

Fuel Properties and Characterization of Coal-Torrefied Woody Biomass Mixtures

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ABSTRACT

The synthesis of biofuels has been perceived as a safe option against COX emissions to lessen the greenhouse effects on the environment and thermochemical conversion of biomass via torrefaction or slow pyrolysis, is claimed to be one of the most efficient methods of producing solid fuels from renewable energy sources. The current study presents characterization of coal, raw, and torrefied biomass, and their blends which covers elemental and proximate analyses, as well as combustion characteristics and co-combustion behaviour of coal-torrefied biomass blends. Torrefaction of woody biomass samples from Acacia Mangium species, were performed at 300 °C with holding time of 1 hour as a pre-treatment process to primarily remove moisture and volatile contents from the biomass. Biomass/torrefied biomass-to-coal blends with five weight ratios was prepared and combusted at a heating rate of 10 °C/min from temperature 25 °C to 900 °C using thermogravimetric analyser. The results showed that torrefied Acacia Mangium has a substantial calorific value of 21 MJ/kg comparable to Mukah-Balingian coal at 23 MJ/kg. As for co-combustion characteristics for the blends, coal to torrefied biomass blend of 50:50 showed the most promising combustibility with lower ignition temperature compared to coal at 323 °C and highest burnout temperature among the blends at 525 °C. The study demonstrated a promising application of torrefied woody biomass to be co-fired with coal for ecologically friendly and sustainable energy production.

Keywords: Combustion; torrefaction; acacia mangium; sub-bituminous coal; thermogravimetric analyser

INTRODUCTION

In the industry sector, coal has been extensively utilised due to its accessibility, economical, high in density and most importantly, its steady supply. Nonetheless, the widespread use of coal has resulted in several environmental issues, including localized air and heat pollution, acid rain, affecting the atmosphere with the greenhouse effect, as well as global warming and climate change. Biomass provides several benefits as a fuel source in comparison to coal. The combustion of coal with adequate supply of oxygen has more direct procedures than coal combustion (Chen et al. 2021). Combustion technology has been applied in daily activities such as heating and cooking, power generation and so many more. Almost all biomass materials can be utilised in combustion with the condition

that their calorific values are sufficiently high (typically > 20 MJ/kg) and consequently, this may reduce the reliance on fossil fuels. The technologies such as co-combustion in fossil fuel power plants, gasification and pyrolysis enable the production of electric energy more efficiently than in biomass- and waste-based steam and power plants (Variny et al. 2021).

Co-combustion of coal with biomass technology is an economical and low-risk approach by feedstock to produce heat and power. It is deemed to be simpler and cost-effective solution as it does not require huge capital investments and the existing coal-fired power plant can be utilized with minor modifications (Knapp et al. 2019). In contrast to coal combustion plant, the simultaneous combustion of coal with biomass will contribute towards great development with low-carbon economy. According

to Xu et al. (2020), by utilising high quality biomass during combustion process can generate a lower emission of greenhouses gases for instance, SO_x and NO_x, hence causing less environmental pollution, due to its lower sulphur and nitrogen contents as well as biomass being a neutral CO₂ source. Despite various applications of biomass, there are several disadvantages raw biomass utilization, which are, having high moisture content, less grindability, low energy density and having lower carbon content as compared to coal. Nevertheless, these shortcomings of biomass can be enhanced via pre-treatment processes such as drying and torrefaction process (Sibiya et al. 2021).

Torrefaction is a pre-treatment procedure whereby biomass will be heated to moderate temperature ranging from 200°C to 300°C in the absence or low-oxygen atmosphere or in the presence of nitrogen/inert gas as medium, inducing the breakdown of hemicellulose particles (Thengane et al. 2022). Via torrefaction, biomass is converted into a solid product with coal-like characteristics but with much lower moisture content than the pre-treated biomass, consequently producing solid char with higher calorific value. Higher moisture content of raw biomass may greatly affect fuel ignition as the production rate of fuel will become slower, leading towards lower combustion efficiency and higher pollutants (Zhao et al. 2021) and this disadvantage can be overcome by torrefaction process. Torrefaction process has proven to enhance biomass energy density, decreases the Oxygen to Carbon (O/C) and increases Hydrogen to Carbon (H/C) ratios, improved grindability due to improved char's brittleness and ignitability as well as the reactivity of the fuel (Mamvura & Danha, 2020).

The chosen biomass in this study is *Acacia Mangium* sp., a common fast-growing woody species that typically grows in low-density areas and specifically grown for timber industry, soil-retaining and town-landscaping purpose (Ahmed et al. 2021). *Acacia Mangium* sp. has high calorific value (17 MJ/kg) which makes it as a good option for firewood and charcoal combustion, hence, the main reason to be utilised in the current study (Marsoem et al. 2016). Applications of torrefied biomass are dependent on its structure, chemical composition, as well as chemical properties of the specific biomass, which is why it is essential to study the characterization of the fuel produced by utilizing several analysis methods on several variables. Thermogravimetric Analysis (TGA) is typically used to analyse the difference in structural and molecular properties by performing proximate and combustion analysis on samples prepared. Meanwhile, elemental analysis will be done using Elemental analyser (CHNS) to examine the properties of biomass and volatile content present within the samples (Agu et al. 2022). The main objective of this

study is to examine and characterize the physico-chemical properties and fuel characteristics of coal, torrefied biomass and mixtures of coal-torrefied biomass.

METHODOLOGY

SAMPLE PREPARATION

Samples of *Acacia Mangium* (AM) woods were collected from tree-pruning activities within UiTM Shah Alam, Selangor whereas, sub-bituminous Mukah Balingian Coal (MBC) originated from Mukah, Sarawak was obtained from Department of Mineral Geosciences, Kuching, Sarawak. The biomass samples and coal were air-dried for 5 days to remove surface moisture content of the samples. The biomass wood samples were then chopped into thin chips and ground to obtain wood fibres smaller than 2.5 mm particle size. Desired particle size of < 215 µm for both samples was obtained using Endecott Octagon 2000 Digital Sieve and then stored into airtight containers.

TORREFACTION EXPERIMENTS

30 g of biomass (AM) samples were placed into a ceramic crucible and inserted into a furnace. AM samples were torrefied at 300°C using nitrogen gas at 200 mL/min and upon reaching this temperature, the samples were held for continuous torrefaction holding time of 60 minutes. The furnace was then turned off, left to cool down to ambient temperature where torrefied *Acacia Mangium* (TAM) samples were taken out, weighed and then stored in air-tight containers (Matali et al. 2017).

CHARACTERIZATION OF COAL AND TORREFIED BIOMASS MIXTURES

Prior to sample characterization, AM and TAM samples were added to coal with weight ratios of 10:90, 20:80, 30:70, 40:60 and 50:50 with a total weight of 20 mg. Proximate analysis (ASTM D 5142 -02a) on all samples was performed using a thermogravimetric analyser (TGA) Mettler Toledo (TGA SDRA51^o) under consecutive inert and oxidative conditions at ambient pressure with constant flow-rate of 100 ml/min and heating rate of 10 °C/min for temperature range of 25-1100°C. The proximate compositions comprised of moisture content, volatile matter, fixed carbon, and ash mass fractions in the sample were analysed from TGA data obtained.

As for the determination of fuel characteristics via TGA, 20 mg samples were subjected to combustion in an oxidative atmosphere with dynamic heating from ambient

temperature to 800 °C at 10 °C/min heating rate. The samples were then kept at 105 °C for 5 minutes to fully remove moisture and to provide a basis for analysis, and further combusted to a final temperature of 800 °C. Ignition (T_i), peak (T_p) and burnout (T_b) temperatures, were determined from thermogram (TG) and differential thermogram profiles analysis. Ignition temperature is determined when fuel is first ignited and can be known as point or temperature whereby weight loss is observed on DTG curve. Peak temperature is the temperature that resembles the maximum rate of weight loss in mg/min caused by the volatile combustion. Peak temperatures also indicate the combustibility of fuel. The lower the peak temperature proves that fuel is easier to ignite. Burnout temperature is the temperature whereby no weight loss is observed on DTG curve. High value of burnout temperature shows that the fuel is difficult to burn and need longer residence time with higher temperature for optimum conversion.

For elemental analysis, all samples elemental compositions were examined using CHNS analyser (Thermo-Finnigan Flashed 1112 analyser). From the analysis, H/C and O/C ratios and calorific values or in this case, High Heating Values (HHV) were also calculated based on the results of elemental analysis (Onokwai et al. 2022).

Calculation for high heating value (HHV) by using elemental analysis data is according to Dulong's equation in Equation (1) for coal (Chen et al. 2022):

$$HHV = 0.3383C + 1.443\left(H - \frac{O}{8}\right) + 0.942S \quad (1)$$

For biomass samples, Equation (2) (Kalivodová et al. 2022).

$$HHV = 0.341C + 1.322H + 0.0686S - 0.12(O + N) - 0.153.Ash \quad (2)$$

RESULTS AND DISCUSSION

PROXIMATE ANALYSIS

Table 1 shows the summary of characterisation for Mukah Balingan Coal (MBC), torrefied (TAM) and raw biomass (AM) materials. As expected of coal properties, MBC has the highest fixed carbon content but having the least volatile matter. Raw AM has the highest volatile matter and moisture contents among all three samples. Upon torrefaction, moisture content and volatile matter content of AM were significantly reduced whereas carbon content has increased by triple amount from 11 wt% to 33 wt%.

This increase in fixed carbon is essential in solid fuel as it will indicate its high energy content (Matali et al. 2017). As for moisture content, the higher moisture content will contribute to a less efficient combustion, as the energy is used to evaporate water content during drying stage of initial combustion and causing delay to the pyrolysis and volatile combustion process to take place (Zhao et al. 2021).

However, torrefied AM has the highest ash due to the high temperature during torrefaction which corresponds to the temperature during torrefaction process. High temperature caused a release of volatile matters, causing the concentration of material increased and hence, increasing the ash content in fuel. The higher the temperature of torrefaction process, the higher the ash content in material. According to studies, ash content in biomass sample is between range 0.86% to 22.39% (Dyjakon et al. 2019). In this study, the ash content for TAM is higher than ash content in raw AM due to this concentration effect. Further study on this ash removal is needed which will take into account other pretreatments such as alkali- or acid-washing to remove mineral contents which are the main components in biomass ash.

TABLE 1. Proximate Analysis of Mukah-Balingian coal and Acacia Mangium (raw and torrefied)

Samples	Moisture Content (MC) (%)	Volatile Matter (VM)	Fixed Carbon (FC)	Ash
Raw AM	9.08	78.22	11.27	1.04
Torrefied AM	3.49	54.76	33.90	6.91
MBC	7.67	43.72	45.98	1.77

All data in wt %

ELEMENTAL ANALYSIS

The results of high heating values (HHV) and elemental analysis for all samples is summarized in Table 2. Upon torrefaction, elemental oxygen and hydrogen were significantly reduced to 25 wt% and 11 wt%, respectively. Meanwhile, elemental carbon has increased to approximately 22 wt% in torrefied AM sample. The decrease in hydrogen and oxygen content is caused by the degradation of hydroxyl group (-OH) and decarbonylation in biomass samples during torrefaction is caused by the solid hydrophobic fuel produced upon the removal of C-O bonds in torrefied samples (Nwabunwanne et al. 2021). As shown in Table 2, calorific value (HHV) for biomass sample has shown an increment after torrefaction process. Torrefied AM has 14% increase in calorific value at 21.23 MJ/kg than raw AM (18 MJ/kg), whereas MB coal has the

highest calorific value at 22.61 MJ/kg. The increase of calorific value in TAM is deemed comparable to that of MBC and this increment of energy density is highly due to increase in carbon content in the torrefied samples. O/C ratio for torrefied AM has decreased significantly from 1.00 to 0.62, nearing that of MBC at 0.53, which indicates a better energy density due to torrefaction effect (Mamvura & Danha, 2020). H/C ratio in TAM has also increased in which, the higher the H/C level, the lower the CO₂ emissions and better combustion rate (Gopalakrishnan et al. 2019).

COMBUSTION PROPERTIES

Table 3 shows the combustion properties of Acacia Mangium samples, torrefied AM sample, and mixture blends of torrefied AM samples. Expectedly, ignition temperature for AM (raw) sample is the lowest (compared to TAM and MBC, which is largely due to their high volatile matter content. Hence, it is easier to ignite compared to other samples. Burnout temperature for coal

samples is the highest at 700 °C, indicating longer burning time, followed by TAM at 540 °C. The lowest burnout temperature was recorded for AM sample at 380 °C as it has the lowest carbon content and fixed carbon content compared to other samples. Commonly, the burnout temperature will correspond to carbon content in samples in which MBC has the highest carbon contents as shown in aforementioned proximate and elemental analyses, thus its highest burnout temperature. As for ignition temperature which closely related to volatile matter content, the higher the volatile matter content, the more combustible the material and hence, faster ignition (Pan et al. 2021).

Among the five blended samples of MBC to TAM, samples of mixtures 50:50 shows the highest ignition temperature and burnout temperature. As it has the highest coal ratio content, this will lead to the highest value of burnout temperature. This is because coal has the highest fixed carbon and carbon content. In addition, the lowest ignition temperature among all blends was due to the highest biomass ratio content, which relates to the higher volatile content in biomass (Sha et al. 2021).

TABLE 2. Elemental Analysis of Mukah-Balingian coal, raw and torrefied *Acacia Mangium*

Samples	C	H	N	O	Ash	High Heating value (HHV) (MJ/kg)	Atomic H/C ratio	Atomic O/C ratio
MBC	60.83	5.37	1.23	32.01	1.77	22.61	0.09	0.53
Raw AM	46.50	5.33	0.16	46.24	4.45	18.02	0.12	1.00
Torrefied AM	56.44	8.61	2.18	34.83	6.91	21.23	0.15	0.62

O – oxygen by difference

All values in w.t %

TABLE 3. Combustion properties of Mukah Balingian coal and biomass samples

Samples	TEP 1				TEP 2	
	T _i (°C)	T _b (°C)	T _p (°C)	DTG max (mg/min)	T _p (°C)	DTG max (mg/min)
Blended samples (MBC: TAM)						
10:90	271.80	421.31	305.45	1.04	414.73	1.75
20:80	284.92	429.10	310.24	2.34	403.67	2.23
30:70	290.95	439.41	312.45	4.74	390.22	2.80
40:60	305.36	505.79	315.15	4.45	399.51	2.89
50:50	323.42	524.91	322.4	5.88	422.31	1.31
AM	140.00	380.00	-	-	-	-
TAM	262.38	540.45	293.59	6.34	413.07	1.79
MBC	397.72	700.00				

T_i – Ignition Temperature; T_b – burnout temperature; T_p – Peak temperature

AM (raw) values are from reference (Yusof et al., 2020) Coal (raw) values are from reference (Idris et al., 2012).

TEP 1 – Thermal Evolution Profile 1; TEP 2 – Thermal Evolution Profile 2

The ignition and burnout temperatures in this analysis is essential to characterize the performance of combustion or fuel combustibility. From Table 3, the combustion for 50:50 MB to TAM sample shows the highest burnout temperature among all five blended samples. This proves that it requires higher temperature to complete burn due to the presence of high amount of volatile matter. Sample blend with ratio 10:90 has the lowest peak temperature at 305.45 °C, which shows that it is easier to ignite. Sample with a ratio of 50:50 has the highest peak value at 422.31 °C, caused by the presence of coal with the highest fixed carbon content and less ash content compared to torrefied AM sample.

CO-COMBUSTION BEHAVIOUR OF MBC:TAM BLENDS

The co-combustion behaviour of fuel produced from all MBC with TAM blends are depicted in Figure 1 (DTG-differential thermogravimetric profiles). The DTG profiles of the blends were presented as the result of combustion analysis. All five samples have depicted two peaks after moisture removal phase. Apart from the drying stage from starting temperature up to 150 °C which is excluded in this discussion, the first peak which is due to oxidative pyrolysis, is where the ignition temperature will be observed in which devolatilization process takes place (Alsulami et al. 2023). The second peak that corresponds to char combustion process, whereby at the end of the peak, burnout temperature will be observed (Jia, 2021). The addition of torrefied biomass to MB coal has reduced the peak height in the oxidative pyrolysis phase, and subsequently, ignition temperature of samples with higher ratio of MBC shows higher values. This finding is agreeable to previous study that the burnout temperature increases with lower biomass ratios in the blends (Wang et al. 2023).

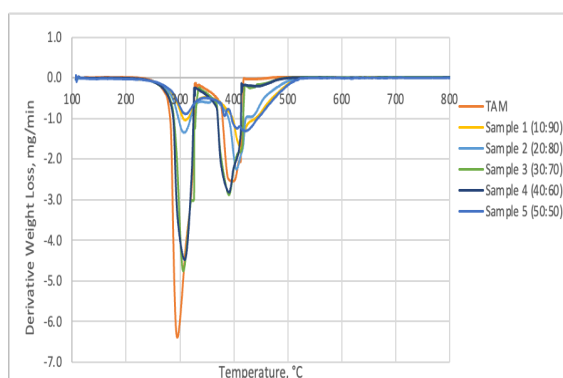


FIGURE 1. DTG decomposition profiles of coal with torrefied AM blends and raw

From Figure 1, the torrefied AM depicted a sharp curve during temperature 200-295 °C which corresponds to the degradation of hemicellulose. According to previous studies, thermal degradation of hemicellulose occurs between the temperature range 220 °C to 300 °C (El-Sayed et al. 2024). The lowest temperature observed was at 305.45 °C in sample with blend ratio 10:90 of MB: TAM with the highest peak DTG max value (1.04 mg/min), indicating easier ignition. Meanwhile, the highest peak DTG value was observed at sample with ratio blends of 50:50 MB: TAM blends with 5.88 mg/min weight loss. DTG curves were observed to be shifted to the right as a result from the peak height reduction, which corresponds to a lesser reactivity in samples.

CONCLUSION

In the current study, physical and chemical properties and several qualities of raw/ torrefied Acacia Mangium and Mukah Balingian coal were evaluated. Increments in energy content, fixed carbon and elemental carbon were observed and decent quality torrefied Acacia Mangium were produced based on the elemental and proximate analyses and, combustion characteristics. From proximate analysis, MB coal shows the highest value of moisture content and fixed carbon, meanwhile raw AM biomass shows the highest value of volatiles. Mukah Balingian coal has the highest calorific value (HHV) at 22.6 MJ/kg, followed by torrefied AM at 21.2MJ/kg. The increment of calorific value is greatly increased by 17% due to the reduction of volatile matter and moisture contents present in raw AM during torrefaction, subsequently increasing the carbon content in the torrefied sample. From elemental analyses, Torrefied AM has the highest H/C ratio which indicates that it has the best combustion rate with lower CO₂ emissions. O/C value also decreased after torrefaction due to the reduction of oxygen content and increment in carbon content during the process. As for combustion characteristics, for individual samples, MBC has the highest ignition temperature at 397.72°C and highest burnout temperature at 700 °C. Meanwhile, raw AM has the lowest burnout temperature at 380 °C due to having lowest carbon and fixed carbon content. For blended MBC:TAM mixture, the lowest ignition temperature for blended mixture is at 271°C for MBC:TAM of 10:90 due to its highest volatile content. Sample of 50:50 MB coal to TAM has the highest burnout temperature at 524.91 °C, which indicates it has the highest thermal energy produced during combustion. The study concluded that torrefaction assisted in increasing biomass energy value and thus, may effectively improve combustion efficiency. Furthermore,

including biomass into energy generation by blending with coal can make the process more sustainable.

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DECLARATION OF COMPETING INTEREST

None.

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