TGA) of co-combustion of torrefied bamboo and coal. Their experimental results showed that the torrefied bamboo had good potential related to its low reactivity as

its thermal profile resulted in increasing the peak temperature and decreasing the maximum rate of weight loss during degradation in an oxidative pyrolysis zone. Manatura (2020) and Valix *et al.* (2017) studied sugarcane bagasse that had been torrefied in the range 160-300 °C using a fixed bed reactor and investigated the torrefaction performance. Their results showed that the torrefied sugarcane bagasse as biochar had combustion characteristics similar to those of various ranks of coal. Such modifications of solid fuels suggest the possibility of co-firing in large-scale furnace applications; however, practical guidelines are needed regarding combustion for applications such as power plants. Nonetheless, the combustion characteristics and kinetic behaviors of torrefied agricultural wastes and coal are rarely available. Thus, more studies on the co-combustion of torrefied biomass and chosen coal are needed to obtain fundamental guidelines for design and operational applications, such as in a steam boiler. The goal of the current work was to investigate the co-combustion characteristics and kinetics behavior of torrefied sugarcane bagasse and domestic Thai lignite. The sugarcane bagasse can be applied as thermochemical route including pyrolysis, gasification, and combustion (Shukla and Kumar 2017; de Palma *et al.* 2019). A summary of the co-combustion characterization for torrefied biomass and coal is presented in Table 1.

Table 1
Summary of co-combustion characterization of torrefied biomass and coal using thermogravimetric analysis.

Co-feeding	TGA process	Main finding	References
Poultry litter and Turkish lignite	TT: 250, 280, 300 °C BR: 50 wt% Agent: air HR: 5, 10, 20, 30 °C.min⁻¹ T: 30-950 °C	- Blending of torrefied poultry litter with low-ranked Turkish lignite improved overall fuel properties similar to higher-ranked Turkish lignite - Activation energies of torrefied poultry litter and their blends were 215-122 kJ/mol	Atimtay *et al.* (2020)
Invasive alien plants (*Lantana camara* and *Mimosa pigra*) and three coal (Inyanda, Tshikondeni and Phalanndwa)	TT: 300 °C BR: 5, 15, 30, 60, 90 wt% Agent: air HR: 10 °C.min⁻¹ T: 30-800 °C	- Blending of reactive biochar with coal resulted in reducing ignition and burnout temperatures	Mundike *et al.* (2018)
Palm kernel shell and Yangquan anthracite coal	TT: 600 °C BR: 20, 40, 60, 80 wt% Agent: air HR: 5, 10, 15, 20 °C.min⁻¹ T: 30-900 °C	- Blending biochar supported combustion reactivity, ignition temperature, and burnout temperature of anthracite - Activation energies of all samples were in the range 90.2-121.8 kJ/mol	Wang *et al.* (2018)
Bamboo and coal	TT: 300 °C BR: 10, 20, 30, 40, 50 wt% Agent: air HR: 20 °C.min⁻¹ T: 30-800 °C	- Torrefied bamboo with coal increased peak temperature and decreased maximum rate of weight loss	Liu *et al.* (2016)

Note: TT - torrefaction temperature (°C), BR - biomass ratio (-), HR - heating rate (°C.min⁻¹), T - combustion temperature (°C), TGA - thermogravimetric analysis

The sugarcane bagasse and lignite were obtained from agricultural areas on the Kasetsart University, Kamphaeng Saen campus and the Mae-moh coal mine, respectively. Severe torrefaction was manipulated at 275 °C as a thermal treatment process of the bagasse to produce the biochar. To achieve the goal, the study involved: (1) proximate and ultimate analysis of the torrefied bagasse and lignite, (2) combustion behavior study via TGA and DTG of torrefied bagasse, lignite, and their blends, and (3) computing the kinetic factors of the all samples in a fitted model based on the Coats-Redfern method (one of the most widely used to determine kinetic parameters). In addition, this method can represent the kinetic characteristic of the reaction in selected temperature ranges and at selected heating rates. Evaluation of the kinetic parameters requires fitting the experimental data with the best statistical models.

2. Materials and Methods

2.1 Fuel Preparation

The sugarcane bagasse sample was obtained from the Sugar Research and Development Institute of Kasetsart University, Kamphaeng Saen campus, Thailand and was used as feedstock for biochar production. The lignite sample was obtained from the Mae-moh coal mine, Lampang province, Thailand. This mine represents one of the highest potential resources of fossil fuels for thermal power plants and cement kilns in northern Thailand.

A basic pre-treatment of samples was carried out using a common protocol. The lignite and sugarcane bagasse were dried in an oven at 105 °C for 24 h. Then, the samples were powdered and sieved using a 40-mesh screen for the lignite whereas the biomass particles were sieved to obtain sizes smaller than 0.42 mm. The sugarcane bagasse was torrefied at 275 °C for 60 min using a laboratory-scale torrefactor under a nitrogen atmosphere at a flow rate of 10 L/min. The details of the experimental set up and operation are described in (Manatura 2020). The final sugarcane bagasse sample after torrefaction had a yield of 55% by weight (wt.%). Samples of torrefied bagasse (TB) and lignite (L) were kept in plastic bags for subsequent analysis. The torrefied bagasse was blended with lignite (TB/L) in three weight ratios of 50:50, 70:30, and 90:10 wt.%, respectively, represented as TB50L50, TB70L30, and TB90L10, respectively.

2.2 Fuel properties and analysis

Proximate analysis was performed according to the ASTM standards for each sample: ASTM-E871 for moisture content, ASTM-E872 for volatile matter, ASTM-D1102 for ash content, and ASTM-E1534 for fixed carbon. The elemental components (C, H, N) were determined on a weight percentage basis according to the BS-EN 15104 standard. The tests were performed using an elemental analyzer (2400 CHNS/O series 2, PerkinElmer). The experimental results of the proximate and ultimate analyses of the raw bagasse, torrefied bagasse, and lignite are listed in Table 2.

2.3. Combustion *behavior and characteristics*

The co-combustion behavior and characteristics were determined using thermogravimetric analysis (TGA) and derivative thermogravimetry (SDT 2960 Simultaneous, USA). Raw bagasse, torrefed bagasse, lignite, and samples of TB/L were analyzed under an air atmosphere with a flow rate of 40 mL/min. Each sample weighed to approximately 10 mg. The TGA chamber was heated from 30 to 800 °C at a rate of 20 °C/min. In addition, combustion behavior was characterized based on the temperature profile of samples which were examined in terms of ignition temperature (Ti), burnout temperature (Tb), peak temperature (Tp), maximum burning rate (DTG_{max}), and mean reactivity (Rm). Ti was defined as the temperature at which the sample start to burn and was determined by the first peak of DTG reaching 1 wt.%/min (excluding the peak in the moisture release zone). T_b was defined as the point at which char oxidation was completely combusted and was determined by the temperature at which the burning rate decreased to 1 wt.%/min in at the end of the combustion process (Mellin *et al.* 2014). T_p was defined as the peak temperature at DTG_{max} due to fast devolatilization resulting in the formation of carbonaceous residue. This represented combustibility and a lower value of T_p indicates easier ignition than for a higher Tp. The mean reactivity (Rm) of a fuel depends on DTG_{max} and T_p (Zheng and Koziński 2000):

$$R_m = \frac{DTG_{max}}{T_p} \tag{1}$$

3. Results and Discussions

3.1. Raw Material and Fuel Properties

Table 2 shows the results of the proximate and ultimate analyses. The values were for three samples of raw bagasse, TB, and L as described in the experimental section. The high volatile matter in the raw bagasse differed from that in TB and L. The fixed carbon and ash contents of the raw bagasse were lower than in TB and L. Consequently, raw bagasse had greater instability during combustion (Valix, Katyal, and Cheung 2017). Moreover, samples of TB and L had similar volatile matter contents, whereas the ash content in TB was lower than in L. It was clear that the fuel properties of TB were better than for L. In addition, the ultimate analysis results showed that there were similar amounts of carbon (C) and oxygen (O) in the TB and L samples. The C values of TB and L were 58.25 and 58.70 wt.%, respectively. The O values of TB and L were 38.68 and 33.40 wt.%, respectively. The experimental results of higher heating values for TB (24.0 MJ/kg) and L (18.4 MJ/kg) indicated that blending these two could improve their combustion behavior due to their energy potential and physicochemical properties. This suggested that samples of torrefied biomass could be used to compensate for lignite in terms of high capability as well as easy ignition for combustion and improved combustion efficiency (Wu, Baeyens, and Chu 1999; Tong *et al.* 2019). Furthermore, gaseous emissions during the combustion process such as NO_x and SO_2 tended to be lower for TB due to its low contents of nitrogen (N) and sulfur (S). Accordingly, torrefaction played an important role in the reduction of the O/C and H/C ratios with decreases from 1.04 to 0.12 and from 0.66 to 0.05, respectively.

Table 2
Proximate and ultimate analysis of raw bagasse, torrefied bagasse, and lignite.

Test	Raw bagasse	Torrefied bagasse	Lignite
Proximate analysis *(wt.%, dry basis)*			
Volatile matter	83. 46	51.85	49.10
Fixed carbon	14.37	44.20	32.60
Ash	2.17	3.95	18.30
Ultimate analysis *(wt.%, dry ash basis)*			
C	46.20	58.25	58.70
H	5.40	2.81	5.00
O[a]	48.11	38.68	33.40
N	0.26	0.31	2.00
S	0.03	0.15	0.90
O/C	1.04	0.66	0.57
H/C	0.12	0.05	0.09
Higher Heating Value (MJ/kg)	18.6	24.0	18.4

[a] by difference

3.2 Combustion characteristics

Figure 1 illustrates the mass loss and rate of mass loss as combustion characteristics of the TB and L samples tested using TGA in an air environment with a heating rate of 20 °C/min. The graphs show the relative curve of the reduction of sample weight (mass loss) and combustion temperature. Both the TB and L curves slightly decreased at the initial mass loss in the range 250-300 °C. Then, the curves of TB and L notably differed after passing 350 °C. TB had a large loss of mass at about 400 °C and the remaining weight of TB was only 9.7%. In contrast, the curve for L slightly decreased with a smooth slope of mass loss after 400 °C and the remaining weight of L was 48.6%. The difference in the remaining weights was about five times greater for L than TB because of the physicochemical properties of the lignite and lignocellulose materials (Toptas *et al.* 2015).

Additionally, the results from DTG showed a small peak occurred between 300 and 352 °C for the curve of TB, as seen in Figure 1. This was due to severe torrefaction. At a torrefaction temperature of 275 °C, hemicellulose was destroyed and this released moisture and light volatile matter from the biomass body, leaving only volatile matter and fixed carbon as reported in the literature (Toptas *et al.* 2015; Xu and Sheng 2012). On the other hand, a main peak occurred in the curve in the temperature range 353-520 °C due to the large loss of mass resulting from the oxidation of residue char from devolatilization. The DTG curve of L showed a large mass loss over a wide peak in the range 280-520 °C which represented the combustion of volatile matter in the lignite. A small peak occurred in the range 500-600 °C caused by the combustion of a small amount of residue char.

The comparative study of combustion behavior of the individual samples of TB and L, and of the samples of blended TB/L was based on TGA in an air environment with a heating rate of 20 °C/min. The data are plotted as curves of TGA and DTG in Figures 2(a) and 2(b). The combustion behavior of TB, L, and samples of blended TB/L (TB90L10, TB70L30, and TB50L50) clearly showed the effect of blending TB with L. There were substantial changes in terms of mass loss and the rate of mass loss during the combustion process. The TGA and DTG curves of the samples of blended TB/L were displayed together with the torrefied sugarcane bagasse and domestic Thai lignite. Raising the amount of TB in samples of blended TB/L led to the TGA curves stepping downward to low temperatures and increasing the percentage of mass loss. The individual TB and L samples showed different amounts of mass loss under the same conditions, while for the blended TB/L, the mass loss depended on the blending ratio of TB and L. The TB90L10 sample produced similar results to TB but was different to samples of TB70L30 and TB50L50 due to the composition of fuels, as seen in the curves in Figure 2(a).

Figure 2(b) displays the DTG curve results of mass loss rate with a peak for the blended samples (TB50L50, TB73L30, and TB90L100) that was a sharp curve depending on the blending amount. The curves of TB70L30 and TB90L10 were similar to that of TB, which had two main peaks at 260-350 and 350-520 °C, respectively. In contrast, the mass loss curve of TB50L50 (equal blending of TB and L), was a curve approaching that of lignite, represented by a humped peak. Therefore, increasing the amount of torrefied sugarcane bagasse in lignite fuel had a direct effect on shifting the mass loss rate peak to a lower temperature. This also indicated that the combustion reactivity was upgraded by adding the torrefied sugarcane bagasse with lignite.

3.3 Combustion properties

The results of the analysis of the combustion properties are shown in Figures 2(a) and 2(b), with characteristic factors of the samples shown in Table 3. Based on determining the capability of the solid fuels under the combustion conditions using the ignition temperature (T_i), burnout temperature (T_b), peak temperature (T_p), maximum burning rate (DTG_{max}), and average reactivity (R_m), the results indicated that T_i of TB was higher than for raw bagasse, which was caused by the low percentage of volatile matter (1.6 times lower) in TB. The data suggested that the T_i of torrefied biomass was greatly facilitated by phase oxidation and did not lengthen the whole process of combustion, as was also noted by Toptas *et al.* (2015). Moreover, torrefaction had an effect on the phase of char combustion of T_p to T_b. The samples of blended TB/L with increasing TB composition produced a gradual reduction in T_i to a low temperature, decreasing from 271 to 254 °C for the samples with TB amounts of 50–

90 wt.%. This indicated that the blended TB/L samples were easily decomposed and ignited during combustion. Thus, the addition of a higher amount of TB boosted the contact of the components in the fuels matrix as well as the higher volatile matter content, resulting in the expansion of the pore structure of the fuel which provided a greater surface area for contact with oxygen (Tong *et al.* 2019).

The burnout temperature results are provided in Table 3, with the T_b values for TB50L50, TB70L30, and TB90L10 being 532, 529, and 528 °C, respectively. Thus, there was a slight decrease to a lower temperature with an increase in the TB blending ratio. This might have been due to the effect of lignocellulose decomposition as well as

the catalytic effect of alkali metals in the ash of the lignite samples (Wang *et al.* 2016). It could be expected that the most reactive (R_m) sample was raw bagasse due to it having the highest DTG_{max} and the lowest T_p according to Eq.(1) compared to the TB, L, and TB/L samples. Furthermore, the raw bagasse had the lowest values for T_i and T_b due it having the greatest volatile matter compared to other samples. Thus, co-combustion of raw bagasse with other fossil fuels such as lignite or coal requires careful control owing to the quick ignition and fast burnout (Vassilev, Vassileva, and Vassilev 2015). Table 4 lists the advantages and disadvantages of raw bagasse, torrefied bagasse, lignite, and blending torrefied bagasse with lignite according to the analysis.
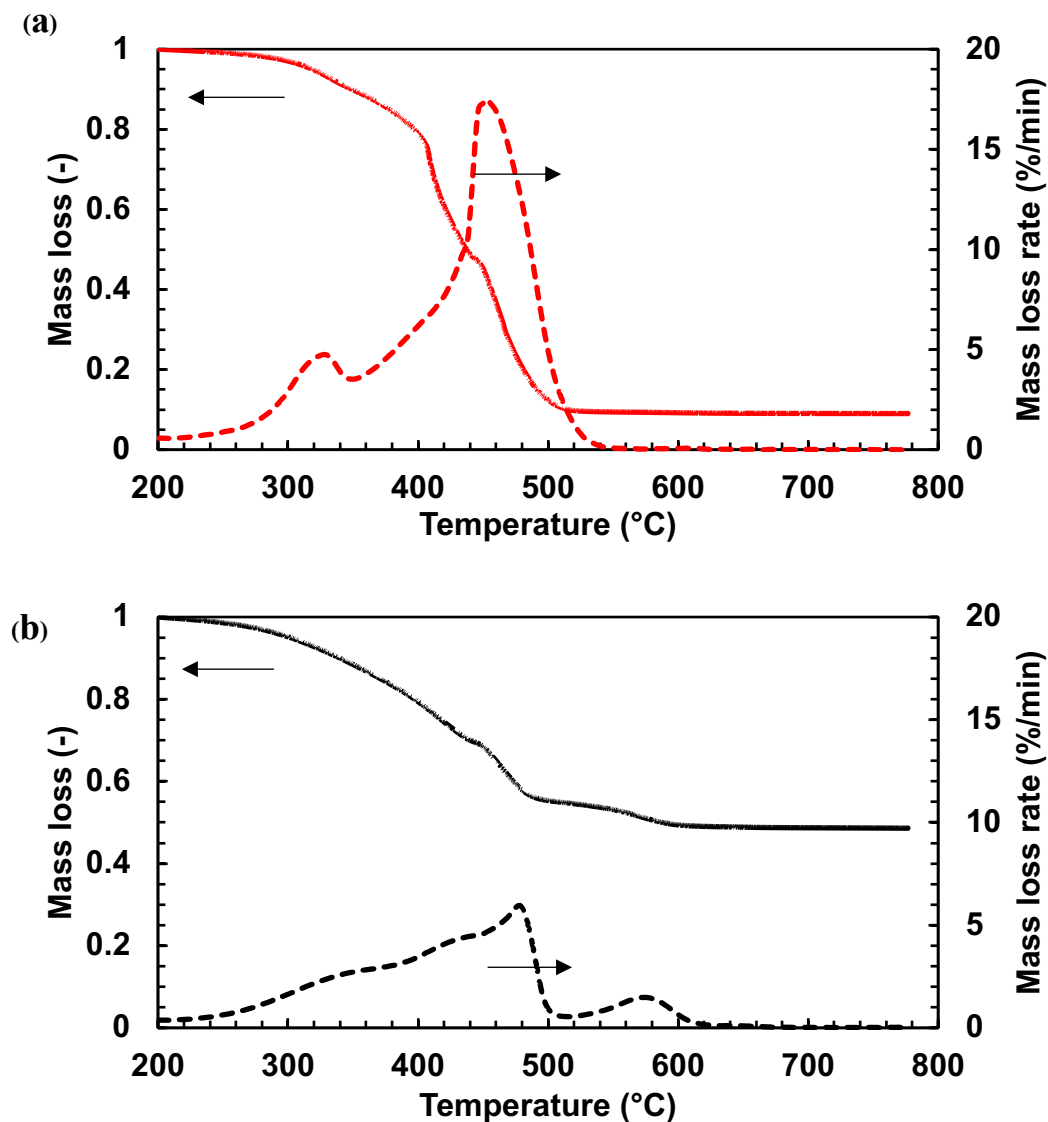

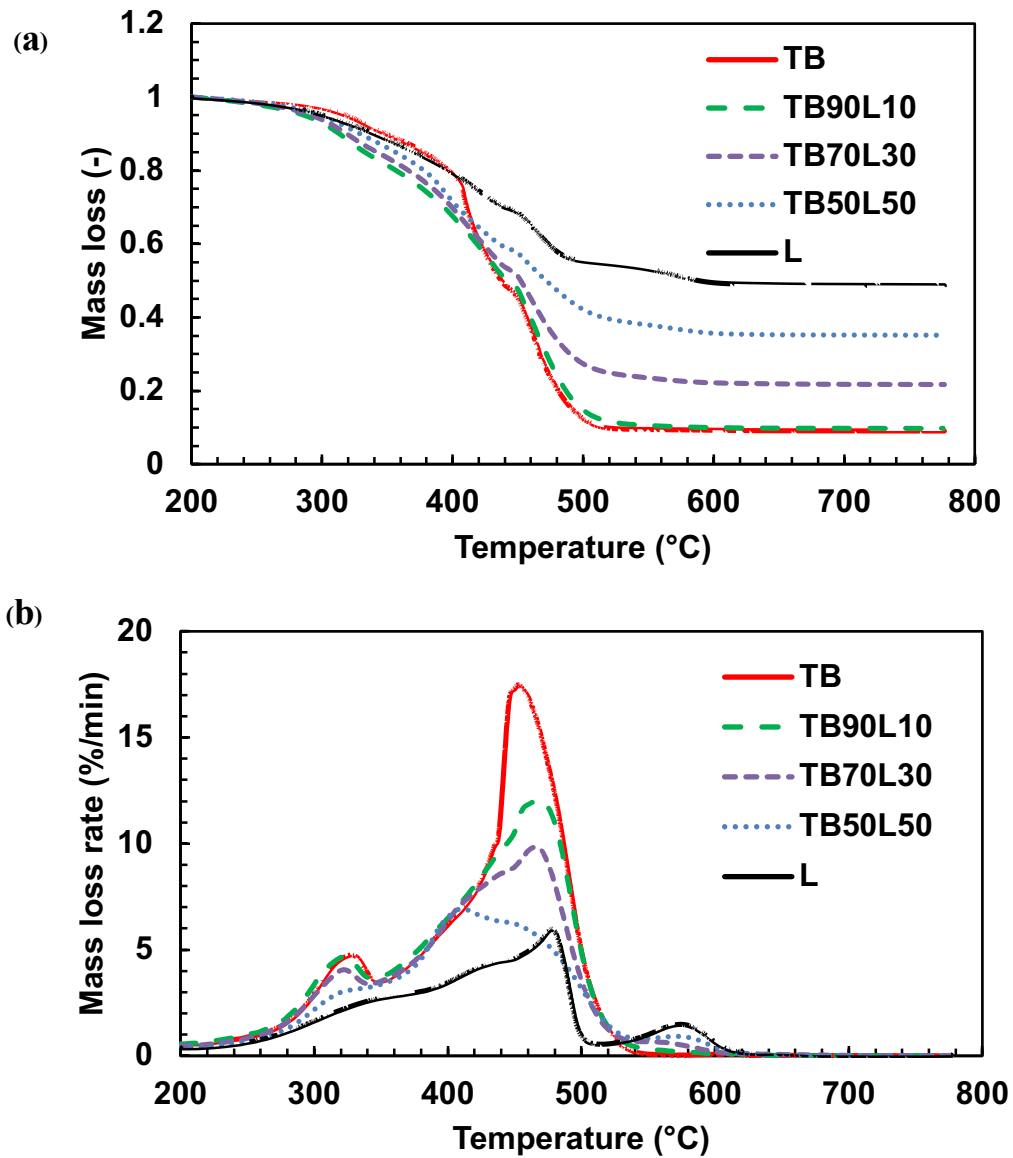**Fig. 1** Mass loss and rate of mass loss for (a) torrefied bagasse and (b) lignite at 20°C/min

Fig. 2 (a)Mass loss and (b)rate of mass loss of different torrefied bagasse (TB) and lignite (L) ratios at 20°C/min

Table 3
Combustion properties of raw bagasse, torrefied bagasse (TB), Lignite (L), and blended TB/L samples at 20 °C/min

Sample	T_i	T_b	T_p	DTG_{max}	R_m
	(°C)	(°C)	(°C)	(wt.%/min)	(%/min/K)
Raw bagasse	239	486	326	21.5	3.59
TB	259	523	453	17.5	2.41
Lignite	280	501	486	6.0	0.79
TB50L50	271	532	421	6.9	1.00
TB70L30	265	529	470	9.8	1.32
TB90L10	254	528	468	12.0	1.62

Note: T_i – ignition temperature, T_b – burnout temperature, T_p – peak temperature, DTG_{max} – maximum burning rate, R_m – mean reactivity

Table 4
Advantages and disadvantages of raw bagasse, torrefied bagasse, lignite, and blending torrefied bagasse with lignite from the co-combustion analysis

Fuel	Advantages	Disadvantages
Bagasse	• Higher volatile matter • Lower NO_x and SO_2 emissions	• Higher moisture content • Lower fixed carbon • Higher H/C and O/C ratios • Lower heating value • Higher burning rate and reactivity • Lower ignition, burnout and peak temperature
Lignite	• Lower moisture content • Tend to higher NO_x and SO_2 emissions	• Higher ash content • Lower heating value (similar to bagasse)

Torrefied bagasse (compared to the raw)	• Improved bagasse energy density
	  • Reduced moisture content
	  • Increased fixed carbon
	  • Reduced volatile matter, H/C and O/C
	  • Increased heating value
	• Reduced reactivity
	  • Increased ignition, burnout, and peak temperature
	  • Reduced burning rate and reactivity
	• Reduced NO_x and SO_2 emissions
		• Increased ash content

Blending torrefied bagasse with lignite	• Support combustion reactivity
	  • Reduced ignition and peak temperature
	  • Increased burnout temperature, burning rate, and reactivity
	• Tend to lower NO_x and SO_2 emissions
		• Complexity and pre-preparation of fuel mixing
		• Tend to higher volatile matter

3.4 Kinetic Factors

The Coats-Redfern method, also known as non-isothermal evaluation, was carried out to determine kinetic parameters (Coats and Redfern 1964). During the co-combustion process, the samples are decomposed by thermal degradation. Thus, the kinetic equation can be described based on the rate of conversion (Eq. 2).

$$\frac{dX}{dt} = k(T)f(X) \qquad (2)$$

where, X is the conversion, dX/dt is the rate of conversion, $k(T)$ is the reaction rate constant depending on temperature, and $f(X)$ is the function of the reaction mechanism. The conversion can be expressed by Eq. 3.

$$X = \frac{m_0 - m_t}{m_0 - m_f} \qquad (3)$$

where m_0, m_t, and m_f represent the initial mass of the sample, the mass of the sample at the time t, and the final mass of the sample, respectively. The reaction rate constant k can be determined based on the Arrhenius law (Eq. 4).

$$k = Ae^{-\frac{E_a}{RT}}$$
$$\qquad (4)$$

where E_a is the activation energy (kJ/mol), A is the pre-exponential factor (min^{-1}), T is the absolute temperature (K), and R is the universal gas constant, 8.314 kJ/(kmol·K).

In non-isothermal kinetics, a linear heating program is usually conducted using TGA. The heating rate can be shown as $\beta = dT/dt$ which is constant. Eq. (4) can be converted into a differential equation (Eq. 5).

$$\frac{dX}{dt} = \frac{1}{\beta}k(T)f(X) = \frac{A}{\beta}e^{-\frac{E_a}{RT}}f(X) \qquad (5)$$

The Coats-Redfern method was chosen to describe the solid reaction mechanism, assuming the reaction model $f(X) = (1-X)^n$ and a reaction order of n. Applying variable separation and integration results in Eq. 6 (Lu et al. 2013).

$$g(X) = \int_0^X \frac{dX}{f(X)} = \frac{A}{\beta}\int_{T_0}^T e^{-\frac{E_a}{RT}}dT \qquad (6)$$

where $g(X)$ is the integral conversion function. The right-hand side term is equivalent to Eq. 7.

$$\int_0^X \frac{dX}{(1-X)^n} = \frac{ART^2}{\beta E_a}\left(1 - \frac{2RT}{E_a}\right)e^{-\frac{E_a}{RT}}$$
$$\qquad (7)$$

Applying logarithms to both sides of Eq. 7

$$\ln\left[\frac{-\ln(1-X)}{T^2}\right] = \ln\left[\frac{AR}{\beta E_a}\left(1 - \frac{2RT}{E_a}\right)\right] - \frac{E_a}{RT} \qquad (n = 1) \quad (8)$$

$$\ln\left[\frac{1-\ln(1-X)^{1-n}}{T^2(1-n)}\right] = \ln\left[\frac{AR}{\beta E_a}\left(1 - \frac{2RT}{E_a}\right)\right] - \frac{E_a}{RT} \qquad (n \neq 1) \quad (9)$$

It can be noted that $E_a/RT \gg 1$ resulting in the term $2RT/E_a$ being close to zero so that term $1 - \frac{2RT}{E_a}$ is approximately equal to 1 (Eq. 10 and Eq. 11).

$$\ln\left[\frac{-\ln(1-X)}{T^2}\right] = \ln\left[\frac{AR}{\beta E_a}\right] - \frac{E_a}{RT} \qquad (n=1) \qquad (10)$$

$$\ln\left[\frac{1-\ln(1-X)^{1-n}}{T^2(1-n)}\right] = \ln\left[\frac{AR}{\beta E_a}\right] - \frac{E_a}{RT} \qquad (n \neq 1) \qquad (11)$$

Plotting $\ln\left[\frac{-\ln(1-X)}{T^2}\right]$ for $n=1$ or $\ln\left[\frac{1-\ln(1-X)^{1-n}}{T^2(1-n)}\right]$ for $n \neq 1$ with $1/T$ results in a straight line with a slope of $-E_a/R$, with interception of $\ln\left[\frac{AR}{\beta E_a}\right]$ leading to determine the activation energy (E_a), and the pre-exponential factor (A), respectively.

From the experimental data, the first-order reaction model (n=1) had a higher correlation coefficient (R^2)

compared to the non first-order reaction (n≠1), so that fitting curves of G(X) as ln[-ln(1- X)/T2] was chosen to plot with 1/T on a linear regression line to estimate kinetic parameters, as shown in Figure 3. The parameter results are shown in Table 5. The R2 values for all samples were greater than 0.92. The activation energy (Ea) for domestic Thai lignite varied greatly, having the lowest (56.10 kJ/mol) and highest (275.77 kJ/mol) values compared to the TB and the blended TB/L samples for first and second stage combustion, respectively. These results were due to their characteristics, as detailed in Table 2. The activation energies for all samples of TB/L were in the range 79.33–169.35 kJ/mol which was consistent with the study of Gao, Li, and Sun (2004) for raw wood and biochar under the same operating conditions. It should be noted that the activation energies are not often coincident with the TB blend and may depend on the properties of the biomass (Toptas *et al.* 2015).
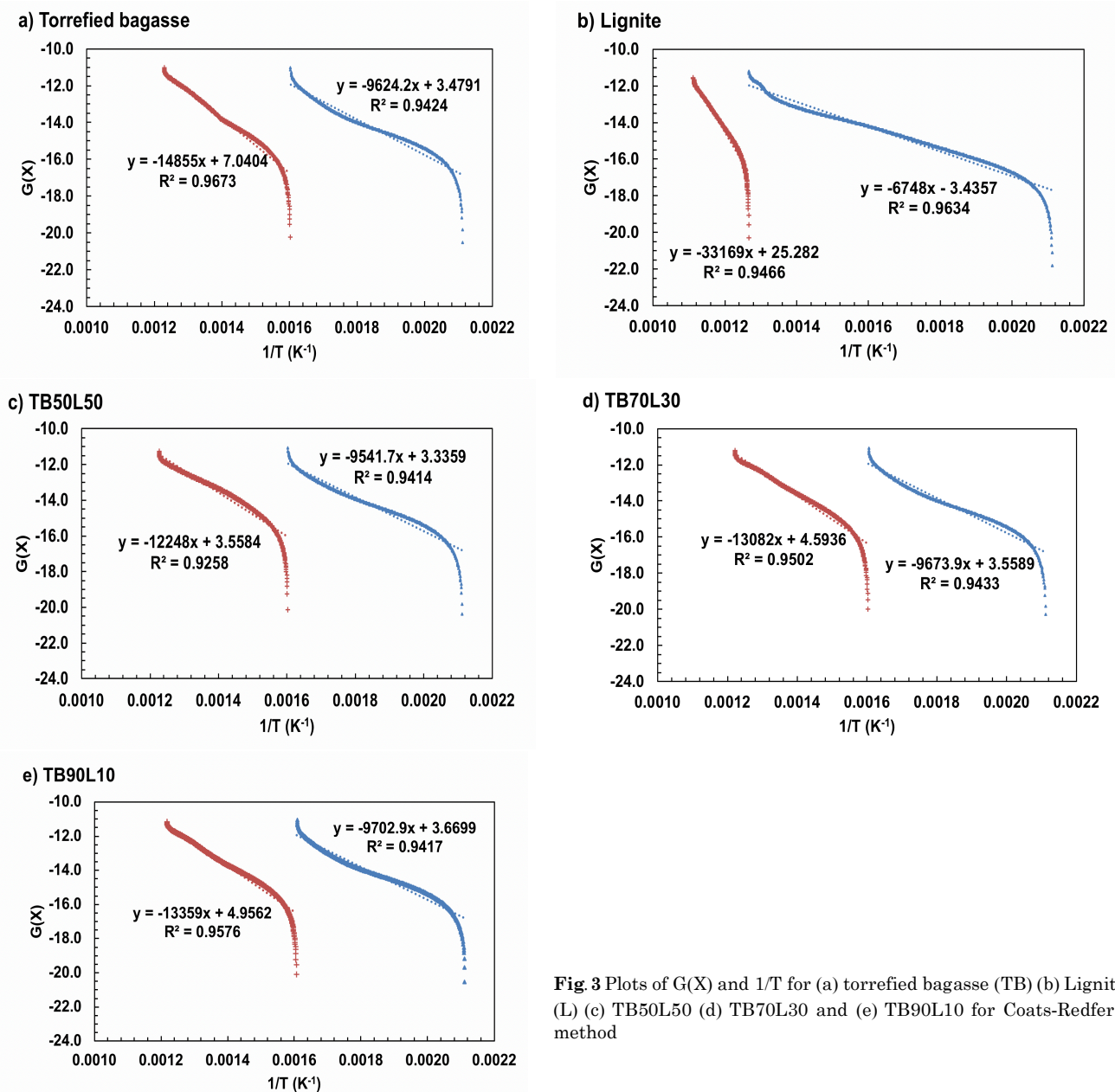

Fig. 3 Plots of G(X) and 1/T for (a) torrefied bagasse (TB) (b) Lignite (L) (c) TB50L50 (d) TB70L30 and (e) TB90L10 for Coats-Redfern method

Table 5
Kinetic factors for torrefied bagasse (TB), Lignite (L), and blended TB/L samples

Sample	Temperature range (°C)	Straight line equation	E_a (kJ/mol)	A (min^{-1})	n	R²
TB	200 – 350	y = -9624.33/x - 3.48	80.02	6.24E+06	1	0.94
	350 – 540	y = -14855.05/x - 7.04	123.50	3.39E+08	1	0.97
Lignite	200 – 516	y = -6748.01/x - 3.44	56.10	4.35E+03	1	0.96
	516 – 625	y = -33169.18/x - 25.28	275.77	6.33E+16	1	0.95
TB50L50	200 – 350	y = -9541.72/x + 3.34	79.33	5.36E+06	1	0.94
	350 – 542	y = -12247/x + 3.56	101.83	8.60E+06	1	0.93
TB70L30	200 – 350	y = -9673.89/x + 3.56	80.43	6.80E+06	1	0.94
	350 – 546	y = -13082/x + 4.59	108.77	2.59E+07	1	0.95
TB90L10	200 – 349	y = -9702.86/x + 3.67	80.67	7.62E+06	1	0.94
	349 – 547	y = -13359/x + 4.96	111.07	3.80E+07	1	0.96

Note: E_a - activation energy, A - pre-exponential factor, n – reaction order, R² - correlation coefficient

4. Conclusion

The co-combustion characteristics were investigated of torrefied sugarcane bagasse, lignite, and their blended samples. Torrefaction of raw bagasse improved the combustion performance, especially when the torrefied bagasse was mixed with lignite. The combustion performance of blended TB/L samples improved combustibility by lowering the ignition and burnout temperatures when the torrefied bagasse was added. A higher torrefied bagasse content in co-fuels increased the mean reactivity. The results of the current study provided comprehensive knowledge to assist the design and operation of a combustion system for adding torrefied bagasse in a co-firing process. Further investigations are required on the direct combustion and co-combustion of macroalgae and microalgae with coal, the effect of thermal pretreatment (dry and wet torrefaction), and the environmental impact of the process.

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