An overview of oil palm biomass torrefaction: Effects of temperature and residence time

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Abstract. Biomass is characterized as high moisture content, low bulk and energy density, possesses hygroscopic behaviour and poor grindability material as compared to the superior coal. A thermal treatment called torrefaction is a heating of biomass in a temperature range between 200°C to 300°C under inert atmosphere in order to upgrade biomass properties. Torrefied biomass has many similar characteristics to coal such as low moisture content, high bulk and energy density, hydrophobic and good grindability. This paper reviews the effects of oil palm biomass torrefaction in terms of temperature and residence time. This is because comprehensive studies on torrefaction parameters need to be carried out since different parameters might affect the chemical and physical characteristic of the torrefied product. Hence, this paper aims to discuss the effects of different torrefaction temperature and residence time towards physicochemical characteristic, mass and energy yield as well as calorific value of torrefied oil palm biomass.

1. Introduction
Waste-to-energy conversion of biomass is an important process to meet the demand of energy savings and subsequently reduces the emission of pollutants to the atmosphere [1]. Sustainable Energy Development Authority Malaysia (SEDA) stated that energy demand in Malaysia is predicted to grow 3.6% per annum until 2016 [2]. Renewable energy from biomass has been given priority as an alternative energy source to fossil fuels and this could possibly because biomass is plentifully available throughout the year. Moreover, biomass has carbon-neutral properties because carbon contained in biomass is cycled in the atmosphere when biomass is burnt as fuel [3]. Apart from that, biomass has low sulfur and nitrogen content, therefore biomass is possible to reduce the emission of pollutants such as SO2 and NOx which are commonly released during pretreatment.

Umar et al. [4] mentioned that biomass is expected to be the most prominent renewable energy source of total world primary energy by the year 2050. Interestingly, biomass from agricultural residue is considered as one of the most viable renewable energy [5]. Palm oil industry has contributed to 85.5% of biomass waste in Malaysia [6]. Oil palm or its scientific name *Elaies guineensis* had been introduced in Malaysia for many decades and its oil palm industry has contributes a huge amount of
biomass residues mainly from its plantation and milling activity [7]. Empty fruit bunches (EFBs), palm kernel shell (PKS), fiber, fronds and trunks are among biomass generated from palm oil industry which has a great potential to be utilized as renewable energy sources.

However, due to high moisture content, low bulk and energy density, hygroscopic behavior and poor grindability, biomass is preferred to undergo thermal pre-treatment process such as torrefaction in order to upgrade its properties. Torrefaction is a heating treatment of biomass which is carried out in the temperature less than 300°C under inert atmosphere. There are various factors need to be taken into account during torrefaction so that a superior torrefied biomass can be produced. This paper highlighted on several operating conditions of torrefaction such as torrefaction temperature and residence time which affects the torrefied products especially in terms of physicochemical properties of biomass. Hence, this paper aims to discuss the effects of different torrefaction temperature and residence time towards physicochemical characteristic, mass and energy yield as well as calorific value of torrefied biomass.

2. Torrefaction
Historically, research on torrefaction has been started in France in the 1930s, but there are limited publications related to this research area [8]. In fact, torrefaction has become an interesting research area in the last two decades and later the process is applied commercially [9]. Torrefaction or mild pyrolysis is defined as thermal treatment of biomass which is carried out in the temperature range between 200°C to 300°C in absence of oxygen at typically less than 30 minutes reaction time [10–12]. The process has been found to lower the moisture content, thereby effectively improving energy density and shelf life of the biomass [13,14]. The process can be divided into three distinct stages namely; light (200°C-235°C), mild (235°C-275°C) and severe (275°C-300°C) [10].

3. Effects of torrefaction parameters
There are a few studies done by previous researchers regarding effects of different heating temperature, residence time as well as heating rate on torrefied biomass. Bergman et al. [15] mentioned that heating period is necessarily important to be considered upon torrefaction process since the biomass is thermally unstable and will rapidly start to decompose during the heating period. However, when it comes to cooling period, the torrefied product is much more stable in terms of thermal condition. On the other hand, Williams et al. [16] stated that higher heating rate resulted in greater amount of volatile released thereby resulting different physical features of the char. Abnisa et al. [17] studied pyrolysis of several types of oil palm wastes namely trunk, frond, palm leaf and palm leaf rib and concluded that most of the biochar sample have comparable high heating value (HHV) to certain ranks of coals thus making pretreated biomass as a promising option to convert raw biomass into higher quality solid fuel. Table 1 shows high heating values (HHVs) of raw and torrefied oil palm biomass residues namely empty fruit bunch (EFB), palm kernel shell (PKS), palm mesocarp fibre (PMF) and oil palm frond (OPF).

Based on Table 1, Uemura et al. [13] studied torrefaction behaviour of EFB, PKS and PMF using three different temperatures; 220°C, 250°C and 300°C with a constant heating rate 10°C/min and residence time 30 minutes. Residence time is defined as total period when the feed biomass was inside the torrefaction reactor [23]. They revealed that torrefaction temperature increase the calorific value of all torrefied biomass studied range between 17-23 MJ/kg which higher than that of untreated biomass. Chin et al. [18] conducted torrefaction of EFB at three different temperature, 200°C, 250°C and 300°C for 15, 30, and 45 minutes and reported that the increase of heating value was influenced by temperature and time. However, HHV was greatly affected by temperature as compared to time. This is similar to Sulaiman and Anas [14] studies regarding torrefaction of OPF at three different temperature 230°C, 250°C and 270°C for 50, 30 and 15 minutes respectively. They found out that torrefaction increased the calorific value of the OPF sample by close to 50%. They concluded that higher torrefaction temperatures resulted in higher calorific values of the torrefied biomass. They also predicted that effect of residence time is comparably small for the range of conditions tested.
al. [24] identified that increasing torrefaction temperature and residence time will improve the HHV of biomass whereby HHV increment was in the range of 1-58% in various types of woody and non-woody biomass. In terms of elemental composition, Aziz et al. [5] studied torrefaction behaviour of EFB, PKS and PMF in temperature ranges between 200°C-300°C using thermogavimetry analyser coupled with mass spectrometry (TGA-MS) and concluded that carbon content was increased while hydrogen and oxygen content decreased as torrefaction temperature increased.

Other than that, mass and energy yield play an important role to determine the effects of temperature or residence time towards torrefied products. Study conducted by Na et al. [25] reported that a high calorific value of the torrefied biomass is indicative of such weight loss during torrefaction. Therefore, torrefied biomass should be evaluated in terms of energy yield so that a high energy density of torrefied biomass can be produced. Chen and Kuo [26] reported that biomass torrefied in less than one hour with light torrefaction are able to produce solid fuel with high energy density. Mass yield is determined as percentage of resulted mass after torrefaction while energy yield is defined as percentage of calorific value of feed materials [27]. The mass and energy yield is closely related to each other since value of mass yield will be used to obtain an energy yield value. Mass yield of torrefied biomass can vary from 24% to 95% of its original weight depending on its hemicellulose content [24]. In terms of fiber compositional analysis, cellulose, hemicellulose and lignin show different thermal decomposition characteristic. Previous study reported that hemicellulose has the thermal decomposition temperature between 220°C-315°C while that of cellulose (315°C-400°C) and finally lignin which undergo gradual decomposition in temperature range from 160°C to 900°C [28]. Aziz et al. [5] reported that based on TGA curves obtained from his study on torrefaction behaviour of EFB, PKS and PMF, hemicellulose degradation was more significant as compared to that of

| Oil palm biomass | HHV of raw biomass (MJ/kg) | Ref. | T (˚C) | t (min) | Mass yield (wt%) | HHV of torrefied product (MJ/kg) | Ref. |
|-----------------|---------------------------|------|--------|---------|-----------------|---------------------------------|------|
| EFB             | 17.02                     | [13] | 220    | 30      | 43.16           | 17.17                           | [13] |
|                 |                           |      | 250    | 30      | 36.98           | 17.67                           |      |
|                 |                           |      | 300    | 30      | 24.18           | 20.41                           |      |
|                 | 18.07                     | [18] | 200    | 15      | 21.01           |                                 |      |
|                 |                           |      | 200    | 30      | 23.02           |                                 |      |
|                 |                           |      | 200    | 45      | 23.80           |                                 |      |
|                 |                           |      | 250    | 15      | 22.24           |                                 |      |
|                 |                           |      | 250    | 30      | 24.17           |                                 | [18] |
|                 |                           |      | 250    | 45      | 24.54           |                                 |      |
|                 |                           |      | 300    | 15      | 22.63           |                                 |      |
|                 |                           |      | 300    | 30      | 24.34           |                                 |      |
|                 |                           |      | 300    | 45      | 25.03           |                                 |      |
| PKS             | 16.14                     | [19] | 220    | 30      | 77.44           | 18.85                           | [13] |
|                 | 18.81                     | [20] | 250    | 30      | 73.83           | 19.07                           | [13] |
|                 | 19.78                     | [21] | 300    | 30      | 71.27           | 21.68                           |      |
| PMF             | 19.61                     | [21] | 220    | 30      | 63.08           | 19.03                           |      |
|                 |                           |      | 250    | 30      | 60.04           | 19.24                           | [13] |
|                 |                           |      | 300    | 30      | 52.45           | 22.17                           |      |
| OPF             | 16.3                      | [14] | 230    | 50      | -               | 20.6                            | [14] |
|                 | 17.28                     | [22] | 250    | 30      | -               | 21.5                            |      |
|                 |                           |      | 270    | 15      |                | 23.8                            |      |
cellulose and lignin. Uemura et al. [13] studied the effects of three different temperatures on torrefaction of oil palm waste and concluded that PMF and PKS exhibited higher energy yield values of more than 95 wt.% compared to EFB energy yield value of 56 wt.%.

Strandberg et al. [23] reported that as torrefaction severity increases, the mass and energy yield decreases and their studies also focused on the importance of temperature and temperature process control. They also concluded that effects of torrefaction temperature were more significant than that of residence time.

4. Conclusion
Torrefaction temperature and residence time are the two important parameters that should be considered in torrefaction process. Even though some studies stated that residence time only has a slight effect in torrefaction, further study is required to investigate the effects of residence time on solid char and energy yield and also determination of their optimum values. This is because shorter residence time will make the torrefaction process cost-effective and yet able to produce a superior solid char to be further used in power generation sector. It is also worth mentioning that investigation of residence time varies between individual biomass from different origin either for lignocellulosic or non-lignocellulosic biomass.

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