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Torrefaction of oil palm fronds for co-firing in coal power plants

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Abstract

Torrefaction of biomass is a thermochemical process to enhance its fuel characteristics such as energy density and hydrophobicity. In this study, oil palm frond, a highly abundant agricultural waste in Malaysia is the feedstock of interest to investigate the influence of torrefaction temperature on its thermochemical properties. A single holding time of 30 min is used, with temperatures in the range of 200°C to 300°C (25°C increments). The mass and energy yields, as well as energy densification ratio are investigated, along with proximate analysis. Both mass and energy yield decreased with increasing torrefaction temperatures. The higher heating value (HHV) of torrefied oil palm fronds increased with increasing torrefaction temperature. Mild torrefaction temperatures (200°C - 225°C) showed insignificant improvements to HHV and slight reductions in mass and energy yields. Moderate and high torrefaction temperatures increased HHV significantly, while mass and energy yields continued to decrease. The optimum torrefaction temperature is determined to be at 250°C, giving the torrefied oil palm frond a respectable HHV of 26.62 MJ/kg, while maintaining an energy yield of 92.70%. This is within the range of HHV of coal, thus positioning torrefied oil palm frond as a suitable co-firing fuel for coal power plants.

Keywords: oil palm frond; torrefaction; co-firing; mass yield; energy yield

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1. Introduction

Biomass wastes can be an alternative co-firing fuel source for coal power plants [1]. Sustainably grown biomass is carbon neutral because the biomass absorbs carbon dioxide (CO_2) during its growth which compensates for the CO_2 released when it is burnt. With biomass being a source of renewable energy, it can be utilized as a fuel source in boilers and power plants [2]. Currently, coal is used to generate 42.6% of power in Malaysia. In 2013 alone, approximately 21 MT of coal was consumed. Coal will be positioned to be the main fuel source for power generation in Malaysia, with 5,000 MW of additional coal-fired capacity to be commissioned in 2015 – 2019 [3]. In 2015, Malaysia has declared its intention to reduce its carbon emissions by 45% by 2030 [4], relative to its emission levels in 2005. This can be made possible by co-firing coal with biomass in power stations, to help reduce carbon emissions. However, biomass wastes are difficult to harvest, transport and store because of it low energy density and high moisture content [2,5]. Today, torrefaction emerges as an attractive biomass treatment process to overcome these drawbacks and improve its competitiveness as compared to coal.

Torrefaction is a thermochemical process in which biomass is heated to 200 – 300°C in an inert atmosphere. It lowers the moisture levels of biomass, which leads to the increased hydrophobicity of the biomass. It also increases the biomass energy density, reduces the O/C and H/C ratios, improves grindability and homogeneity [6-8]. Due to its increased energy density and improved resistance to biological degradation, the torrefied biomass becomes more suitable for transportation and storage purposes [6,7]. Currently, torrefaction has been carried out with woody biomass such as Mesquite and Juniper [9], Eucalyptus [10] and spruce [11,12]. Other types of biomass including coffee residue [13], corn stover [14] and cotton stalk [15] have also been tested. There is also an abundance of torrefaction experiments on oil palm wastes such as empty fruit bunches, mesocarp fibre and kernel shells [16-18]. With oil palm wastes being one of the most abundant agricultural wastes in Malaysia, it is worth investigating the wastes as a potential feedstock for torrefaction.

Malaysia was estimated to produce 46.53 MT of oil palm fronds, closely followed by 22.43 MT of palm empty fruit bunches in 2012 [19]. This represents an opportunity for the Malaysia biomass market. These oil palm wastes could potentially be used to co-fire with coal in power stations. In particular, oil palm fronds form the majority of the oil palm wastes. The potential of utilizing oil palm fronds for co-firing with coal in power plants in Malaysia is immense. Currently, oil palm residues such as the kernel shell, mesocarp fibre and empty fruit bunches are used to generate electricity in power plants [20]. Due to the lower energy density, storage and logistics issue of oil palm fronds, it has not been a popular choice as an alternative co-firing fuel in coal power plants. Thus, torrefaction is a potentially feasible upgrading process for oil palm fronds. The parameters that are usually used for torrefaction of biomass are temperature and holding time. However, the impact of torrefaction holding time is found to be less significant as compared to torrefaction temperature [12,14,21,22]. An investigation by Grigiante and Antolini [23] concluded that the combination of torrefaction temperature and holding time applied to reach a selected value of mass yield had no influence on the energy parameters of the torrefied biomass. Comparing two torrefied spruce pine samples of similar yields, an increment in torrefaction temperature from 280°C to 310°C allowed a reduction in holding time of 59 min to obtain similar mass and energy yields [23]. This increase of 30°C saved 1 h of time.

Set against this background, the aim of this study is to investigate the effect of torrefaction temperature on oil palm fronds in order to improve its properties as a co-firing feedstock in coal power plants. Both mass and energy yields were measured and proximate analysis was conducted in order to determine the optimum torrefaction temperature which resulted in the best trade-off between higher heating value (HHV) and energy yield.

2. Methodology

2.1. Biomass sample

The oil palm fronds were obtained from the oil palm estates surrounding the University of Nottingham Malaysia Campus in Semenyih, Selangor, Malaysia. The oil palm fronds obtained for this experiment were naturally fallen to the ground. The fronds are usually picked up after they have been left to naturally dry under the sun. The dried oil palm fronds were then ground and sieved using an Ultra Centrifugal Mill ZM 200. The sieve size used was the trapezoid-hole type at 0.5 mm. The ground oil palm fronds were then stored in an airtight container until torrefaction was conducted.

2.2. Torrefaction experiments

A Carbolite CTF 12/65/550 horizontal tubular furnace was used for the torrefaction experiments. The furnace has a 65 mm inner diameter and a heated length of 550 mm. A ceramic work tube was used instead of the integrated work tube to prevent damage to the tubular furnace. Approximately 1.5 – 2.0 g of ground biomass was weighed and put into a ceramic boat. The loaded ceramic boat was then placed in the middle of the tubular furnace and sealed at both ends. Nitrogen gas (N_2) was allowed to flow through the furnace for 5 min at 1 L/min to purge inert gases from the ceramic work tube. After this, the temperature level of the furnace was raised to 200°C, 225°C, 250°C, 275°C or 300°C, at a heating rate of 10°C/min. The N_2 flow rate was kept at 1 L/min throughout the experiment. The holding time was set at 30 min. After 30 min of holding time at the desired torrefaction temperature, the furnace was turned off and allowed to cool until it reached 150°C, as per temperature reading from the PID controller. The ceramic boat with the torrefied product was carefully removed from the furnace and kept in a desiccator. The new weight was measured when the ceramic boat reached room temperature. The torrefied product was then transferred to an airtight glass bottle and stored until further analyses were conducted. This process was repeated twice. The mass yield (%) for each run was determined using the following equation:

Mass yield = (Final torrefied mass (g) / Initial mass before torrefaction (g)) x 100 (1)

2.3. Calorimetry

The calorific value of the samples (torrefied and raw) was measured using a Parr 6100 Bomb Calorimeter. The bomb calorimeter gives the HHV (MJ/kg) of the sample. The HHV of raw and torrefied samples were determined 3 times each, and then averaged to obtain their respective mean HHVs. The energy densification ratio (EDR in %) and energy yield (%) were calculated as follows:

$EDR = (HHV_{torrefied} / HHV_{untreated}) \times 100$ (2)

$\text{Energy yield} = (HHV_{torrefied} / HHV_{untreated}) \times \text{Mass yield}$ (3)

2.4. Proximate analysis

The proximate analysis of the torrefied samples were conducted using a thermogravimetric analyser (TGA) Mettler Toledo TGA/DSC 1. By utilising the British Standards BS EN 14774-2 (moisture content determination), BS EN 15148 (volatile matter content determination) and BS EN 14775 (ash content determination), the thermal profile for determining the moisture, volatile matter, fixed carbon and ash content was developed.

With a N_2 flow rate of 50 mL/min, the sample was heated from 30°C to 105°C at 10°C/min and held at that temperature for 40 min. The mass loss here represented the moisture content of the sample. Then, at 20°C/min, the temperature was raised to 900°C and held at that temperature for 7 min. The temperature was subsequently dropped to 550°C at the same rate. The mass loss in this segment represented the volatile matter content of the sample. Upon reaching 550°C, the gas was changed to oxygen flowing at 50 mL/min and this temperature was held isothermal for 2 h. The mass loss in this segment was the fixed carbon content and the remaining mass was the ash content. The equation below was used for the proximate analysis:

Total mass (wt%) = moisture (wt%) + volatile matter (wt%) + fixed carbon (wt%) + ash (wt%) (4)

Due to inhomogeneity of biomass in general, the moisture and ash content may vary across different samples from proximate analyses. As such, the dry ash free (DAF) basis was used to compare the volatile matter and fixed carbon content of the torrefied oil palm frond samples. The DAF basis only includes the sum of the volatile matter and fixed carbon content as the total mass. This is represented by the equation below:

Total mass (DAF) = volatile matter + fixed carbon (5)

3. Results and Discussion

3.1. Mass yield

Table 1 summarises the mass yields of the torrefied oil palm fronds at different torrefaction temperatures. The decrease in mass after torrefaction is linked to the removal of moisture content and the thermal decomposition of hemicellulose, cellulose and lignin. The extent and type of component that decomposes thermally in biomass during torrefaction is dependent on the severity of torrefaction [24]. There is a slow decrease in mass yield, from 89.24% at 200°C, to 87.10% at 225°C, suggesting that only minor thermal degradation has occurred in this temperature range. This drop of mass yield of approximately 2% can possibly be due to the loss of moisture content and the slight thermal decomposition of hemicellulose. It is also observed that the decrease in the mass yield after 225°C is more significant and at a higher rate than that from 200°C to 225°C. It has a linear decrease of approximately 9% for every increment of 25°C. This is likely caused by the larger degree of the thermal decomposition of hemicellulose in the oil palm frond samples. It may also be caused by the onset of thermal decomposition of cellulose and lignin, as the torrefaction temperatures approach 300°C [14]. The results show that torrefaction does not significantly affect the mass yield at light torrefaction temperatures of 200°C and 225°C. At moderate and high torrefaction temperatures of 250°C, 275°C and 300°C, torrefaction decreases the mass yield of the torrefied oil palm frond samples steadily and at a higher rate than at low torrefaction temperatures. Thus, at higher torrefaction temperatures, more mass is lost from the oil palm frond samples.

Table 1. Mass and energy measurements of raw and torrefied oil palm frond samples.

Temperature (°C)	Mass yield (%)	HHV (MJ/kg)	EDR (%)	Energy yield (%)
Raw	-	22.55	-	-
200	89.24	24.54	108.8	97.12
225	87.10	24.97	110.8	96.46
250	78.50	26.62	118.1	92.70
275	69.61	27.87	123.6	86.04
300	60.40	29.22	129.6	78.29

3.2. Energy densification ratio

The energy densification ratio (EDR) represents the ratio of the increase in the HHV of the torrefied sample to the raw sample. From Table 1, it can be seen that the range of the EDR is from 108.8% at 200°C, to 129.6% at 300°C. The increase in the energy densification ratio from 200°C to 225°C is about 2%. This slow increase may be due to the release of moisture and slight thermal decomposition of hemicellulose, as similarly explained for mass yield. From 225°C onwards, the EDR increases at approximately 6% on average for each 25°C increment. This significantly higher rate of increase in the EDR can be explained by the loss of hydrogen and oxygen in the form of light volatiles from the biomass, resulting in the reduction in the O/C and H/C ratios of the biomass [8,25]. This is later confirmed in Section 3.5, showing that the increase in the fixed carbon content is related to the increase in the EDR with torrefaction temperature. This increase in the energy density of the torrefied oil palm fronds is consistent with other torrefaction studies [10,12,17]. Table 2 shows that at higher torrefaction temperatures, a higher HHV can be expected of the torrefied biomass. Comparing oil palm fronds with other types of biomass, it is clear that torrefied oil palm fronds exhibit a higher HHV overall. This makes torrefaction a suitable thermal upgrading process for oil palm fronds. However, a balance between the increase in energy content (HHV) and loss in mass must be taken into consideration. The balance can be measured using the energy yield, as discussed in the following section.

Table 2. HHV of different torrefied biomass from literature.

Torrefied biomass	Temperature (°C)	Time (min)	HHV (MJ/kg)	Reference
E. grandis wood	200	60	20.8	[10]
	250	60	21.7	
	280	60	23.0	
Norwegian spruce wood	260	8	20.7	[12]
	285	16.5	22.2	
	310	25	27.8	
Palm mesocarp fibre	220	30	17.2	[17]
	250	30	17.7	
	300	30	20.4	
Oil palm fronds	200	30	24.54	This study
	225	30	24.97	
	250	30	26.62	
	275	30	27.87	
	300	30	29.22	

3.3. Energy yield

Energy yield is the ratio of the energy content of the torrefied sample to that of the raw sample. It is also the product of the mass yield and EDR. As observed in Table 1, the energy yield is always less than unity, showing that the decrease in mass yield is more significant than the increase in the EDR. This implies that the increase in HHV (EDR) cannot compensate the much higher decrease in the mass yield. The data also shows an increasing rate of decrease in energy yield with increasing torrefaction temperatures. The energy yields of torrefied oil palm frond samples range from 97.12% at 200°C, to 78.29% at 300°C. From 275°C onwards, the energy yield drops to below 90%. The increasing rate of decrease in energy yield can be explained by the increase in the extent of the thermal decomposition of oil palm frond. With increasing torrefaction temperature, more mass is loss, resulting in a decrease in the overall energy content of the torrefied oil palm frond samples.

3.4. DAF volatile matter content

Volatile matter released from biomass usually contains compounds of hydrogen and oxygen, and some light hydrocarbons. Table 3 confirms that with increasing torrefaction temperatures, the volatile matter in the torrefied oil palm frond samples decrease. At 200°C, the amount of DAF volatile matter present in the torrefied oil palm frond sample is at 87.32%. This decreases to 72.11% at a torrefaction temperature of 300°C. The average linear decrease of DAF volatile matter is approximately 4% for every increment of 25°C. The decrease in volatile matter is linked to the mass loss of the torrefied samples and thus explains the reduction in mass yield as torrefaction temperature increases.

Table 3. Proximate analysis measurements of torrefied oil palm frond samples.

Temperature (°C)	Moisture (wt%)	Dry basis ash (wt%)	DAF volatile matter (wt%)	DAF fixed carbon (wt%)
200	2.00	2.33	87.32	12.68
225	1.93	3.42	83.08	16.92
250	1.26	2.97	79.67	20.33
275	0.23	4.83	77.60	22.40
300	1.53	3.44	72.11	27.89

3.5. DAF fixed carbon content

A high level of fixed carbon content is usually desirable in a fuel, to allow the fuel to release more heat energy during combustion and burn longer [6]. Thus, the increase of the percentage of DAF fixed carbon content can be correlated to the EDR increment of the torrefied oil palm frond samples. Referring to Eq. (5), the DAF fixed carbon content should also be increased as the DAF volatile matter content decreases in the torrefied samples. From Table 3, the DAF fixed carbon content shows an increasing trend, almost linear, with increasing torrefaction temperatures. The DAF fixed carbon content increases at an average of 3% – 4% for every increment of 25°C in torrefaction temperature. The DAF fixed carbon content ranges from 12.68% at 200°C, to 27.89% at 300°C. The increase in the fixed carbon content is attributed to the loss of volatile matter, which mostly contains hydrogen and oxygen based compounds and some light hydrocarbons. While volatile matter is lost, most of the fixed carbon remains in the biomass during torrefaction, leading to the increase in the fixed carbon content which corresponds to the increase in HHV after torrefaction, as discussed in Section 3.2.

3.6. Potential as a fuel for co-firing with coal

Coal used in power plants has an average HHV of 29.5 MJ/kg [26]. It is therefore desirable for the HHV of the torrefied oil palm frond to reach this value. The torrefied oil palm frond achieves a HHV of 29.22 MJ/kg when torrefied at 300°C. However, the energy yield of that same sample is 78.29%. This low energy yield means that only 78.29% of the energy content is retained after torrefaction. While the HHV increases by 29.6%, this energy loss is too significant, caused by the mass loss as volatile matter during torrefaction. Simply put, the torrefied product is very energy-dense, but there is very little of it left in mass. It should be noted that the higher temperature also incurs higher operating costs. Thus, to determine the most feasible torrefaction temperature, a balance between the increase in energy density or HHV and the energy yield of the torrefied product must be found. It is recommended for the energy yield to be above 90%. Based on the data obtained, the optimum torrefaction temperature of 250°C results in a HHV and energy yield of 26.62 MJ/kg and 92.70%, respectively. It has an improvement of 18.1% over the HHV of raw oil palm frond, while retaining most of the energy after torrefaction. This optimum torrefaction temperature only holds true for a holding time of 30 min. The HHV of 26.62 MJ/kg then makes the torrefied oil palm frond suitable as a co-firing fuel for coal power plants.

4. Conclusions

The effect of temperature on the torrefaction of oil palm fronds, an abundant agricultural waste, has been studied. The mass and energy yields decreased, while the HHV increased with increasing torrefaction temperatures. At low torrefaction temperature of 200°C, the decrease in mass and energy yields, and the increase in EDR were insignificant. At moderate and high torrefaction temperatures from 225°C to 300°C, the mass and energy yields decreased at a higher rate. The EDR also increased, but the increase was not high enough to compensate the mass loss and thus the drop in energy yield. Increasing torrefaction temperature increased the DAF fixed carbon content, but decreased the DAF volatile matter content. The optimum torrefaction condition of 250°C and 30 min of holding time resulted in the torrefied oil palm frond having a HHV of 26.62 MJ/kg while being able to maintain an energy yield of 92.70%. The benefits derived from the torrefaction of oil palm fronds from the increased energy density, combined with its abundance in Malaysia, demonstrate that torrefied oil palm frond is worthy of being a fuel for co-firing with coal in power plants.

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