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Effects of torrefaction on the physiochemical properties of oil palm empty fruit bunches, mesocarp fiber and kernel shell

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ABSTRACT

In this work, the effects of torrefaction on the physiochemical properties of empty fruit bunches (EFB), palm mesocarp fiber (PMF) and palm kernel shell (PKS) are investigated. The change of properties of these biomass residues such as CHNS mass fraction, gross calorific value (GCV), mass and energy yields and surface structure when subjected to torrefaction process are studied. In this work, these materials with particle size in the range of 355–500 μm are torrefied under light torrefaction conditions (200, 220 and 240 °C) and severe torrefaction conditions (260, 280 and 300 °C). TGA is used to monitor the mass loss during torrefaction while tube furnace is used to produce significant amount of products for chemical analyses. In general, the study reveals torrefaction process of palm oil biomass can be divided into two main stages through the observation on the mass loss distribution. The first stage is the dehydration process at the temperature below than 105 °C where the mass loss is in the range of 3–5%. In the second stage, the decomposition reaction takes place at temperature of 200–300 °C. Furthermore, the study reveals that carbon mass fraction and gross calorific value (GCV) increase with the increase of torrefaction temperature but the O/C ratio, hydrogen and oxygen mass fractions decrease for all biomass. Among the biomass, torrefied PKS has the highest carbon mass fraction of 55.6% when torrefied at 300 °C while PMF has the highest GCV of 23.73 MJ kg^{-1} when torrefied at the same temperature. Both EFB and PMF produce lower mass fraction than PKS when subjected to same torrefaction temperature. In terms of energy yield, PKS produces 86–92% yield when torrefied at light to severe torrefaction conditions, until 280 °C. However, both EFB and PMF only produce 70–78% yield at light torrefaction conditions, until 240 °C. Overall, the mass loss of 45–55% of these biomasses is observed when subjected to torrefaction process. Moreover, SEM images reveal that torrefaction has more severe impact on surface structure of EFB and PMF than that of PKS especially under severe torrefaction conditions. The study concludes that the torrefaction process of these biomass has to be optimized based on the type of the biomass in order to offset the mass loss of these materials through the process and increase the energy value of the solid product.

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1. Introduction

Due to depletion of fossil fuels and serious environmental problems associated with the usage of fossil fuels, renewable energy supply is necessary. Biomass is one of the promising renewable energy sources, and it can be utilized as solid, liquid and gas fuels. Growing concerns about the effects of CO_2 emissions from fossil fuels call for sustainable energy sources, such as biomass, because of its carbon neutrality, relative abundance and nonedible [1]. Due to their availability in Malaysia, oil palm residues are considered to be the most abundant biomass and the best options for fuel generation. Malaysia produces about 47% of the world's palm oil supply and can be considered as one of the world's largest producers and exporters of palm oil. Due to the intensive planting and mill operations, Malaysia generates huge quantity of oil palm biomass including oil palm trunks, oil palm fronds, empty fruit bunches (EFB), shells and fibers as residues from harvesting and processing activities. Every year, palm oil industry produces roughly about 17.08 Tg of EFB, 12.9 84 Tg of frond, 8.2 Tg of trunk, 9.66 Tg of mesocarp fiber and 5.3 Tg of kernel shell [2–4]. Each type of these biomasses has different fractions of constituents as summarized in Table 1 [5–7,16].

Due to the huge quantities of biomass generated from the oil palm industry, it will be a waste if the biomass is not properly utilized. In 2005, with production of 15 Tg of oil, energy value of the EFB residue alone is around 125 pJ. This would amount to 1200 M$ for an assumed price of oil of $400 per tonne [8]. The processing of fresh fruit bunches of oil palm results in different types of residues including empty fruit bunch (EFB), mesocarp fiber (PMF) and kernel shell (PKS), which are considered to be harmful wastes to the environment if released untreated [9]. Discharging the biomass waste on the land may lead to pollution and might deteriorate the surrounding environment. Traditionally, EFB is burnt in simple incinerators as a mean of disposal and the ash recycled to the plantation as a fertilizer. Due to air pollution generated from this practice and stringent regulations impose on the burning of biomass residues, EFB is currently used as mulch in the field. This could cut back fertilizer use and improve the soil structure [10]. For last few years, most of the oil palm mills start to use the oil palm residues as fuels in co-generation process of their boiler [11]. Due to their characteristics, some of these resources have to be pretreated before they can be utilized as fuel. Therefore, pretreatment process is required to improve the energy yield of biomass.

Table 1 – Oil palm chemical composition analysis.

Component (W_B on biomass raw sample)			
Components	EFB	PMF	PKS
Holocellulose	0.3530	0.3180	0.2230
Cellulose	0.3830	0.3440	0.2080
Lignin	0.2221	0.2527	0.5070
Ash	0.0167	0.0350	0.0104
Moisture	0.6700	0.3700	0.1200

Refs. [5–7,16].

Several challenging properties of biomass including high moisture, low energy density, hygroscopic nature, low heating value and soot formation during combustion limit its usage as a resource for the bio-energy [12–14]. The utilization of the raw biomass during thermo-chemical conversion processes such as pyrolysis and gasification entailed several problems. In most cases, biomass has relatively high moisture value [15–18]. In the case of EFB, the moisture can be as high as 60–67% where as PMF and PKS have 30–37% and 12–20% of moisture, respectively [19–21]. This leads to the difficulty in handling and transportation of these biomass residues [15,22,23]. Secondly, due to its fibrous and tenacious nature, biomass is difficult to grind into small homogenous particle. This poor grindability issue can cause serious problems especially when the biomass is used in the pulverized system such as co-firing with coal [13,15,18]. Moreover, very high load of untreated biomass is required to generate an equivalent amount of energy from coal due to its relatively low carbon [13]. Finally, raw biomass is also characterized as having low heating value, high O/C ratio and low energy density [15–18]. All these drawbacks contribute to the difficulty of utilization of untreated biomass.

In order to overcome these limitations, a pre-treatment process is often necessary to improve the quality of biomass. One of the processes that are often applied is torrefaction process [15–18]. Torrefaction is a thermal treatment process where biomass is heated within a temperature range of 200–300 °C under an inert atmospheric condition. The products of torrefaction consist of dark color solid, condensate including moisture and acetic acid, and gases which are mainly CO_2, CO and small amounts of CH_4 and H_2 [13,16]. The torrefied solid has lower moisture and O/C ratio with higher carbon mass fraction and calorific value compared to the raw biomass. The low moisture can prevent biodegradation, thus can increase the storage duration of the treated solid. The higher carbon and calorific value are contributing to the increase in the energy yield of the torrefied solid. Besides, the tenacious and fibrous nature of biomass becomes more brittle once torrefied, which improves the grindability of the solid [13,16,17,24].

One important parameter that influenced the torrefaction process is temperature. Many researchers have reported that torrefaction temperatures for lignocellulosic biomass range from 250 to 300 °C [2–4,22–36]. Aziz et al. have reported that torrefaction of oil palm biomass residues is affected by the chemical composition and decomposition temperature [25]. Chen et al. showed that torrefaction at 230 °C has a relatively small impact on the decomposition of basic biomass components. However, as the temperature is increased to 260 °C, a significant amount of hemicellulose decomposed, and at 290 °C, a larger amount of hemicellulose and cellulose decomposed [26]. In addition, Yan et al. reported that an increase in the torrefaction temperature will result in a decrease in mass fraction and an increase in densification of torrefied biomass, which produce a solid with an increase of C and a decrease of O and volatiles [27]. Similarly, Deng et al. also reported that an increase of torrefaction temperature leads to a decrease in solid bio-char yield and an increasing yield in volatile matters including liquid and noncondensable gases