UNIVERSITI PUTRA MALAYSIA

EVALUATION OF OIL PALM BIOMASS AND FAST GROWING TIMBER SPECIES AS POTENTIAL SOLID BIOFUEL

CHIN KIT LING

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By

CHIN KIT LING

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the degree Doctor of Philosophy

July 2014

SPECIAL DEDICATION TO…

To my beloved father, mother, brothers, sisters,

friends and specially remembered one

Thank you for everything…….

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

EVALUATION OF OIL PALM BIOMASS AND FAST GROWING TIMBER SPECIES AS POTENTIAL SOLID BIOFUEL

By

CHIN KIT LING

July 2014

Chairman: Paridah Md Tahir, PhD

Faculty: Institute of Tropical Forestry and Forest Products

Lignocellulosics have been identified as one of the renewable energy sources. The conversion process for this purpose must be flexible enough to accommodate various types of biomass. Among the numerous methods for converting lignocellulosic biomass into usable energy, direct combustion is still the dominant technology employed by industry. This work evaluates the potential variation of two lignocellulosic biomass available in Malaysia, i.e. oil palm waste and timbers from fast growing species to be utilized as solid biofuel for heat and electricity generation.

The study was divided into five parts. The first part evaluates the fuel properties of oil palm biomass (empty fruit bunch (EFB) and oil palm trunk (OPT)), wood from a range of fast growing timber species (*Paraserianthes falcataria*, *Acacia* spp., *Endospermum* spp. and *Macaranga* spp.), inclusive and exclusive of bark. These fibres were chosen because of their abundance and readily available. Heating value and ash forming elements are found to be much higher in timbers inclusive of bark than those without. On the other hand, oil palm biomass contains higher ash forming elements and lower heating value than any of the timber species. The study also suggests lignocellulosic in its raw form, is not efficient as raw material for power plant due to its high moisture content, low bulk energy density, high ash content and low ash melting temperature.

The second part of the study investigates the effects of torrefaction treatment on the weight loss and energy properties of *Paraserianthes falcataria*, *Acacia* spp., *Endospermum* spp. and *Macaranga* spp. and oil palm biomass (oil palm trunk and empty fruit bunch). The lignocellulosic biomass was torrefied at three different temperatures 200, 250 and 300 °C, each for 15, 30 and 45 min. Response surface methodology was used for optimization of torrefaction conditions, so that biofuel of high energy density, maximized energy properties and minimum weight loss could be manufactured. The analyses showed that increase in heating values was affected

by treatment severity (cumulated effect of temperature and time). It was demonstrated that each biomass type had its own unique set of operating conditions to achieve the same product quality. The optimized torrefaction conditions were verified empirically and applicability of the model was confirmed. For respective types of lignocellulosic biomass, the optimization experiment gave results of HHV and weight loss as follows: 27.96 MJ/kg, 10.12% for *Acacia spp.*; 19.14 Mj/kg, 6.17% for *Paraserianthes falcataria*; 27.19 Mj/kg, 13.41%, for *Macaranga spp*.; 19.68 MJ/kg, 8.09% for *Endospermum spp*; 23.08 MJ/kg, 9.55% for EFB and 23.22 MJ/kg, 14.94% for OPT. These experimental findings were in close agreement with the model prediction. Torrefaction markedly improved the biofuel characteristics except for ash melting which apparently similar to the raw material and was more severe with raw material initially with problematic ash such as EFB and OPT.

The subsequent study aims at studying the effectiveness of leaching on removing ash forming elements and on ash melting using water and acetic acid as the extraction agent. Leaching by acetic acid solutions removed most of ash forming elements, both water soluble and insoluble from the selected lignocellulosic biomass. Ash melting characteristics of lignocellulosic biomass under high temperature were considerably improved by both leaching treatment; water and acetic acid leaching. A model comprising leaching parameters and fuel properties for different types of lignocellulosic biomass was established. This model was later employed to predict the optimal leaching conditions for maximized ash removal efficiency without sacrificing the higher heating value (HHV). To generate optimal leaching conditions, the ash removal efficiency was set to a maximum while the HHV was set in the range of not lower than the initial HHV of the respective lignocellulosic biomass. For respective types of lignocellulosic biomass, the optimization experiment gave results of ash removal efficiency and HHV as follows: 68 %, 18.52 MJ/kg for *Acacia spp.*; 72%, 17.94 Mj/kg for *Paraserianthes falcataria*; 72%, 18.13 Mj/kg for *Macaranga* spp.; 81%, 18.58 MJ/kg for *Endospermum* spp; 85%, 18.53 MJ/kg, for EFB and 63%, 16.21 MJ/kg, for OPT.

Part four of the study explores the possibility of combining leaching and torrefaction treatment to create an improved solid biofuel from lignocellulosic biomass. The focus lies on determining the effects of the combination treatments on ash removal efficiency and on ash melting characteristic of the treated biomass. Two possible pathways were implied; applying torrefaction followed by leaching and leaching followed by torrefaction. Incorporating both leaching and torrefaction treatments irrespective of sequence generated a solid biofuel with better fuel properties particularly HHV yield and ash melting temperature compared to singular treatment; torrefaction or leaching treatment. The ash yield reduction from raw biomass ranged 60 – 86%, whereas the ash yield reduction from torrefied biomass ranged 47 – 68%. Leaching prior to torrefaction proved to be a better combination.

The final part of the study evaluates the effect of kaolin and calcite addition on the ash melting characteristic, heating value and ash content of the lignocellulosic biomass. The additives addition to selected lignocellulosic biomass with low ash melting temperature, i.e. *Acacia* spp., *Endospermum* spp., EFB and OPT The results show that both additives significantly improved the bottom ash melting characteristic with mixed results. Kaolin is a promising choice since it reduced the sintering degree of the ashes with the formation of inorganic elements mixtures mostly held in the ash sediments. In contrast, the presence of calcite helped to increase the ash melting temperature but at the same time induce higher concentration of fly ash in the flue gas. In general, kaolin is more effective than calcite to reduce molten or strong sintering to weak sintering or loose ash at the dose of 0.25 - 0.5 g/g ash while calcite in general require higher dose at dose equal or higher than 0.5 g/g ash. While the concentrations of additives act as a variable to increase the sintering temperature, it also had strong impacts on HHV reduction and ash content increment. In conclusion, fast growing timber species served as a better solid biofuel than oil palm biomass due to higher HHV and less ash forming elements. The high alkali metals (potassium and sodium) mainly consist in oil palm biomass was found to be one of the main factors that create slagging during high temperature combustion. Ash that is with high K/(Ca + Mg) ratio (alkali metals (potassium) to alkaline earth metals (calcium and magnesium) ratio) tend to have low melting temperature. Novelty approach by combining leaching followed by torrefaction treatment on lignocellulosic biomass was found to be able to create the optimal quality solid biofuel with low ash content, high energy density and high ash melting temperature. The ash related problematic lignocellulosic biomasses (oil palm biomass, *Acacia* spp. and *Endospermum* spp.) with low ash melting temperature during high temperature combustion can be solved by additional fuel additives; with kaolin as a better ash melting inhibitor than calcite.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan Ijazah Doktor Falsafah

PENILAIAN BIOJISIM KELAPA SAWIT DAN SPESIES POKOK CEPAT TUMBUH SEBAGAI BIOBAHAN API PEPEJAL YANG BERPOTENSI

Oleh

CHIN KIT LING

Julai 2014

Pengerusi: Paridah Md Tahir, PhD

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Lignocellulosa telah dikenali sebagai salah satu sumber tenaga yang boleh diperbaharui. Proses konversi untuk tujuan ini perlu mempunyai daya ubahsuai yang tinggi bagi penggunaan biomass yang pelbagai. Antara kaedah-kaedah untuk menukarkan biojisim lignoselulosa kepada tenaga gunaan, pembakaran secara langsung merupakan teknologi yang dominan digunakan oleh industri. Kajian ini dijalankan untuk mengkaji potensi biojisim lignoselulosa yang terdapat di Malaysia (sisa kelapa sawit dan spesies pokok cepat tumbuh) untuk digunakan sebagai bahan api bio pepejal bagi penjanaan haba dan elektrik.

Kajian ini terbahagi kepada lima bahagian. Dalam bahagian pertama, ciri-ciri bahan api bagi biojisim kelapa sawit (tandan kelapa sawit (EFB) dan batang kelapa sawit (OPT)), kayu termasuk dan tidak termasuk kulit kayu daripada pelbagai spesies pokok cepat tumbuh (*Paraserianthes falcatari*, *Acacia* spp., *Endospermum* spp. dan *Macaranga* spp.) dikaji. Gentian-gentian ini dipilih atas sebab ketersediaan sumber yang banyak di Malaysia. Sampel kayu termasuk kulit mempunyai nilai tenaga (HHV) dan kandungan elemen-elemen pembentukan abu yang lebih tinggi berbanding dengan sampel kayu tidak termasuk kulit. Sebaliknya, biojisim kelapa sawit mengandungi kandungan elemen-elemen pembentukan abu yang lebih tinggi berbanding dengan kayu dari spesis cepat tumbuh. Bagaimanapun, biojisim lignoselulosa yang mentah, bukan merupakan bahan mentah yang optimum bagi penggunaan dalam loji kuasa. Tanpa rawatan yang bersesuaian, biojisim lignoselulosa tidak sesuai untuk dimasukkan ke dalam sistem pembakaran yang sedia ada kerana kandungan kelembapan yang tinggi, ketumpatan tenaga pukal yang rendah, kandungan abu yang tinggi dan sifat abu yang rendah suhu lebur.

Dalam kajian ke-2, tujuannya adalah untuk menyiasat kesan-kesan rawatan torifikasi ke atas kehilangan berat jisim serta ciri-ciri bahan api bagi spesies pokok cepat tumbuh (*Paraserianthes falcatari*, *Acacia* spp., *Endospermum* spp. dan *Macaranga*

spp.) dan biojisim kelapa sawit (OPT dan EFB). Biojisim lignoselulosa dirawat pada tiga suhu yang berbeza 200, 250 dan 300 ° C selama 15, 30 dan 45 minit. Kaedah *response surface method (RSM)* telah digunakan untuk mengoptimalkan keadaan torifikasi, supaya bahan api bio dengan kepadatan tenaga yang tinggi, iaitu nilai HHV yang maksimal dengan pengurangan berat jisim yang minimal dapat dihasilkan. Hasil analisis menunjukkan bahawa peningkatan dalam nilai HHV terjejas dengan tahap genting rawatan (kesan terkumpul suhu dan masa). Ia telah menunjukkan bahawa setiap jenis biojisim mempunyai set keadaan operasi yang unik untuk mencapai kualiti produk yang sama. Keadaan torifikasi yang dioptimumkan telah disahkan secara empirik dan keboleh-aplikasi model juga dikenalpasti. Untuk setiap biojisim lignoselulosa, kajian pengoptimuman memberikan hasil HHV dan pengurangan berat seperti berikut: 27.96 MJ/kg, 10.12% bagi *Acacia spp.*; 19.14 Mj/kg, 6.17% bagi *Paraserianthes falcataria*; 27.19 Mj/kg, 13.41%, bagi *Macaranga spp*.; 19.68 MJ/kg, 8.09% bagi *Endospermum spp*; 23.08 MJ/kg, 9.55% bagi EFB and 23.22 MJ/kg, 14.94% bagi OPT. Biojisim lignoselulosa yang telah dirawat secara *torifikasi* mempunyai banyak kebaikan berbanding bahan mentah, tetapi kecenderungan ciri-ciri leburan abu menjadi lebih teruk dengan bahan mentah yang pada mulanya mempunyai abu yang bermasalah.

Dalam bahagian ke-3, penyelidikan ini bertujuan untuk mengkaji keberkesanan kaedah larut lesap untuk menyingkirkan elemen pembentukan abu dan kesan-kesan larut lesap ke atas ciri-ciri leburan abu dengan penggunaan air dan asid asetik sebagai ejen pengekstrakan. Kaedah larut lesap dengan penggunaan asid asetik dapat mengeluarkan kebanyakan elemen-elemen pembentukan abu yang terdiri daripada elemen-elemen yang larut dan tidak larut dalam air daripada biojisim lignoselulosa yang digunakan. Ciri-ciri leburan abu biojisim lignoselulosa di bawah suhu yang tinggi telah bertambah baik apabila dirawat dengan kaedah larut lesap; air atau asid asetik. Model telah dibina untuk mengkaji kesan parameter kaedah larut lesap ke atas biojisim lignoselulosa yang digunakan. Model ini kemudiannya digunakan untuk meramal keadaan larut lesap yang optimum bagi kecekapan penyingkiran abu yang maksimal tanpa mengorbankan nilai tenaga (HHV) dengan menggunakan kaedah *response surface method (RSM)*. Untuk menjana keadaan larut lesap optimum kecekapan penyingkiran abu ditetapkan pada tahap maksimal manakala HHV telah ditetapkan dalam lingkungan tidak rendah daripada nilai HHV awal biojisim lignoselulosa masing-masing. Hasil kajian ini boleh digunakan sebagai panduan untuk meningkatkan ciri-ciri bahan api yang lebih baik dari segi jumlah kandungan abu dan ciri-ciri leburan abu biojisim lignoselulosa yang digunakan. Untuk setiap biojisim lignoselulosa, kajian pengoptimuman memberikan hasil HHV dan pengurangan berat seperti berikut: 68 %, 18.52 MJ/kg bagi *Acacia spp.*; 72%, 17.94 Mj/kg bagi *Paraserianthes falcataria*; 72%, 18.13 Mj/kg bagi *Macaranga* spp.; 81%, 18.58 MJ/kg bagi *Endospermum* spp; 85%, 18.53 MJ/kg bagi EFB and 63%, 16.21 MJ/kg bagi OPT.

Bahagian ke-4 untuk kajian inin meneroka kemungkinan untuk menggabungkan kaedah larut lesap dan torifikasi untuk menghasilkan bahan api bio pepejal yang lebih baik daripada biojisim lignoselulosa yang dipilih. Tumpuan diletak ke atas penentuan kesan kombinasi rawatan dalam kecekapan penyingkiran abu, serta ciri-ciri leburan abu bagi biojisim lignoselulosa yang dirawat. Dua proses kombinasi prerawatan yang berpotensi telah diaplikasi; torifikasi diikuti dengan kaedah larut lesap dan kaedah larut lesap diikuti dengan torifikasi. Penggabungan kaedah larut lesap dengan rawatan torifikasi menghasilkan bahan api bio pepejal yang mempunyai ciri-ciri bahan api yang lebih baik terutamanya kepadatan tenaga dan suhu leburan abu berbanding dengan bahan api yang dirawat dengan rawatan tunggal; torifikasi atau kaedah larut lesap. Pengurangan hasil abu daripada biojisim mentah adalah dalam lingkungan 60 – 80%, manakala pengurangan hasil abu daripada biojisim yang telah ditorifikasi adalah dalam lingkungan 47 – 68%. Rawatan kombinasi, kaedah larut lesap sebelum torifikasi terbukti sebagai rawatan kombinasi yang lebih baik berbanding dengan kombinasi rawatan torifikasi diikuti dengan kaedah larut lesap.

Kajian terakhir bertujuan untuk mengkaji kesan tambahan kaolin dan kalsium karbonat pada ciri-ciri leburan abu, HHV dan kandungan abu biojisim lignoselulosa. Penambahan bahan tambahan kepada biojisim lignoselulosa yang mempunyai sifat abu yang bermasalah (*Acacia* spp., *Endospermum* spp., EFB and OPT) telah ditentukan dan dilapor secara kualitatif dan kuantitatif. Telah dibuktikan bahawa penggunaan kedua-dua bahan tambahan membawa kepada peningkatan yang ketara dari segi ciri-ciri leburan abu. Penambahan kaolin merupakan pilihan yang baik kerana tahap leburan abu jelas dikurangkan dengan pembentukan unsur-unsur bukan organik dalam bentuk mendapan abu. Sebaliknya, penambahan kalsium karbonat membantu meningkatkan suhu leburan abu tetapi pada masa yang sama mendorong kepada kepekatan tinggi abu terbang dalam gas serombong. Secara umum, kaolin lebih efektif berbanding kalsium karbonat dalam mengurangkan peleburan abu atau pensinteran kuat kepada pensinteran lemah atau abu longgar dengan penggunaan dos 0.25 – 0.5 g/g abu manakala kalsium karbonat secara umum memerlukan dos yang lebih tinggi dengan dos bersamaan atau lebih tinggi dari 0.5 g/g abu. Walaupun kepekatan bahan tambahan bertindak sebagai pembolehubah untuk meningkatkan suhu peleburan abu, ia juga mempunyai kesan yang kuat ke atas pengurangan HHV dan peningkatan kandungan abu dalam biojisim lignoselulosa. Kesimpulannya, kayu spesis pokok cepat tumbuh merupakan bahan api bio pepejal yang lebih baik berbanding biojisim kelapa sawit dengan nilai HHV yang lebih tinngi dan kandungan abu yang lebih rendah. Logam alkali yang tinggi (kalium and natrium) yang terkandung dalam biojisim kelapa sawit telah didapati sebagai satu faktor utama yang menghasilkan sanga pada suhu pembakaran yang tinggi. Abu dengan nisbah K/(Ca + Mg) yang tinggi (nisbah logam alkali (potassium) kepada logam bumi alkali (calcium and magnesium)) cenderung kepada sifat suhu leburan yang rendah. Pembaharuan dari segi penggabungan kaedah larut resap dan torifikasi keatas biojisim lignoselulosa didapati menghasilkan bahan api bio pepejal yang berkualiti dengan kandungan abu yang rendah, ketumpatan tenaga yang tinggi dan suhu leburan abu yang tinggi. Biojisim lignoselulosa yang bermasalah (biojisim kelapa sawit, *Acacia* spp., *Endospermum* spp.) dengan suhu leburan abu yang rendah semasa pembakaran suhu tinggi boleh diatasi melalui penambahan bahan tambahan bahan api; dengan kaolin sebagai perencat leburan abu yang lebih baik berbanding kalsium karbonat.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirements for the degree of Doctor of Philosophy Degree. The members of the Supervisory Committee were as follows:

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Date:

DECLARATION

Declaration by graduate student

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- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
EFB	Empty Fruit Bunch
OPT	Oil Palm Trunk
LSD	Least Significant Difference
MC	Moisture Content
RH	Relative Humidity
RSM	Response Surface Method
SAS	Statistical Analysis Software
HHV	Higher Heating Value
ICPOES	Inductively Coupled Plasma Optical Emission Spectrometer
UPM	Universiti Putra Malaysia
MPOB	Malaysia Palm Oil Board
PTM	Pusat Tenaga Malaysia
AEBIOM	European Biomass Association
NCRS	Natural Resources Conservation Service

CHAPTER 1

INTRODUCTION

1.1 General

Malaysia is presently still very much dependent on non-renewable fuels as the main source of energy with all major power stations still using fossil fuels, such as oil, gas and coal to generate electricity. Currently, 93% of the rural areas and all the urban areas in Malaysia have access to electricity thanks to those power stations located in Malaysia (Energy Commission, 2010). At the moment, the crucial challenge facing by the energy sector in Malaysia is the issue of sustainability of energy supply and the diversification of the various energy resources. Despite the matter of prices, these fossil fuels have two major disadvantages. The nature of these fossil fuels makes it deplete to a finite depletable resource and secondly, the combustion of non-renewable energy like oil, coal and natural gas contributes significantly to the emission of greenhouse gasses which raise the issue of climate change. These two issues are major global environmental concerns that will have disastrous impact on the socio-economic development in Malaysia. Furthermore, Malaysia is also a signatory to the UN Convention on Climate Change and the Kyoto Protocol which commit Malaysia to move forward to reduce green house gas emissions (Rahman and Lee, 2006). The Malaysian Government is forced to look into other alternative energy sources with the emphasis on renewable energy. As mentioned, in the 8th Malaysia Plan (2001–2005), the government has replaced the Four Fuel Diversification Policy with a Five Fuel Diversification Policy in 1999 by the addition of renewable energy as the fifth source of fuel (Tenth Malaysia Plan, 2011). During that time, it was estimated that by utilizing only 5% of renewable energy in the energy mix could save the country RM 5 billion over a period of 5 years (Mariyappan, 2000). In line with the objective, many efforts were undertaken to encourage the utilization of renewable resources, such as mini-hydro, biogas, solar and biomass, for energy generation (Ölz and Beerepoot, 2010). The Fifth Policy was continually giving priority in the 9th and 10th Malaysia Plan (2006-15) which provided a more conducive environment to support renewable energy projects. Additionally, the 10th Malaysian Plan (2011 – 2015) announced a target of 985 MW or 5.5% share of grid-connected renewable electricity generation by 2015 (Tenth Malaysia Plan, 2011). In 2011, Malaysia government has launched the National RE Policy 2011 after analysing the issues which brought upon the previous policies. The vision of National RE Policy 2011 is to enhance the utilization of renewable resources to contribute towards national electricity supply security and sustainable socio-economic development (Tenth Malaysia Plan, 2011).

There are different types of renewable energy that are currently being extensively researched, namely solar, wind, hydro power and biomass (burning of biomass for electricity). The question being raised is on their reliability. People came up with the perception that renewable energy technologies are intermittent, providing power only some of the time; when the bright sun is shining or the strong wind is blowing. Some renewable energy technologies like hydro power and bioenergy (direct combustion of biomass) are highly predictable and controllable. Currently, the biggest hydropower project in Malaysia is the on-going Bakun hydropower project having a capacity of 2400 MW (Lim *et al.*, 2006). However, the hydroelectric power plants cannot be constructed at any locations and only in places where abundant quantity of water is available throughout the year at sufficient height. A number of other safety parameters also have to be considered. Construction of the dams at inappropriate locations can cause human casualties.

Apart from being renewable, biomass for the production of green electricity could be the answer for all the disadvantages; from the conventional non-renewable energy to the renewable energy (e.g. solar, wind and hydro power). Under the 5th fuel policy, the government of Malaysia has identified biomass as one of the potential renewable energy (Lim *et al.*, 2006). It is the oldest source of renewable energy known to humans, used since our ancestors learned the secret of fire. When the biomass is burned, it emits carbon dioxide, but the next crop of trees absorbs the carbon dioxide, and the overall process can be nearly carbon neutral, and therefore reduces the carbon dioxide emissions of the power plant significantly. Besides, any existing coal-fired power stations can be adapted at modest cost to replace coal with biomass (Lim *et al.*, 2006).

1.2 Statement of Problem

Biomass solid biofuel can be derived from lignocellulosic biomass either through natural processes, or it can be made available as a by-product of human activities which includes agriculture activities in the form of organic wastes. Biomass solid biofuel to be served for the top end of consumer and industrial energy markets involves a series of processes, which need to be taken into consideration in order to tailor the fuel specification to the desired end use.

The biomass solid biofuel has to sustainably meet the demands from consumers and power stations if it wants to be recognized as a commercial fuel in Malaysia. To meet the demands, the industrial production should not be limited in its flexibility for acceptance of different types of biomass. Increasing the range of suitable raw materials is a central component of current efforts to increase biomass solid biofuel supply. Besides, biomass solid biofuel need to achieve several fuel characteristics, namely calorific value, ash content, ash forming elements and ash melting characteristic in order to be used in existing power plant. The consistencies of these characteristics are also the major concerns. Processing lignocellulosic biomass to produce a consistent biomass solid biofuel that is easy to handle and can be utilized in existing systems provides a significant motivation for utilization. Providing a system that can produce a consistent fuel that is easy to handle as well as increasing combustion efficiency and reducing any ash related problems associated with the use of lignocellulosic biomass will help to create a viable and sustainable biomass solid biofuel industry in assisting Malaysia towards energy independence and security. Basically, two main issues hindering lignocellulosic biomass from becoming an efficient solid biofuel are low energy density and high ash forming elements. Thus, pretreatment of the lignocelluloses may be required to overcome these problems. Furthermore, optimizing the pretreatment process parameters for different types of biomass is crucial to solve the optimization problem in the manufacturing environments. This study was carried out to evaluate the potential of oil palm waste and fast growing timber species available in Malaysia for biomass solid biofuel production. To improve the low energy density, high ash content and low ash melting temperature of these biomasses, pretreatment using torrefaction and leaching method were applied. The study of the effect of pretreatments parameters on the characteristics of raw materials as well as the novelty method for achieving a practical solid biofuel from raw materials was presented. In-depth analysis using microscopic observation on the ash related problem during the combustion and methods preventing the forming of slagging were reported in this study.

1.3 Justification

Lignocellulosic biomass is an indigenous energy source and the availability of these materials tends to be intertwined with activity of the major economic sectors of the respective country. One such example is the palm oil industry. Malaysia has been one of the largest producers and exporters of palm oil for the last 40 years. In 2011, Malaysia had approximately five million hectares of land under oil palm plantation (MPOB, 2011). The main products generated from oil palm industry are palm oils, palm kernel oil and palm kernel cake. The byproducts generated from palm oil milling are empty fruit bunch (EFB) and oil palm trunk (OPT), which have great potential to be used as biomass fuel for energy production. During replanting programme, 74 tonnes of dry OPT per hectare are generated. On the other hand, approximately 23 % of the EFB byproduct comes from the processing of fresh fruit bunch (FFB) in the palm oil mill. The consistency of the supply of lignocellulosic biomass byproduct from the palm oil industry has made it an ideal source of raw materials for biomass fuel production. Undoubtedly, oil palm biomass is a great choice as a source for biomass fuel production in terms of the current abundant amount. Nonetheless, the capacity of the oil palm biomass supply has to meet the demands from consumers and power stations. Oil palm biomass is a byproduct whose availability largely depends on the primary production of palm oil industry. If biomass fuel is intended to be used as a commercial fuel, there is a need to look for alternative sustainable feedstock resources such as energy crops to support the solid biofuel production.

Increasing the lignocellulosic biomass yield can be achieved by energy crops. Several studies on the long-term contribution of biomass to future global energy supply highlighted dedicated energy cropping as the major potential for increasing this supply (Berndes *et al.*, 2003; Smeets *et. al.*, 2007). These crops are fast-growing plants or trees which are harvested specifically for energy production. Ideally, these would allow us to grow our fuel, thus reducing the dependence on fossil fuel and our vulnerability to disruption in energy supply. These crops are fast growing timber species harvested within five to eight years after planting; they generate logs with smaller diameters (<20 cm) compared to trees planted specifically for timber production, which requires a longer growth period. Characteristics of the ideal energy crop are high yield, low production costs, low nutrient requirements, and a composition with low amounts of contaminants (McKendry, 2002). Moreover, these desired characteristics highly depend on the local climate, soil conditions, and access to water. In Malaysia, fast growing tropical trees have the entire year in which to grow, and would be expected to outgrow temperate trees on an annual basis, even if their instantaneous growth rates are not as high. *Acacia* spp., *Paraserianthes falcataria*, *Macaranga* spp. and *Endospermum* spp. are among the indigenous and exotic species that have been selected as plantation species in Malaysia based on their excellent growth performance and ease of management (Rasip and Najib, 2009).

1.4 Research Objectives

The general objective of this study is to develop processing treatments that enhance the solid fuel properties of oil palm biomass and some selected fast growing timber species.

The specific objectives of this study include;

a) To determine the chemical composition and fuel characteristic of oil palm biomass and fast growing timber species.

b) To optimize the torrefaction conditions for oil palm biomass and fast growing timber species with maximized HHV yield.

c) To optimize the leaching conditions for oil palm biomass and fast growing timber species with maximized ash removal efficiency without sacrificing the HHV.

d) To develop a process sequence from the combination of torrefaction and leaching treatment to produce solid biofuel with lower ash content and higher heating value (HHV).

e) To determine the effect of kaolin and calcite addition on ash melting characteristic, higher heating value and ash content of the oil palm biomass and fast growing timber species.

1.5 Thesis Outline

This thesis comprises eight chapters and was organized as follows: Chapter 1, general introduction, introduces the research background and objectives. Chapter 2 gives a comprehensive literature review of lignocelulosic biomass as solid biofuel for heat and electricity generation. The potential of lignocellulosic materials as feedstock for solid biofuel production in the near future is also reviewed. Chapter 3, the fundamental research, discusses on the chemical composition and fuel characteristics determined from the lignocellulosic biomass used in this study. Chapter 4 discusses the individual effect of torrefaction parameters (temperature and reaction time), and also their interdependence effect on higher heating value (HHV), weight loss and HHV yield of the lignocellullosic biomass. The optimum torrefaction parameter was also investigated to maximize the HHV yields. Chapter 5 studies the effectiveness of leaching on removing ash forming elements and the leaching effects on ash melting characteristics using water and acetic acid as the extraction agent. Optimum leaching parameter that maximized the ash removal efficiency without reducing the initial HHV of the lignocellulosic biomass was obtained. The fuel characteristic was determined for the lignocellulosic biomass leached under optimal condition. Chapter 6 explores the possibility of combining leaching and torrefaction treatment to create an improved biomass solid biofuel from lignocellulosic biomass. The focus lies in determining the effects of the combination treatments on ash removal efficiency, as well as the ash melting characteristic of treated biomass. Chapter 7 studies the effect of additional kaolin and calcite on the ash melting characteristic, higher heating value and ash content of the lignocellulosic biomass. The additives addition to selected lignocellulosic biomass with problematic ash have been qualitatively and quantitatively determined and reported. And finally, Chapter 8 summarizes the research performed in this study and recommendations for future work.

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