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Influence of torrefaction temperature and time on the yields and properties of torrefied biomass

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Abstract

Thailand has great potential to use biomass from agricultural wastes for renewable fuels and energy. However, its current utilization is rather low due largely to the high moisture content and low energetic density of these materials. A simple thermal pretreatment such as torrefaction may be useful in adding value to these solid agricultural wastes. The objective of this work was to investigate effect of torrefaction temperature and time on the yields and physico-chemical properties of agricultural wastes (wood chips and oil palm fronds). The torrefaction experimental work was carried out in a laboratory reactor with varying temperatures of 200 to 400 °C and reaction times of 20 to 60 min. A 5 kW electrical heater was used to heat the reactor. From the results obtained, it was found that torrefaction temperature and time affected the solid product proximate and energy properties. The higher heating value of torrefied fuel was increased with torrefaction temperature and time. Optimum torrefaction temperature for wood chips and oil palm fronds was identified at 200 °C, while optimum times were 20 and 40 min, respectively, for maximum mass and energy yields. At these conditions, the energy content of both biomass materials was improved to 17.65 MJ/kg and 16.34 MJ/kg, 20-30% higher than the original values. The value and energy yield of wood chips and oil palm fronds could be improved through torrefaction.

Keywords: Agricultural residues, Bioenergy, Pyrolysis, Thermal pretreatment

1. Introduction

Over the last 10 years, Thailand has faced a serious problem of declining agricultural commodity prices. For example, longan, palm oil and rice [1] prices have fallen, affecting the income of farmers. Utilizing agricultural wastes as renewable fuel and energy will be economically attractive to add value to these residues, hence, increase the earnings of farmers. Previously, utilization of agricultural wastes was relatively low [2]. They are usually burned to prepare the area for next planting season. This is considered a low cost solution and the easiest way to manage these wastes. Burning contributes to air pollution problems throughout the region and impacts human health as well as the tourism industry [3]. Converting agricultural waste into torrefied solid fuels with pyrolysis technology is a good alternative to address this problem. Torrefied solid fuel can be used in industrial processes.

Torrefaction is a relatively mild thermal treatment that reduces the moisture content and initial volatile content of a solid biomass, transforming it into a brittle, char-like material. Generally, lignocellulosic biomass material consists of approximately 80% volatile matter and 20% fixed carbon on a dry basis. In torrefaction, a solid biomass is heated with an external heat source in the absence of oxygen at temperatures of 250-350 °C, leading to a loss of moisture and partial loss of the volatile matter in the biomass. The characteristics of the biomass are considerably changed. The tenacious fiber structure of the original biomass material is largely destroyed through the breakdown of hemicellulose and cellulose molecules. The material becomes brittle and easy to grind [4]. The originally hydrophilic material can become hydrophobic. With the removal of the light volatile fraction that contains most of the oxygen in the biomass, the heating value of the remaining material is increased. Torrefaction can increase energy density of a biomass by an average of about 20-30% [5-7]. The torrefaction process can reduce the mass of fresh wood by 20-30%, resulting in a denser, higher-valued product that can be transported more economically than traditional wood chips. The product can be used as a coal replacement or co-fired/co-milled with coal in electricity generating power plants, thereby reducing greenhouse gas emissions. At the same time, the use of torrefied fuel in a gasification power plant will increase the efficiency of system and reduce the tar content of the burning gas [8].

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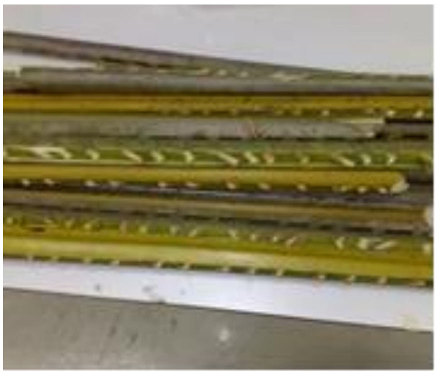

Figure 1 Wood chips (left) and oil palm fronds (right) for producing torrefied fuels

The focus of the current study was on utilization of agricultural wastes to produce torrefied solid fuels. Torrefaction of wood chips and oil palm fronds was carried out in a fixed bed thermal reactor. N_2 was used as the conditioning gas. Process temperatures were varied as 200, 250, 300, 350 and 400 °C for 20, 40, and 60 min of residence time. Performance and properties in terms of solid yields, proximate analysis, higher heating value (HHV), and energy yields were examined.

2. Materials and methods

2.1 Raw materials

The raw materials used were wood chips and oil palm fronds from northern Thailand, as shown in Figure 1. Wood chips were derived from longan wood residues. It is estimated that there were about 625-1875 kg/hectare of longan wood residue remaining in the plantations of northern Thailand. Their average bulk density is approximately 530 kg/m^3 with moisture contents of less than 10%. Oil palm fronds were obtained locally from Maejo University, with an average bulk density of 445 kg/m^3 and moisture contents of more than 50%. They were pre-dried to less than 10%, prior to torrefaction. The samples were then ground into powders passing a 16 mess sieve (1 mm). Table 1 shows the proximate and ultimate analyses of the raw biomass materials. The composition of wood chips and oil palm fronds was found to be similar, except for their ash and HHV values. The HHV of wood chips and oil palm fronds was about 15.9 MJ/kg and 17.2 MJ/kg, respectively.

Table 1 Properties of agricultural wastes considered in this work

	Wood chips	Oil palm fronds
Moisture (%)	8.96	8.69
Volatile matter (%)	73.09	70.31
Fixed carbon (%)	15.23	12.72
Ash (%)	2.73	8.68
C (%)	44.95	45.39
H (%)	6.61	6.68
O (%)	0.37	1.61
N (%)	45.32	41.43
S (%)	0.02	0.08
HHV (MJ/kg)	15.92	13.84
Bulk density (kg/m^3)	530	445

2.2 Experimental

The experimental setup for torrefaction is shown in Figure 2. The torrefaction reactor was heated using a 5 kW electrical heater that could produce a maximum temperature of 1500 °C. Temperature measurement was performed using a type K thermocouple, connected to an electronic control system. The combustor was 608 cm^3 in volume and made of stainless steel. The biomass basket could be moved up and down during the experiment. A nitrogen gas system was controlled by a regulator and flow rate control valve. A water cooling system was used. Proximate and ultimate analyses were conducted for the raw biomass materials and torrefied products. HHV analysis was done in a bomb calorimeter. In the torrefaction experiments, temperature was varied over the range of 200-400 °C, while reaction times were between 20-60 min. For each condition, the experiment was started by loading about 20 g of biomass material into the reactor, and switching on the heater with a nitrogen feed into the test chamber. The biomass was initially at an elevated position in the chamber that was cooled to keep its temperature less than 40 °C. Once the temperature inside the test chamber reached a desired torrefaction temperature, the biomass was lowered into the test chamber to start the thermal treatment. After a set treatment time elapsed, the biomass was once again pulled up into the cooled section to stop further thermal degradation. The biomass was subsequently taken out and stored for future analysis.

The high heating value (HHV) [9], mass yield and energy yield [10] were calculated from eqs (1-3).

$$\text{HHV} = 0.3536\text{FC} + 0.1559\text{VM} - 0.0078\text{Ash} \quad (1)$$

$$\text{Mass yield}\,(Y_{mass}) = \frac{\text{mass after torrefaction}}{\text{mass of raw sample}} \text{x}100\% \quad (2)$$

$$\text{Energy yield} = Y_{mass}\,\frac{\text{HHV (torrefied fuel)}}{\text{HHV (raw sample)}} \text{x}100\% \quad (3)$$

3. Results and discussion

3.1 Physical appearance of torrefied biomass products

Figure 3 shows changes in appearances of wood chips and oil palm fronds, especially their color before and after the torrefaction process at various temperatures. The wood chips and oil palm fronds were brown at temperatures less than 250 °C, and gradually became darker and eventually black with increasing temperatures to 400 °C. Comparatively, the color of both biomass materials was similar to other solid biomasses such as beech wood,

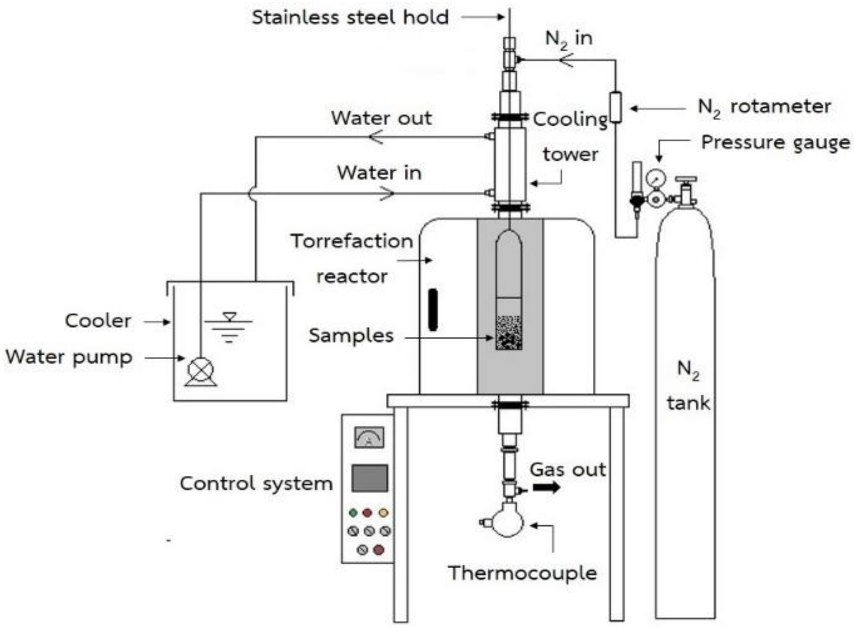

Figure 2 Schematic of torrefaction experimental setup

Figure 3 Wood chips and oil palm fronds at various torrefaction temperatures

miscanthus and the macroalga, Laminaria japonica [11]. Color change was caused by the exothermic nature of the reaction above 280 ºC. For torrefaction at temperatures greater than 280 ºC, an exothermic reaction took place resulting in hemicellulose decomposition [12].

3.2 Product yields

The solid product yields from torrefaction of wood chips and oil palm fronds are shown in Figure 4, for various reaction temperatures and residence times. Both materials appeared to behave in a similar fashion. Temperature was found to affect the mass yields significantly, while the effect of reaction time on yield was less. At 200 ºC, the effect of residence time changed the final mass yields little for both biomass materials. At higher temperatures, wood chips and oil palm fronds showed slight mass loss with reaction time. At the highest temperature and longest residence time, significant mass losses of over 60% were evident for both materials. Loss in mass yields may be due to the decomposition of hemicellulose and cellulose. Wood chip mass losses were slightly higher than for oil palm fronds, and hence resulted in a rapid rate of mass yield, compared to that of oil palm fronds [13].

3.3 Proximate analysis

Figure 5 shows changes in the proximate analysis of wood chips and oil palm fronds with torrefaction temperature at a fixed reaction time of 40 min. The moisture and volatile matter content of both biomass materials were found to decrease with increasing temperature. Loss of moisture was expected at temperatures < 200 °C. At higher temperatures, release of volatiles was expected to occur [14]. The lowest volatile matter contents were found to be 43.5% and 41.9%, for wood chips and oil palm fronds, respectively, at the highest torrefaction temperature. Reduction of volatile matter was caused by decomposition of biomass components such as the extractives, hemicellulose, lignin and cellulose [15]. Decreasing volatile matter in torrefaction led to reduced mass and energy yields [16]. Increasing torrefaction temperature also resulted in an increased proportion of fixed carbon and ash, as moisture and initial volatile matter were released from the raw materials [16]. The fixed carbon content had an inverse relationship with the volatile content. Due to the high volatile content of wood, elevated treatment temperatures increased the fixed carbon [17]. Torrefaction increased the fixed carbon of wood chips and oil palm fronds by about 29-85% and 76-97%, respectively. The highest

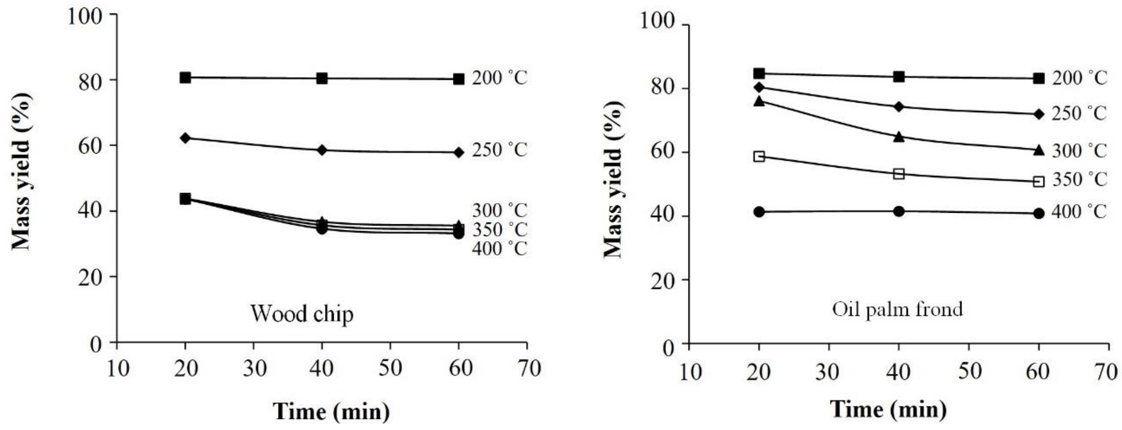

Figure 4 Mass yield analysis

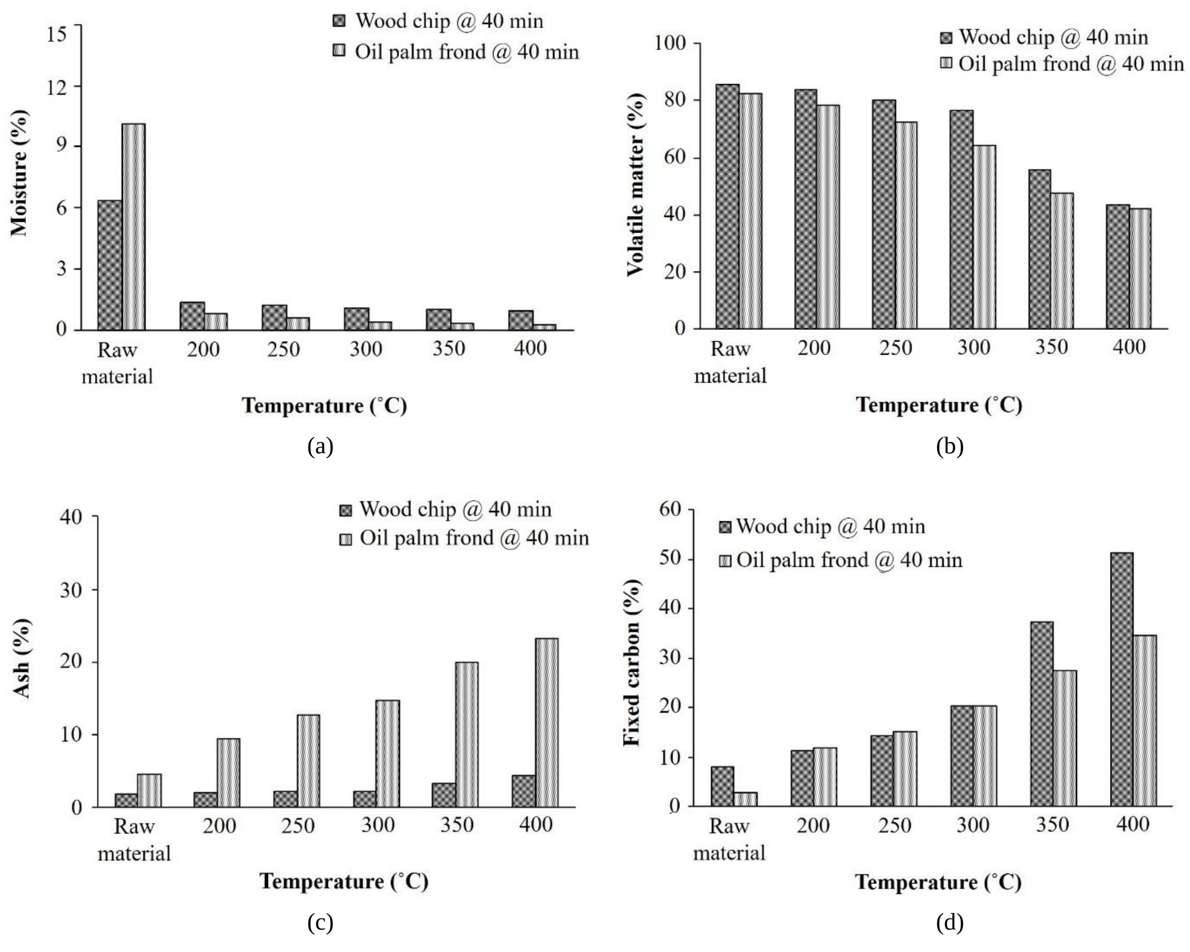

Figure 5 Effect of torrefaction temperature on biomass proximate properties

fixed carbon found for wood chips and oil palm fronds were 51% and 35%, respectively.

Figure 6 shows effect of reaction time on the moisture, volatile matter, fixed carbon and ash content of wood chips and oil palm fronds processed at a constant reaction temperature of 300 °C. It can be seen that increasing reaction time resulted in reduced moisture and volatile matter contents of both biomass materials. The volatile matter of wood chips was lower than that of oil palm fronds since their high hemicellulose and cellulose content were more easily decomposed into gas [18]. At the longest time, the volatile matter of wood chips and oil palm fronds were about 60% and 55%, respectively. The fixed carbon and ash contents were found to increase with torrefaction time. Increased fixed carbon led to higher HHVs of the biomass [19]. The maximum fixed carbon content obtained for wood chips and oil palm fronds were approximately 35% and 23%, while their ash contents were 2.4% and 16%, respectively.

3.4 HHV and energy yields of torrefied fuels

Figure 7 shows the HHV of wood chips and oil palm fronds before and after torrefaction. It was found that increased torrefaction temperatures and reaction times led to

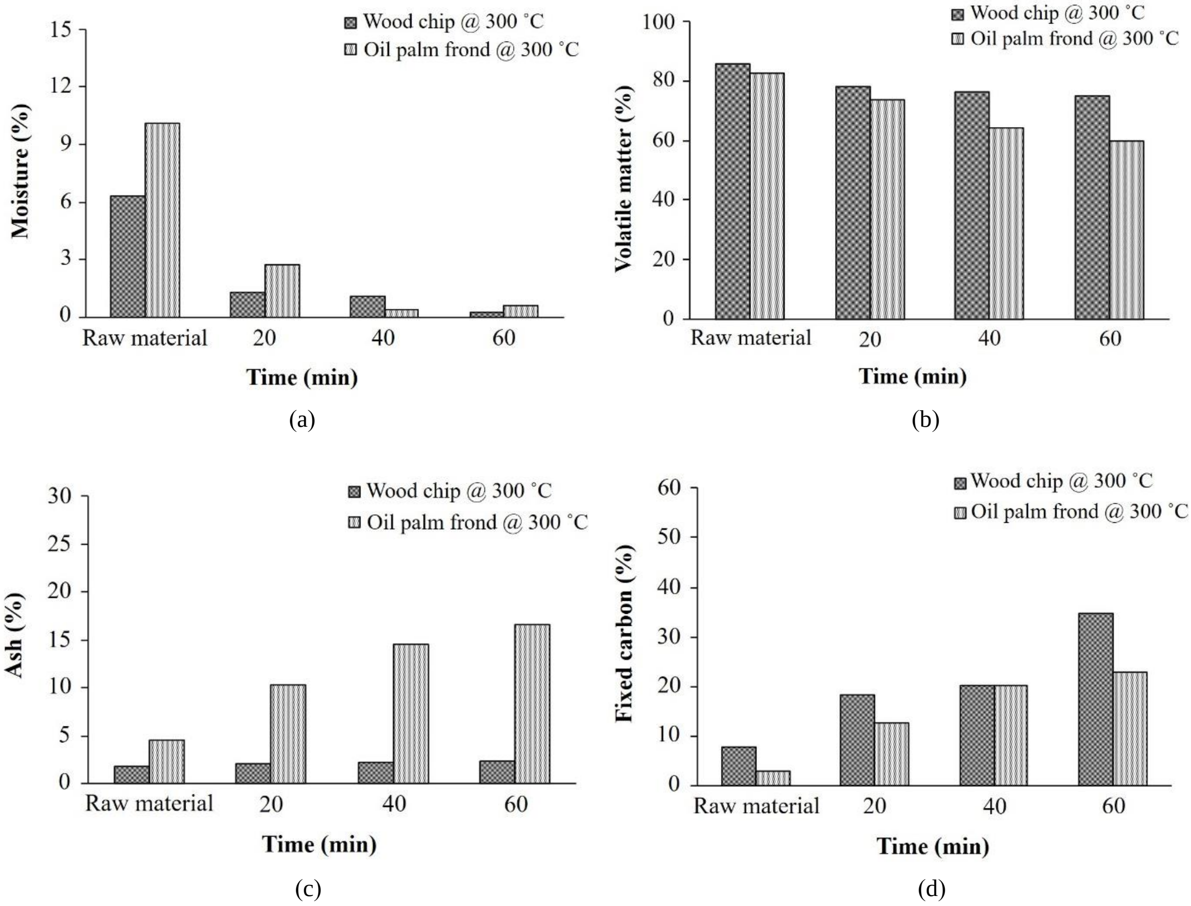

Figure 6 Effect of reaction time on the biomass proximate properties

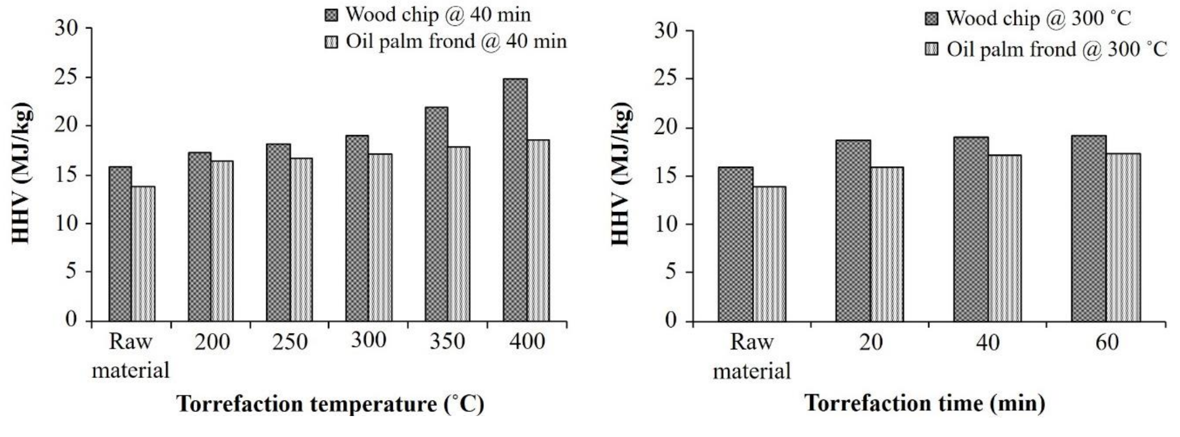

Figure 7 Effect of torrefaction temperature and time on HHV

increased HHVs of the torrefied products. This was due to their reduced moisture content and increased carbon content. Wood chips had more fixed carbon and volatile matter than oil palm fronds, affecting their final HHV [11] which is clearly seen at torrefaction temperatures above 300 ^oC. For torrefaction temperatures lower than 300 ^oC, the fixed carbon of wood chips was increased to 28-60%. At higher temperatures, 78-85% fixed carbon was obtained. At the torrefaction temperatures in the range of 200-400 ^oC, the HHV of wood chips was between 17.65 - 24.86 MJ/kg, while for oil palm fronts, it was 16.34-18.58 MJ/kg. The higher ash content in oil palm fronds resulted in lower HHVs compared to wood chips [12]. Thermal treatment at higher temperature resulted in higher HHVs for both biomass materials. Treatment at longer reaction times did not show any significant improvement in HHV after 20 min.

Figure 8 shows the effect of torrefaction temperature and reaction time for wood chips and oil palm fronds. It was observed that increasing the temperature and time led to decreased energy yields. This was due to mass loss from degradation of hemicellulose, cellulose and lignin [20]. The reaction temperature was the major factor affecting mass and energy yields [10]. The information is very useful for future fuel production for selection of the optimal process conditions for each biomass.

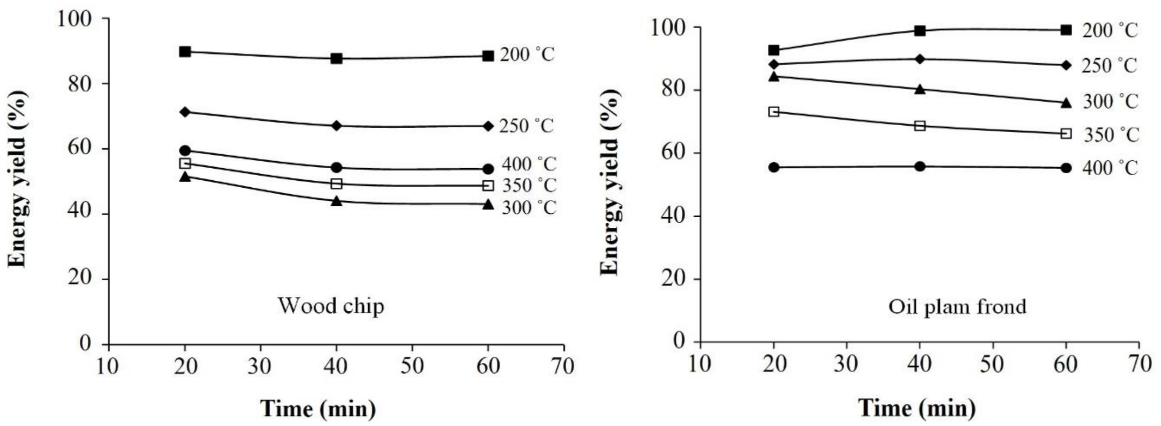

Figure 8 Energy yield analysis

4. Conclusions

Torrefaction temperature and time were found to affect yields and properties of torrefied fuels. Moisture and volatile matter were reduced, while the fixed carbon and HHV were increased. For maximum mass and energy yields with improved HHV, the optimum conditions for torrefaction of wood chips and oil palm fronds were obtained at 200 °C and 20 and 40 min, respectively. At these conditions, HHVs were improved by 20-39% to 17.65 MJ/kg and 16.34 MJ/kg, respectively.

5. Acknowledgements

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