CO-COMBUSTION PERFORMANCE OF OIL PALM TRUNK BIOCOAL BLENDED WITH SUBBITUMINOUS COAL

By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

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Chair : Professor Ir Wan Azlina Wan Abdul Karim Ghani, PhD
Faculty : Engineering

Biomass, particularly from oil palm waste is seen to has huge potential as fossil fuel replacement in Malaysia as well as minimizing the effects of prolonged fossil fuel consumption on environment. However, biomass has known issues pertaining to the inefficiency of the energy generation processes as well as its quality compared to the conventional coal in power plants. Therefore, this study was aimed to address these issues by converting the oil palm trunk (OPT) biomass thermochemically into biocoal. The objectives of this research are to prepare and characterise the OPT derived biocoal on its solid fuel candidacy, to evaluate co-combustion performance of OPT biocoal and its blend with sub-bituminous coal and to optimize and validating the optimal conditions for the combustion blended OPT biocoal and coal. OPT biomass was pyrolyzed into biocoal using a top-lit, updraft reactor with a peak temperature of 350°C and fixed air flowrate of 4.63 L/min. Its physical and chemical characteristics were analyzed by the means of bulk density, proximate and ultimate analyses, and oxygen bomb calorimetry. To determine the best blending configuration, combustion test was conducted involving five different blending ratios of OPT biocoal and coal. To optimize the co-combustion process, two operating variables which operating temperature and the air flowrate were studied on its effects on the CO2 level and combustion efficiency. Response surface methodology (RSM) was used to study the influence of each factors as well as their combined interactive effect on the said responses. The results were analysed statistically using the developed design. The ash samples from the co-combustion process was analysed by X-ray dispersion (XRD) on its mineral composition. Noticeable changes in terms of mass and density reduction, energy content increase and chemical composition was observed on OPT biomass during pyrolysis. The bulk density of OPT biocoal was 87.7 kg/m3 which is lower than its biomass due to the increased porosity. The carbon content increased while reducing its hydrogen and oxygen contents which resemble low rank coal. Volatile matter decreased by the factor of 1.87 while fixed carbon content of biocoal increased by 26.6%. The higher heating value increased by a factor of

1.36 compared with the raw OPT. However, the energy yield was low (37.6%) due to the low biocoal yield of 27.8%. In addition, the ash content is increased by the factor of 1.5. The increment may amplify the effects of slagging and fouling in the furnaces and boilers as shown by the slagging and bed agglomeration indices which increased from 2.0 to 5.2 and from 0.4 to 0.7, respectively. For the combustion testing, the emissions of SO2 and NOx of all samples were below the emission limits. Blend composition with 20% biocoal and 80% coal has the best criteria tested, which has high combustion efficiency and also relevantly low CO2, NOX and SO2 emissions, compared to the 100% coal. ANOVA analysis implied that temperature has major influence over the CO2 emission than air flowrate, while the latter has higher influence on the combustion efficiency. The regression model indicates excellent fit of the data to the model. Maximum combustion efficiency of 92.16% and CO2 concentration at 16.38% were predicted to be obtained under optimized operating factors of 774.33 °C and 7.84 litre per minute with desirability of 0.896. These predictions were validated with the obtained experimental values of CO2 concentration of 16.59% and combustion efficiency of 91.63%, which are within 5% deviation from the predicted values. These findings shown that better combustion performance can be attained with the co-combustion of OPT biocoal and sub-bituminous coal, rather than sub-bituminous alone in the current practice of coal-fired power plants. XRD analysis has shown that the ash formed are almost equally crystalline and amorphous, proving that both sub-bituminous coal and biocoal are present in the sample. The detected mineral phases shown that silicone dominated the chemical compounds formed in the ash. The formation of some of the minerals also indicates the interaction between elements present in both sub-bituminous coal and OPT biocoal. Based on these findings, OPT biocoal has promising potential to supplement sub-bituminous coal as solid fuel to generate energy due to its lower CO2 concentration and higher combustion efficiency relative to sub-bituminous coal, as well as comparable physicochemical characteristics. However the other properties such as mass and energy yields, handling capacity as well as the ash behaviour are need to be improved in future studies.

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PEMBAKARAN SECARA BERSAMA BIOARANG DARI BATANG KELAPA SAWIT DAN ARANG SUBBITUMEN SERTA KESANNYA TERHADAP PRESTASI PEMBAKARAN

Oleh

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Januari 2020

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Biojisim khasnya dari sisa kelapa sawit dilihat mempunyai potensi sebagai pengganti kepada bahan api fosil di Malaysia dan juga mengurangkan kesan penggunaannya dalam jangka masa Panjang terhadap alam sekitar. Walau bagaimanapun, biojisim mempunyai kekurangan dari segi ketidakberkesanan dalam penghasilan tenaga dan juga kualiti yang kurang berbanding dengan arang yang digunakan di stesen janakuasa masa kini. Oleh yang demikian, kajian ini bertujuan untuk menyelesaikan isu-isu ini dengan penghasilan bio-arang dari kayu batang kelapa sawit (OPT). Objektif-objektif kajian ini ialah untuk menyedia dan mengkaji karakter bioarang OPT dari segi kesesuaiannya sebagai bahan bakar pepejal, menilai prestasi pembakarannya Bersama arang sub-bitumin serta mengoptima dan mengesahkan kondisi optimum pembakaran tersebut. Biojisim OPT telah melalui proses pirolisis menggunakan penggegas updraf dengan suhu maksimum 400°C serta kadar aliran udara sebanyak 4.63 liter seminit. Ciri fizikal dan kimianya dianalisis dengan cara ketumpatan pukal, analisis proksim dan elemen, dan kalorimetri bom oksigen. Untuk menentukan konfigurasi pencampuran yang terbaik, ujian pembakaran dilakukan dengan melibatkan lima nisbah pencampuran yang berbeza dari bioarang OPT dan arang batu. Untuk mengoptimumkan proses pembakaran bersama, dua pembolehubah yang melibatkan suhu dan aliran aliran udara dikaji kesannya pada tahap CO2 dan kecekapan pembakaran. Kaedah tindak balas permukaan (RSM) digunakan untuk mengkaji pengaruh setiap faktor serta kesan interaktif gabungan mereka terhadap tindak balas tersebut. Hasilnya dianalisis secara statistik menggunakan rekaan yang dibangunkan. Sampel abu dari proses pembakaran bersama dianalisis dengan penyebaran sinar-X (XRD) pada komposisi mineralnya. Perubahan yang ketara dari segi pengurangan jisim dan ketumpatan, peningkatan kandungan tenaga dan komposisi kimia diperhatikan

pada biomass OPT semasa pirolisis. Ketumpatan pukal biocoal OPT adalah 87.7 kg / m3 yang lebih rendah daripada biojisim kerana keliangan yang meningkat. Kandungan karbon meningkat sambil mengurangkan kandungan hidrogen dan oksigennya yang menyerupai arang batu rendah. Bahan meruap menurun sebanyak faktor 1.87 manakala kandungan karbon bioarang tetap meningkat sebanyak 26.6%. Nilai pemanasan yang lebih tinggi meningkat dengan faktor 1.36 berbanding OPT mentah. Walau bagaimanapun, hasil tenaga adalah rendah (37.6%) disebabkan hasil bioarang yang rendah sebanyak 27.8%. Di samping itu, kandungan abu meningkat dengan faktor 1.5. Penambahan ini dapat menguatkan kesan pengotoran dalam relau dan dandang seperti yang ditunjukkan oleh indeks agregat pensisikan dan penggumpalan yang meningkat daripada 2.0 kepada 5.2 dan dari 0.4 kepada 0.7. Untuk ujian pembakaran, pelepasan SO2 dan NOx semua sampel adalah di bawah had pelepasan yang ditetapkan oleh Jabatan Alam Sekitar. Komposisi campuran dengan 20% biocoal dan 80% arang batu mempunyai kriteria terbaik yang diuji, yang mempunyai kecekapan pembakaran yang tinggi dan juga relevan. Anggaran kecekapan pembakaran maksimum 92.16% dan kepekatan CO2 pada 16.38% diperolehi di bawah faktor operasi yang optimum iaitu 774.33 ° C dan 7.84 liter seminit dengan faktor 0.896. Ramalan ini telah disahkan dengan nilai eksperimen CO2 kepekatan 16.59% dan kecekapan pembakaran 91.63%, yang berada dalam sisihan 5% dari nilai yang diramalkan. Penemuan ini menunjukkan bahawa prestasi pembakaran yang lebih baik dapat dicapai dengan pembakaran bersama bioarang OPT dan arang sub-bitumen. Analisis XRD menunjukkan bahawa abu yang terbentuk mempunyai jumlah kristal dan amorfus yang sama banyak, membuktikan bahawa kedua-dua arang batu bitumen dan bioarang terdapat di dalam sampel. Fasa mineral yang dikesan menunjukkan bahawa silikon menguasai sebatian kimia yang terbentuk dalam abu. Pembentukan beberapa mineral juga menunjukkan interaksi antara unsur-unsur yang ada di kedua-dua arang batu bitumen dan bioarang OPT. Berdasarkan penemuan ini, bioarang OPT berpotensi sebagai bahan tambahan bersama arang batu bitumen untuk untuk menjana tenaga, sekiranya keberhasilan massa dan tenaga, keupayaan pengendalian serta kualiti abu diperbaiki dalam kajian-kajian masa depan.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the Master of Science. The members of the Supervisory Committee were as follows:

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Date: 11 June 2020

Declaration by the Graduate Student

I hereby confirm that:

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LIST OF ABBREVIATIONS

AC	Ash content
ANOVA	Analysis of variance
BAI	Bed agglomeration index
CCD	Central composite design
CPO	Crude palm oil
DOE	Development of experiment
EDR	Energy densification ratio
EFB	Empty fruit bunch
EJ	Exajoule
ER	Equivalence ratio
FC	Fixed carbon
FFB	Fresh fruit bunch
FI	Fouling index
GDP	Gross domestic product
GHG	Greenhouse gases
HHV	Higher heating value
ICDD	International centre for diffraction data
kWh	Kilowatt hour
ktoe	Kilotonnes of oil equivalent
MAP	Microwave assisted pyrolysis
MC	Moisture content
MCL	Material characterization laboratory
MF	Mesocarp fiber
MW	Microwave
OPF	Oil palm frond

OPT	Oil palm trunk
PAH	Polyaromatic hydrocarbon
PKO	Palm kernel oil
PKS	Palm kernel shell
PM	Particulate matter
POME	Palm oil mill effluent
PTE	Potentially toxic element
RSM	Response surface methodology
SCFH	Standard cubic feet hour
SEM-EDX	Scanning electron microscopy-Energy dispersed X-ray
SI	Slagging index
TGA-DTG	Thermogravimetric analysis-derived thermogravimetry
TOC	Total organic compound
VM	Volatile matter
XRD	X-ray dispersion

CHAPTER 1

INTRODUCTION

1.1 Background and Motive

Energy is crucial for economics, technology and social growth. In the world nowadays, the energy demand and consumptions are expected to rise significantly. The demand is largely on the electricity. It is known that electricity is crucial to modern life as it powers household, commercials and industrial processes. Due to the new major economies' development in places such as China and India, the demand for electricity is high rising with the installation of thousands of power plants over the coming decades. In terms of electricity generations, all of the current forms are subjected to strengths and weaknesses and future electricity generation needs variety of options which in general should be low carbon emission to reduce the greenhouse gas emissions.

Currently, fossil fuels such as crude oils, coal, natural gases and so on are the largest contributors to the available energy supply, which is predicted to remain so until 2030 (Pinto et al., 2012; M. H. Sulaiman, Uemura, & Azizan, 2016). In Malaysia, fossil fuels account for 81% of the fuel mix as reported by the Energy Commission Malaysia on 2017 ("Laporan Tahunan Suruhanjaya Tenaga 2017," 2017). Malaysia's energy demand in 2016 is shared by sectors such as transportation (42%), industry (28%), non-energy use (15.3%), residential and commercial (14.1%) and agriculture 0.7% ("Laporan Tahunan Suruhanjaya Tenaga 2017," 2017). These figures signified that there are 8.8% overall increase since 2014 which is illustrated in Figure 1.1. This also portrays the growing energy demands in contradiction of the industrial sector, which was exceeded in the year 2006, and has persisted to increase annually.

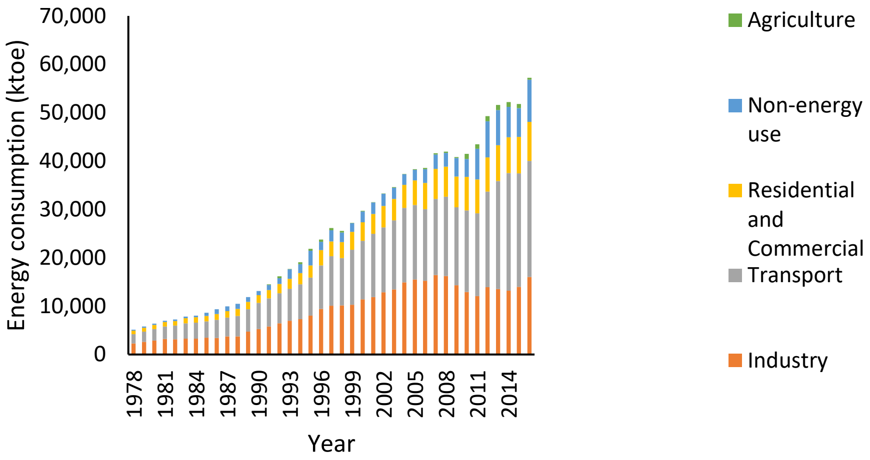

Figure 1.1 : The Energy Consumption by Sector from 1978 to 2016.
(Source: "Laporan Tahunan Suruhanjaya Tenaga 2017," 2017)

Given the current scenario, fossil fuel is finite, and depleting rapidly given by the current consumption rate (Samiran, Mohd Jaafar, Chong, & Jo-Han, 2015). If there are no efforts made to mitigate this issue, the world will be facing energy crisis that will affect the economics, technology and social advancement. Economic wise, fossil fuel-derived electricity will become more expensive as the results from its scarcity. Moreover, as the living standard increase, the construction and operation of power plants are becoming more costly due to the compliances with improved safety and pollution control (Kåberger, 2018) .Other than that, fossil fuels consumption also has another issue, which is regarding its emission to the surrounding. The emissions release harmful pollutants to human and environment, such as carbon dioxide, methane, dioxins, nitrogen oxides and many more (Basu, Butler, & Leon, 2011). In Malaysia, there are few acts and regulations which are imposed particularly on the coal fired power plant. These included Environmental Quality Act 1974 and Environmental Quality (Clean Air) Regulations 2014. Regulated pollutants under this regulation includes sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), particulate matter (PM), mercury and few others (Motokura, Lee, Kutani, & Phoumin, 2017).

To avoid the consequences, efforts must be put on the clean energy alternatives. These efforts including the ongoing research to increase the efficiency of existing processes, and to promote the use of renewable energy sources. Renewable energy sources have many potential advantages over fossil fuels. Firstly, the consumption of renewable resources can reduce the amount of greenhouse gases (GHG) released to the environment using fossil fuels (Van Huynh & Kong, 2013). This facilitates the fact that countries participated in Kyoto Protocol should reduce GHG emissions to 30% by 2020 as stated in Doha amendment (Moghadam et al., 2014). Secondly, the use of renewable energy may support economic growth for rural areas. With the available resources around the area, proper processing and equipment, energy can be generated to cater the electricity demand around the rural areas, without having to rely on the diesel and petrol. Moreover, many industrial sectors will have no more problem obeying the strict regulations imposed by the authorities on the pollution. Renewable energy is known for its cleanliness and biomass for example, is known for its carbon-neutral property (Pio, Tarelho, & Matos, 2017). Therefore, less or none of the harmful substances are being released to the environment.

In Southeast Asia, particularly in Malaysia, biomass such as animal and agricultural waste are abundant and easily procured for the energy generation purposes. For example, waste from oil palm plantations is the second largest biomass energy potential in the country after the forest residue (Jaafar, Kheng, & Kamaruddin, 2003). Biomass is defined as any organic materials from biological origin. It is a natural substance comprising of cellulose, hemi-cellulose and lignin with empirical formula of $C_1H_{1.4}O_{0.6}$ which have slight differences based on the biomass nature (Kumar & Dasappa, 2017). Biomass was among the earliest energy resource collected and used by human, for example to light up fire by using animal droppings and fat. However, with the discovery of fossil fuels in the last two centuries, the use of biomass has been significantly declined. But as the issues mentioned earlier on the increasing energy demand combined with the fossil fuels depletion at alarming rate, there has been an interest in reviving the use of biomass as energy source.

In 21st century, renewable energy resources are known as an attractive energy resources which provide between 50 and 150 EJ/year (Ozturk et al., 2017) on global basis. The current bioenergy use in industrial sector is expected to increase in the coming 10 to 20 years. From the projection made, it will increase from 526 Mtoe (million tons of oil equivalent) in 2010 to almost 1200 Mtoe to 2035. In Malaysia, however the electricity generation from biomass-based fuel is rather small, which is around 2% as shown in figure 1.2 (“Laporan Tahunan Suruhanjaya Tenaga 2017,” 2017). Even the energy production and use are currently small, biomass is expected to play an essential role in the future energy supply, given the current commitment and initiatives by the Malaysian’s government and research agencies. This is proven by the government commitment on focusing to replace about 5.5% of electricity source using renewable energy by 2020 (Abas, Kamaruddin, A Nordin, & Simeh, 2011). Previously, the Small Renewable Energy Power (SREP) was initiated to encourage the use of renewable energy among project developers. It allows independent power plant providers to sell generated electricity up to 10 MW to the power grid (W. S. W. Abdullah, Osman, Kadir, & Verayiah, 2019). However, the initiative failed to meet its target as specified in Ninth Malaysia plan due to the low tariff, inconsistent biomass supply, high capex (capital expenditures) and lack of incentives and supporting infrastructures. Under Renewable Energy Act 2011 and Sustainable Energy Development Authority Act 2011, Feed-in Tariff (FiT) policy was introduced in 2011 with the target of achieving 800 MW of supplied energy into the power grid by 2020, which is 20 times more than the

SREP target (W. S. W. Abdullah et al., 2019; Umar, Jennings, & Urmee, 2013). Under this initiative, energy generated from biomass is sold at fixed rate and period with the guaranteed payment is made to the energy developer. FiT system is monitored and evaluated by The Sustainable Energy Development Authority (SEDA). Even so, it is found that the FiT implementation outcome in 2014 only achieved a quarter of its projected target on 2015 which is therefore urging the new mechanism to cope with the issue, as well as achieving the stipulated target in 2020 (W. S. W. Abdullah et al., 2019).

Due to the steady productivity of palm oil industry in Malaysia, oil palm biomass can be obtained in a vast amount. There are two sources of oil palm biomass, which are from the plantations and milling processes. From the plantation, the biomass is mostly in the form of oil palm frond (OPF) and oil palm trunk (OPT) (Sukiran, Abnisa, Wan Daud, Abu Bakar, & Loh, 2017). OPF is obtained from pruning activity but it is usually left on the ground as the fertilizer. OPT is available during the replanting season. From the mills, empty fruit bunches (EFB), palm kernel shell (PKS), mesocarp fibre (MF) and palm oil mill effluent (POME) are produced. These are produced on daily basis and more readily available compared to the biomass from plantation (Abas et al., 2011). The current biomass utilization practice within the oil palm plantation is to burn products such as MF and PKS in the boilers to produce steam which is used for the milling processes and to generate electricity. EFB is normally returned to the plantations while POME is generally treated before being discharged into the water system.

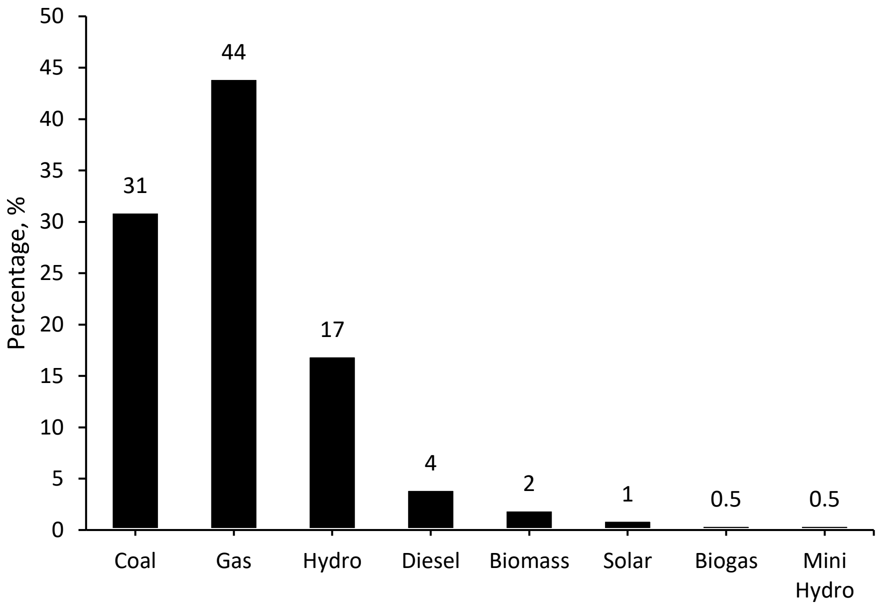

Figure 1.2 : The Fuel Mix of Energy supplied from Various Resources in Malaysia, Fossil and Renewable
(Source: Laporan Tahunan Suruhanjaya Tenaga 2017)

There are many known advantages of biomass energy, including that it generates much smaller amount of greenhouse gases than fossil fuel. As it produces lower level of sulphur dioxides (SO_2) and NO_x, the pollution in the form of acid rain and others can be reduced as well. The sustainability of biomass energy can be easily maintained as the biomass sources are readily available all year round, which is oil palm biomass in Malaysia's case. As the demand is growing, biomass sources which were usually discarded as waste can therefore be minimized. Biomass is known as a "carbon-neutral" resource as it sequesters CO_2 during its growth which pay off CO_2 released when it is burnt (Lau, Ng, Gan, & Jourabchi, 2018). In general, biomass has an advantage over other energy sources due to its availability, rapid renewability and net below zero CO_2 emissions (Ghani, Moghadam, Salleh, & Alias, 2009). However, despite all of the benefits mentioned, biomass still has its limitations if it were to be used as direct feedstock for power generation. Due to its attributes of high moisture content, low bulk and energy density, susceptibility to biodegradation due to its high oxygen content, these cause the combustion efficiency reduced which therefore affected the energy production performance (Matali, Rahman, Idris, Yaacob, & Alias, 2016). Moreover, during the fuel preparation, high energy consumption is inevitable due to the complexity of oil palm biomass which is fibrous as it is ligno-cellulosic. Lignocellulosic is defined as the constituted structure made from carbohydrate polymers and an aromatic polymer (Z. Liu & Han, 2015). Furthermore, the release of some substances such as hydrogen chloride (HCl) from biomass combustion caused damage to the process equipment such as boiler (Ren et al., 2017). Thermal treatment is therefore needed to overcome these issues, which made biocoal as having potential to be the ideal replacement for fossil fuel (Kosov, Kuzmina, Sytchev, & Zaichenko, 2016).

The suitability and fuel efficiency of biocoal depends on few aspects which are the biocoal properties and the thermal treatment parameters. The biocoal properties that being studied are including its moisture content, higher heating value (HHV), ash content, fixed carbon content, volatile compounds and few others (Pulka, Wiśniewski, Gołaszewski, & Białowiec, 2016; X. Yang et al., 2017). Ideally, the biocoal selected should has low moisture content, high HHV, low ash content, high fixed carbon content, and low volatile matter. In terms of thermal processing, biocoal is produced from pyrolysis or torrefaction of biomass. Therefore, the important parameters during these processes are the temperature and heating rate (Białowiec, Pulka, Stępień, Manczarski, & Gołaszewski, 2017). Ideally, the temperature is to be kept particularly low (to keep mass and energy yield high) and with moderate heating rate. These, however, vary depending on the type of biomass.

To improve its quality, biocoal can be blended with coal. This has potential to increase the combustion efficiency and improved the thermal characteristics in comparison to coal and/or biomass-coal fuel (Rashid et al., 2018). While there are so few studies on the coal-biocoal blend combustion, co-combustion and co-gasification of some biomass such as rice husk, straw, corn cobs, sugarcane bagasse and many others are considered to be significant as the fractional replacement of fossil fuels is seen as the viable and possible option currently in the power sector. Co-combustion signifies a cheaper and self-reliant option that could reduce the pollutant emissions resulting in several benefits. Hence, by incorporating biocoal into coal-fired power plants it could increase the efficiency of both fuels utilization (Hu, Jin, et al., 2018). The modification costs for converting a coal-fired power plant to a co-combustion power plant is considered as cheaper compared to the dedicated biomass fired plant (Basu et al., 2011). In the case of biocoal supply shortage, the co-combustion process can be done under flexible option where the portion of biocoal supplied can be adjusted. In terms of the combustion process, biomass fuels in general have higher volatile matter than coal, which ease the release of volatiles in the combustion chamber compared with coal. All of these reasons provide a reasonable option for biomass utilization in the existing power plants in Malaysia. It is also seen as a relevant technology to reduce the pollutant emissions to the surrounding environment.

1.2 Problem Statement

Oil palm trees are replanted every 25 to 30 years after their useful lifespan within 25 years, which therefore resulted in the accumulation of OPT biomass (Loh, 2017; F. Sulaiman, Abdullah, Gerhauser, & Shariff, 2011). Currently, oil palm trunk is estimated to be 74.5 tonne per hectare annually in terms of abundance (Abnisa, Arami-Niya, Wan Daud, Sahu, & Noor, 2013; Loh, 2017). As it was no further use, OPT biomass was once disposed by open burning. But as it causes air pollution, this practice was banned and as the alternative, OPT biomass was left to decompose in the plantations which usually takes time for complete decomposition (Department of Environment Ministry of Natural Resources and Environment., 2010).
Currently, the known use of OPT is within the timber industry where parts of it are used for fibreboards, plywood, and furniture (Awalludin, Sulaiman, Hashim, & Nadhari, 2015). However, this is only limited to the outer parts of OPT as its core has poor mechanical structure. Therefore, the central part of OPT biomass is often left as waste. Few studies were conducted on the possible conversion into biofuel as OPT biomass is rich with sugar (Eom, Yu, Jung, & Hong, 2015; Sumathi, Chai, & Mohamed, 2008). Yet, the efficiency of the conversion process through biochemical route is considered low (Rattanaporn, Tantayotai, Phusantisampan, Pornwongthong, & Sriariyanun, 2018).

Thermochemical route is seen as a viable option for OPT biomass conversion into energy. In oil palm mill context, it can be used as solid fuel for the steam boilers to produce electricity through steam turbines. However, there are also challenges with direct OPT biomass utilization as the process incurs high fuel production expenses and incompetent energy conversion due to the nature of

OPT biomass which has high moisture content, low energy density and very low grindability (Ren, Sun, Chi, et al., 2017). Due to the aforementioned issues regarding the direct use of OPT biomass as energy feedstock, biocoal is seen as a viable option to address such issues. Biocoal is better than biomass as it has low moisture content, higher calorific value, lower density for storage and also durable for long term storage. Therefore, this study has focused on the characterisation of biocoal for better understanding in terms of the elemental composition of biocoal altogether with its chemical and physical properties, and how all of these attributes affect its combustion for energy generation, particularly on its co-combustion with coal.

The characterisation includes the comparison between OPT biomass and biocoal together with the coal used for the combustion. For the co-firing with coal, preliminary stage combustion was conducted to deduce the suitable blending ratio of coal-biocoal based on the selected combustion parameters including the combustion efficiency, and the obnoxious gases emission such as CO_2, SO_x and NO_x. From there, the combustion process is optimized by the means of response surface method (RSM) and further validated through experimental runs.

1.3 Research Objectives

The objectives of this study are outlined as follows:

a) To characterise the OPT derived biocoal on its solid fuel candidacy.

b) To evaluate combustion performance of OPT biocoal and its blend with sub-bituminous coal in fixed bed reactor over a range of air flowrate and temperature.

c) To optimize and validate the optimal conditions for the co-combustion of OPT biocoal and sub-bituminous coal.

1.4 Scope of work

The scope of work for this study is divided based on the outlined objectives.

a) For the first objective, OPT biocoal was prepared by conventional pyrolysis method under the best operating conditions as mentioned in the literature. Characterization were based on the physical and chemical properties of the biocoal which includes bulk density, ultimate and proximate analyses, the calorific value and thermogravimetric derivative analysis. Prediction of the combustion behaviour includes the propensities of slagging, fouling and bed agglomeration indices, which cover only the powder form of OPT biocoal.

b) Combustion testing involves the controlled combustion of five different feedstock configurations under fixed air flowrate which temperature was adjusted at three different values (600, 750, 850°C). Measurement was done on the efficiency of the process and the pollutants concentration in the flue gas.

c) The application of response surface methodology (RSM) was conducted to evaluate the interaction between selected parameters with the method of central composite design (CCD). The parameters are the operating temperature and air flowrate while the recorded responses are the CO_2 concentration (v/v%) and combustion efficiency, E (%). Optimization step known as "the desirability approach" was conducted to predict the optimum operating conditions. Validation of the predicted optimum conditions was conducted. X-ray diffraction (XRD) analysis was conducted to study the mineral phase of the ash formed from the combustion under optimized conditions.

1.5 Thesis Structure

There are five chapters in this thesis which are summarized as follows:

Chapter 1 introduces the research background and motives, the problem statement and the research objectives.

Chapter 2 recaps the literature review on the potentials of biomass as renewable energy, the insights within oil palm industry with emphasizing Malaysian scenario, the biomass conversion into biocoal and also cofiring with coal.

Chapter 3 presents the methods used on the preparation of OPT biocoal and its characterization analyses, the preliminary combustion of cofired OPT with sub-bituminous coal and finally on the optimization and validation of the combustion process.

Chapter 4 discusses fuel and ash properties through the findings of the conducted analyses. It also discusses the findings and selection of coal-biocoal blending ratio for the optimization step. The optimal co-combustion operating conditions are deliberated as well.

Chapter 5 concludes this research and recommendations are suggested for further studies.

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