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# Optimization of palm kernel shell torrefaction to produce energy densified bio-coal

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ABSTRACT

Biomass torrefaction is a thermal process, which is similar to a mild form of pyrolysis at temperatures ranging from 200 to 320 °C to produce energy densified solid fuel. The torrefied biomass is almost equivalent to coal and is termed as bio-coal. During torrefaction, highly volatile fraction of biomass including moisture and hemicellulose are released as vapors, providing energy enriched solid fuel, which is hydrophobic and brittle. In this study, bio-coal is produced from palm kernel shell (PKS) in a batch feeding reactor. The operating variables such as temperature, residence time and swiping gas flow rate are optimized. Around 73% yield of bio-coal with calorific value of 24.5 MJ/kg was achieved at optimum temperature 300 °C with residence time of 20 min and nitrogen gas flow rate of 300 mL/min. The thermal yield was calculated to be maximum of 94% for the bio-coal produced at 300 °C. The temperature and residence time of torrefaction are found to be the most sensitive parameters in terms of product yield, calorific value and thermal yield of bio-coal.



## 1. Introduction

The extensive use of fossil fuels for energy (coal, natural gas and petroleum) has become a major cause of global warming due to increasing of carbon dioxide into the atmosphere. In addition, the reserve of fossil fuels is also continuously declining. Besides, the utilization of fossil fuels, especially the coal for power generation, generates hazardous products in different ways. During coal extraction, the toxic inorganic heavy metals such as arsenic and mercury are released into the environment, while during combustion of coal; it generates particulate matters, $SO_x$ and $NO_x$ which are potentially hazardous to the environment and public health. Therefore, to maintain the sustainability of the environment and to prevent the health risk, the alternative energy sources which are renewable, sustainable and cost effective are essentially shouted. Biomass is one of such a renewable energy sources which can be converted to solid, liquid and gaseous fuels to be used as alternatives to fossil fuel [1].

Four thermochemical conversion technologies including combustion, gasification, pyrolysis and torrefaction are being utilized for converting biomass into useful form of energy. The combustion of biomass is used for direct heat generation, while the gasification produces burnable gas, which is termed as producer gas [2–5] and can be used for secondary burning to generate heat and power. Pyrolysis on the other hand produces liquid bio-oil [6–8] and torrefaction produces solid fuel which is comparable to coal and is termed as bio-coal. Any type of biomass can be considered for torrefaction including woody biomass, forestry by-products, agricultural biomass and even municipal solid wastes. However, abundantly available oil palm biomass, especially in Malaysia and Indonesia who are the leading palm oil producer in the world, could be the most suitable feedstock to produce bio-coal.

Torrefaction is a thermochemical process for biomass pretreatment within the temperature range of 200–300 °C [9]. This process is carried out in the absence of oxygen to prevent the biomass from being burned under atmospheric pressure. During torrefaction, the bound and unbound moisture as well as high volatile fraction of organic components are released from biomass. The organic volatiles mostly include extractive and hemicellulose with a little fraction of cellulose and lignin. During torrefaction, approximately 25–30% of mass reduction occurs and most of which is accounted by the vaporization of oxygen-containing molecules [10]. The energy loss associated with the mass loss for optimum product is approximately 10% of total energy content in the feedstock [11]. Finally, the resulting product appears as energy densified deep brown to black solid with highly hygroscopic in nature. The product is quite easy to handle, store and transport and most importantly it is suitable to burn in existing coal fired power plant.

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Because of the advantages of torrefied biomass (bio-coal) to be used as co-firing with coal or full replacement of coal in the existing coal fired power plant and a potentially huge market for electricity generation, the process of torrefaction has received potential interest over the last years [11,12]. Because of its potential market, many technology suppliers, developers and knowledge based institutions are actively involved for faster development of the optimized technology to uptake into the commercial market [13,14]. Under different financial facilities, about 30 projects are being implemented; most of which are in Europe and North America [15], while at least four industrial scale projects are being running [16]. Most of the research based works in those projects emphasizes to solve the problems related to the applied aspects rather than to solve the fundamental aspects. As a result, more than 50 patents on biomass torrefaction have been granted over the past five years, indicating the growing interest in investigation into the technology [17]. The investigations, including fundamental and applied, mainly focus to some key factors including the reactor technologies and the optimization of the operating variables for different biomasses. However, most of the plants that have been built for commercial production could not achieve their design capacities [18].

In terms of reactor, most of the torrefaction technologies being developed are fundamentally based on already existing biomass drying and pyrolysis reactor concepts [19]. It needs only the technical upgradation for torrefaction applications. Therefore, there is no single technique fundamentally superior to the others; however, each of them has their advantages and disadvantages for specific types of biomass. It implies that the selection of the reactor and optimization of operating variables are the key factors for torrefaction of an individual biomass [17,20].

Even though the torrefaction process enhances the effectiveness of biomass as solid fuel, there are some setbacks that make this process still unpopular in the industry. Since this process is in the development stage, there are still some technological inadequacies, which need further investigation to enhance the effectiveness into the commercial level [16]. Since the torrefaction process is still immature, the scientific aspects including physico-chemical changes of feedstock and chemical reaction kinetics are not fully understood and the effects of reaction parameters are still being investigated. The torrefaction process is highly sensitive to temperature and solid residence time in the reactor, which needs to be optimized to obtain the desired and most optimized yield and quality of the final product. Due to the difficulty of controlling operating variables, a high quality bio-coal with consistent characteristics is also hard to attain. A little variation of excess temperature may affect the yield greatly and causes the energy and mass yield significantly reduced. Based on the thermogravimetric analysis in the literature and in our investigation, most of the mass loss of biomass occurs due to thermal decomposition within a very short range of temperature and it varies significantly for various biomasses. Although the operating variables are sensitive in mass and energy yields a significant progress has been achieved to optimize the operating variables for different biomasses within a relatively short period [21].

In this work we have torrefied palm kernel shell biomass to produce energy densified bio-coal. Detailed optimization in terms of temperature, residence time and swiping gas flow rate are investigated.

## 2. Experimental

### 2.1. Feedstock

There are different varieties of oil palm (*Elaeis guineensis*) available in the world; however, in Malaysia Tenera hybrid, which is a cross product of Dura (thick shell palm) and Pisifera (shell-less palm) is available. Even though the same variety is mostly cultivated in Malaysia, the location, weather, and soil quality can vary the biomass characteristics. Therefore, it is specifically mentioned that the palm kernel shell (PKS) used in this study is collected from the Selangor State (Geographical Coordinates 3.3333°N, 101.5000°E) in Malaysia. More specifically, the PKS collected was generated from fresh fruit bunches (FFB), which were harvested from 12–15 years old of Tenera variety oil palm. In addition, since the PKS was collected from the outlet of a palm oil mill it was passed through each of the procedure of oil extraction such as sterilization under 145 °C and 0.27 MPa for 90 min, digestion at 90–100 °C for 30 min and pressing. The raw PKS collected contained around 22% moisture which was then sun-dried for two days in order to remove unbound moisture. The final moisture content in PKS was around 10% and it was stored in an air insulated bag and placed in a freezer bellow 0 °C in order to avoid any degradation for using it throughout the investigation. The PKS was characterized by evaluating the proximate and ultimate analyses. The volatile and fixed carbon contents of PKS were determined using a Thermogravimetric Analyzer (TGA) (Model DTA 60A), while the ash content was determined using a Muffle furnace. The detailed description of proximate and ultimate analyses is published elsewhere [6] and also summarized in Table 1. The proximate and ultimate analyses of Loy Yang coal are collected from Ref. [22] and also added in Table 1 to compare with the physical characteristics of PKS.

### 2.2. Procedure for torrefaction

The torrefaction of PKS was carried out in a batch feeding reactor heated by a gas fired burner. The reactor diagram is shown in Fig. 1, which is consisted of a screw feeder, a stainless steel reactor, a ring gas burner and a quick liquid condenser with a liquid collector. The feeder comprises a feed hopper and a screw with a speed controlled motor. The feeder is connected to the top of the reactor. The reactor is made of stainless steel of grade 316 with dimension of 6 cm inner diameter and 50 cm height. It has feeding line and gas outlet at the top and an inert gas inlet at the bottom. The furnace is a gas heating tube furnace, where a specially designed and highly controlled ring burner is used. The ring burner is a round shaped squire hollow pipe (2 cm each side) tangentially connected to a tube of 1.5 cm diameter. A liquefied petroleum gas is injected through a nozzle, mixed up with air drafted proportionally from the side hole of the injection tube. Finally, the gas is released into the burning zone through perforation of the squire hollow pipe. The temperature was controlled by controlling the burnable gas

**Table 1**
Physical and chemical characteristics of palm kernel shell and coal.

| | PKS [6] | Loy Yang coal [22] |
|---|---|---|
| Moisture content (%) (dry basis) | 10 | 15.6 |
| Particle size (mm) | 7–15 | – |
| Bulk density (kg $m^{-3}$) | 0.56 | – |
| Proximate analysis | | |
| Volatile mass fraction (%) | 74 | 51.7 |
| Fixed carbon mass fraction (%) | 23 | 47.2 |
| Ash mass fraction (%) | 3 | 1.1 |
| HHV (dry basis, MJ/kg) | 17.58 | 26.16 |
| Ultimate analysis (daf)* | | |
| C | 45.10 | 68.2 |
| H | 5.10 | 4.9 |
| N | 0.56 | 0.57 |
| S | 0.04 | 0.32 |
| O | 49.2 | 26.0 |

* Ultimate analysis is calculated under dry and ash free basis.