EFFECT OF DENSIFIED OIL PALM EMPTY FRUIT BUNCH TOWARD THE TORREFACTION PROCESS

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ABSTRACT

Biomass refers to raw organic material from plant or animal is used to generate a number of energy resources which convert chemical energy to heat energy through combustion. Oil palm empty fruit bunch (EFB) is one of the biomass which has high moisture content and very bulky in term of storage. Thus, this study is to upgrade the EFB waste to a valuable biofuel using pelletization and torrefaction processes. The pelletization process able to remove the moisture content of raw EFB, increase the energy content and easy for storage. In this study, different ratio of EFB and starch will be made to test the effect of ratio on the quality of biofuel produced. Torrefaction process is a process which the EFB will be heated in an inert atmosphere at temperature of 250°C. The EFB will have higher energy content, lower moisture content and higher stability in storage of EFB. The torrefied EFB pellets will undergo characterization to determine the optimum ratio of EFB and starch. The calorific value of the torrefied EFB pellet is measured by using bomb calorimeter. The lowest and the highest calorific values are19.69MJ/kg for no starch content and 20.02 MJ/kg for 15% starch content EFB pellets. The mass yield of EFB pellet after torrefaction process is about 81% to 84% which increases directly proportional to the starch content in the EFB pellets. The highest energy yield of torrefied EFB pellet is 90.54% while the lowest is 85.59% which is the pellet with no starch content. The fourier transform infrared spectroscopy (FTIR) analysis analyzed the components such as starch, lignin, hemicelluloses and cellulose in the torrefied EFB pellets as compare to the raw EFB. As a conclusion, 10% starch content EFB pellet is the optimum condition because it has the calorific value, energy yield and mass yield which are approximately same as the 15% starch content EFB pellet.

ABSTRAK

Biomass merujuk kepada bahan organik mentah sama ada dari tumbuhan atau haiwan digunakan untuk menjana beberapa sumber tenaga yang menukar tenaga kimia kepada tenaga haba melalui pembakaran . Kelapa sawit tandan buah kosong (EFB) adalah salah satu daripada biojisim yang mempunyai kandungan air yang tinggi dan sangat besar dari segi penyimpanan . Oleh itu , kajian ini adalah untuk menaik taraf sisa EFB untuk bahan api bio yang berharga dengan menggunakan pelletization dan torrefaction proses . Proses pelletization adalah untuk meangurangkan kandungan lembapan EFB mentah bagi meningkatkan kandungan tenaga dan mudah untuk penyimpanan . Dalam kajian ini , nisbah EFB dan kanji yang berbeza akan dibuat untuk menguji kesan nisbah kepada kualiti bahan api bio yang dihasilkan . Proses Torrefaction adalah satu proses yang mana EFB akan dipanaskan dalam suasana inert pada suhu 250 ° C . EFB akan mempunyai kandungan yang lebih tinggi tenaga , kandungan lembapan yang lebih rendah dan kestabilan yang lebih tinggi dalam penyimpanan EFB . Pelet EFB torrefied akan menjalani pencirian untuk menentukan nisbah optimum EFB dan kanji . Nilai kalori EFB pelet yang torrefied diukur dengan menggunakan bom kalorimeter . Nilai kalori yang paling rendah dan paling tinggi ialah 19.69MJ / kg tanpa kandungan kanji dan 20.02 MJ / kg untuk 15 % kandungan kanji EFB pelet . Hasil jisim EFB pelet selepas proses torrefaction adalah kira-kira 81 % kepada 84 % yang meningkatkan berkadar terus dengan kandungan kanji dalam pelet EFB . Hasil tenaga tertinggi torrefied EFB pelet adalah 90,54 % manakala yang terendah adalah 85,59 % iaitu pelet dengan tiada kandungan kanji . Fourier Transform Infrared Spectroscopy (FTIR) menganalisis komponen seperti kanji , lignin , hemicelluloses dan selulosa dalam pelet EFB torrefied berbanding dengan EFB mentah . Kesimpulannya , 10 % kandungan kanji EFB pelet adalah keadaan yang optimum kerana ia mempunyai nilai kalori , hasil tenaga dan jisim hasil yang lebih kurang sama dengan 15 % kandungan kanji EFB pelet .

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1 INTRODUCTION

1.1 Motivation and statement of problem

Fossil fuels which are currently the world's primary energy source are the main cause of the pollution to the environment. Since 1990, greenhouse gas emissions have increased by 5%. Human activities are responsible for almost all the increase in greenhouse gases because the largest source of greenhouse gas emissions from human activities is from burning fossil fuels for electricity, heat, transportation, industry and commercial and residential. (EPA Director, 2014).

The greenhouse gas will cause greenhouse effect which leads to global warming. The greenhouse effect is caused by the concentration of water vapour, carbon dioxide, and other trace gases in the atmosphere which absorb the terrestrial radiation leaving the surface of the Earth. If the greenhouse gases continue to increase, the average temperature on the Earth surface could increase from 256.48 K to 261.76 K as predicted by the climate models (EPA Director, 2014). Changes in the atmospheric concentrations of these greenhouse gases can alter the balance of energy transfer between atmosphere, space, land, and the oceans. Overall, water vapour is the most abundant content in greenhouse gas. The water vapour easily mixes in the atmosphere and can exist in several physical states which are gaseous, liquid and solid (NOAA Director, 2014).

Although the global concentration of water vapour are not believed are affected by human activities, the radiative forcing which is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system produced by the increased concentration of other greenhouse gases may indirectly affect the hydrologic cycle. This can be proven that the warmer atmosphere will have higher water holding capacity which affects the formation of clouds and this can absorb and reflect solar and terrestrial radiation(Lamb, 2013). One of the content of greenhouse gases is carbon dioxide.

Carbon dioxide constitutes about 0.04% of the air currently. It increases from approximately 280 parts per million by volume (ppmv) in pre-industrial times to 391 ppmv in 2012 which increase about 39.6%. The predominant source of anthropogenic carbon dioxide emission is the combustion of fossil fuels (EPA Director , 2014). When the fossil fuels are burned, they also released nitrous oxide into the atmosphere which contributes to the formation of smog and acid rain. This will affect the life of living things on the Earth (Moses, 2014). Fossil fuels are not enough to support the basic need of population in the future because it is non-renewable energy. Thus, getting biomass energy as a substituent for the non-renewable energy is the way to avoid the depletion of non-renewable energy.

Oil palm has become the most important commodity crop in Malaysia. The total planted area reaches 1.917 million hectares in year 2011 (MPOB Director, 2014). Malaysia is producing about 1.66 million tons of oil palm in a month. The oil palm fruit generates two products namely crude palm oil which is obtained from mesocarp and crude palm kernel oil which is from the endosperm (kernel). After the harvested oil palm bunch being processed, it generates by-products and wastes which are empty fruit bunch, palm oil mill effluent (POME), sterilizer condensate, palm fibre and palm kernel shell.

EFB is a lignocelluloses material which typically contains 25% lignin, 50% cellulose and 25% hemicelluloses in their cell wall (Kavitha *et. al*, 2013). EFB contains neither chemical nor mineral additives, and depending on proper handling operations at the mill. (Salman, 2014) Every year, palm oil industry produces roughly about 17.08 teragram of EFB. It will be wasteful if it is not properly utilized due to huge quantities of EFB generated (Khalik *et. al*, 2013). These wastes are left in a space or being burnt which are so wasteful and cause many problems to the industry and environment.

Burning of EFB causes air pollution and the authority imposed strict rules to curb air pollution from such activities. The bulkiness of the oil palm empty fruit bunch is costly for the industry to store it. Thus, there is strong motivation to pelletize the oil palm empty fruit bunch and torrefied it to become a better source of energy. By making the oil palm empty fruit bunch into pellet, the space needed to store the waste will be lesser and the pellet can keep for longer time if compare with moist empty fruit bunch. The oil palm empty fruit bunch is unusable due to its high moisture content and normally unsalable (Rahman *et. al*, 2013). Other than that, the volume of palm oil production is projected to increase by more than 65% by year 2020 which means that the pollution and wastage will keep increasing if we do not make use of the oil palm waste (Morgan, 2014). Thus, this study is to do research on the processes such as pelletization and torrefaction which are used to improve the characteristics of the EFB.

1.2 Objectives

The following is the objective of this research:

- To determine the optimum condition for pelletized EFB for torrefaction process towards the energy production from oil palm empty fruit bunch.

1.3 Scope of this research

The following are the scope of this research:

i) To examine the effect of pelletization of oil palm empty fruit bunch for different empty fruit bunch to starch ratios of 0%, 5%, 10% and 15%.

ii) To explore the torrefaction process of oil palm empty fruit bunch pellet at 250°C.

iii) To determine the characterization of torrefied densified EFB through bomb calorimeter and FTIR.

1.4 Organisation of this thesis

The structure of the reminder of the thesis is outlined as follow:

Chapter 2 provides the general information about this study which can provide more understanding about this study. It explains about theory, application, general knowledge and concept of this study. This chapter start with providing information about biomass which explains the reason for using biomass in this study. Then, it explains the reason for using oil palm empty fruit bunch which is so abundantly available in Malaysia. It also explains about the theory for the condition set up in this study.

Chapter 3 explains about the method and set up in this study. It states the steps and precautions that needed in this study. It includes the preparation before the experiment, set up the experiment, data collection, and measurement for the results obtained.

Chapter 4 provides the result which are tabulated in table form or plotted as graph form which can be clearly explains the results obtained in the experiment.

2 LITERATURE REVIEW

2.1 Overview

This paper presents about a critical review of current pelletization and torrefaction technologies based on the research objectives focus. To that end, fundamental aspect of pelletization and torrefaction are presented towards detail understanding of its science.

2.2 Biomass

Biomass is a renewable energy derived from animal and plant which are organic matter. The plants absorb energy from the sun by photosynthesis process and the energy is stored inside the plants which are then the biomass contains stored energy (US EPA Director, 2013). The energy in the plants may be transferred through the food chain to animals which may produce wastes and the waste also contains stored energy which can be classified as biomass. The chemical materials are stored in the animals and plants on this Earth can be used to generate energy which makes it as one of the well-utilised source of renewable energy in the world. The most common biomass used for energy is wood from trees. Humans used wood for getting the warm and cooking since few thousand years ago.

Charcoal is one of the biomass which is converted by partial-pyrolysis for thousands of years. The wood and charcoal play an important role in the early Industrial Revolution which they fully used them to produce energy in industry (Alternative Energy Director, 2014). Biomass will generate carbon dioxide when utilized, but it was created from solar energy, water and carbon dioxide, so it does not increase the net volume of carbon dioxide on the Earth (Kamimoto, 2006). It maintain the stocks of carbon stored in soil or plants and also displaces the carbon emissions from fossil fuels which will add additional carbon to atmosphere when burning and causes global warming (UCSUSA Director, 2010) The biomass for energy generation holds a large potential as a source of renewable energy and reduce the greenhouse gas emission.

According to EU Commission's report on sustainability of biomass, the biomass for energy generation can reduce emission by 55 to 98 percent if compare to fossil fuel mix (Micheal, 2010). Biomass is not commonly use in all over the world because there are some people believe that more fossil energy is required to produce the bio-fuel than it provides as fuel. But in fact, a recent study by DOE's Argonne National Laboratory and General Motors Corp. concluded that it takes less energy to produce bio-fuel than is supplied by the fuel, so the bio-fuel provides a net energy benefit (NREL Director, 2006).

Biomass energy can be classified into five class namely virgin wood, energy crops, agricultural residues, food waste, and industrial waste and co-products. Virgin wood is the wood and other products such as bark and sawdust which had no undergo any chemical treatments or finishes applied. It may be in a range of physical forms which are bark, brash and arboriculture arising, logs, sawdust, wood chips, wood pellets and briquettes. This virgin wood is suitable for a range of energy applications. The wood received may be physical inclusions from the growing and harvesting processes such as mud, stones, nails or moss which may need to be removed before further process it. There may also be chemical contaminants from the soil, water, air or pesticides which may contain heavy metals, halogens or other trace metals (Biomass Energy Centre Director, 2011).

Energy crops are grown specifically for use as fuel and offer high output per hectare with low inputs. There are four classes of energy crops which are the short rotation energy crops, grasses and non-woody energy crops, agricultural energy crops and aquatics. Vegetable oil is one of the examples of the energy crops which can be converted to biodiesel and the sugar or starch also can be use for fermentation to produce bio-ethanol which can be used for combustion. The grain could be used to produce liquid transport fuels and the straw could be burned to produce heat or electricity (Biomass Energy Centre Director, 2011).

Agricultural residues have many potential to be used widely in energy applications. It sources are wide which include arable crop residues such as straw or husks, animal manures and slurries, animal bedding such as poultry litter, and most organic material from excess production or insufficient market such as grass silage. All of these sources can be classified into dry residues and wet residues. Straw, corn Stover and poultry litter are the dry residues while the animal slurry and farmyard manure, and grass silage are the wet residues which have high moisture content as collected. However, the moisture in it must be removed before combustion can take place (Biomass Energy Centre Director, 2011).

Food wastes are the residues and waste at all points in food supply chain from initial production, through processing, handling and distributions to post-consumer waste from hotels, restaurants and individual houses. Food waste also can be classified into dry and wet waste. Many manufactured food and beverage generate large quantities of organic waste material such as spent grains and organic residues. Used cooking oils and food which are bad for health are also the residues from the food preparation on both the commercial and domestic (Biomass Energy Centre Director, 2011).

The industrial waste and co-products are produced by industrial processes and manufacturing operations which can be used to convert to biomass fuel. These can be divided into woody and non-woody materials. The woody materials are same as the virgin wood which can be used in combustion system such as boiler for the generation of heat or electricity. Alternatively, it can be undergo combustion, gasification, and pyrolysis. For the non-woody wastes and residues which are the paper pulp and wastes, textiles, and sewage sludge which are also potentially suitable as biomass fuel (Biomass Energy Centre Director, 2011).

2.3 Nature of biomass

2.3.1 Lignocellulosic biomass

Lignocellulosic biomass is the non-starch and fibrous part of plant material. It is renewable and abundant which makes it a good source of energy. One of the key factors that affecting the efficiency of biofuel production is the chemical composition of lignocellulosic. The lignocellulosic biomass is composed primarily of carbohydrate polymers such as cellulose and hemicelluloses, and phenolic polymers which is lignin (DoKyoung *et. al.*, 2007).

2.3.2 Cellulose

Cellulose is one of many polymers found in nature such as in wood, paper and cotton. It is made of repeat units of the monomer glucose which is linked by beta-1,4 glycosidic bonds. It is a pure polymer of glucose. It is non-soluble in water under standard conditions and it has a very high degree of polymerization. The thermal degradation of cellulose starts at a temperature range of 300 – 400°C (Harpreet, 2014).

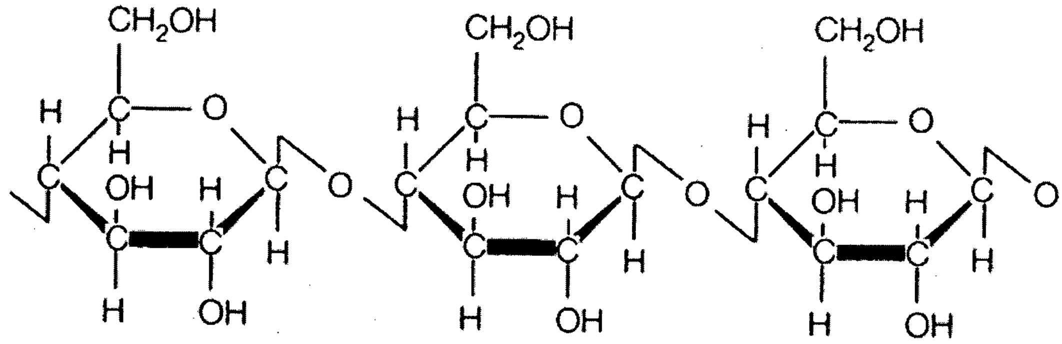


Figure 2-1: Illustration for Cellulose.

(Omega Fields Director, 2014)

2.3.3 Hemicelluloses

Hemicelluloses are polysaccharides in plant cell walls that have beta-linked backbones. Hemicelluloses include xyloglucans, xylans, mannans and glucomannans, and beta-glucans. Hemicelluloses are low molecular weight polymers. The solubility and susceptibility to hydrolysis of hemicelluloses are greater if compare to cellulose. (Scheller & Ulvskov, 2010). The thermal degradation of hemicelluloses starts at a temperature range of 220 - 315°C (Yang *et. al.*, 2006).

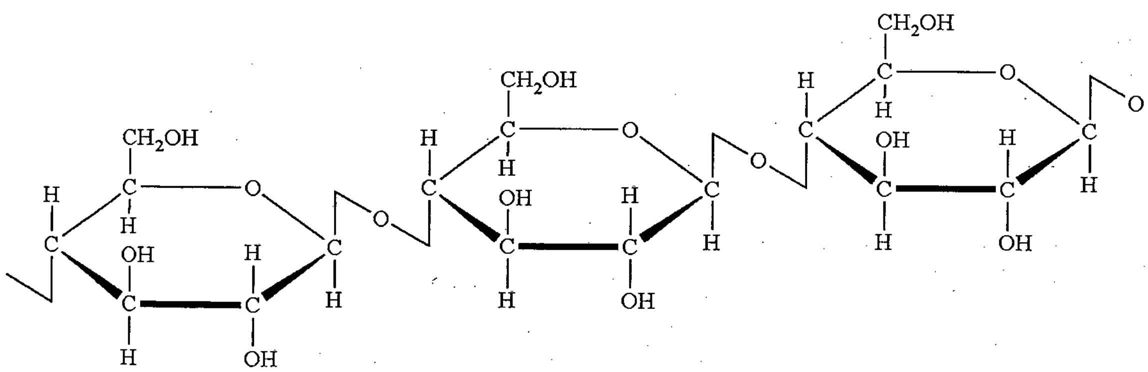


Figure 2-2: Illustration for Hemicelluloses.

(Chen, 2013)

2.3.4 Lignin

Lignin is an organic substance binding the cells, fibres and vessels which constitute wood and the lignified elements of plants. It is one of the most abundant renewable carbon sources on Earth. It is a polymer which is a benzene ring with a tail of three carbons. Its main function of lignin is to provide structural strength of the plant. It starts to degrade at the temperature about 220°C (Harpreet, 2014)

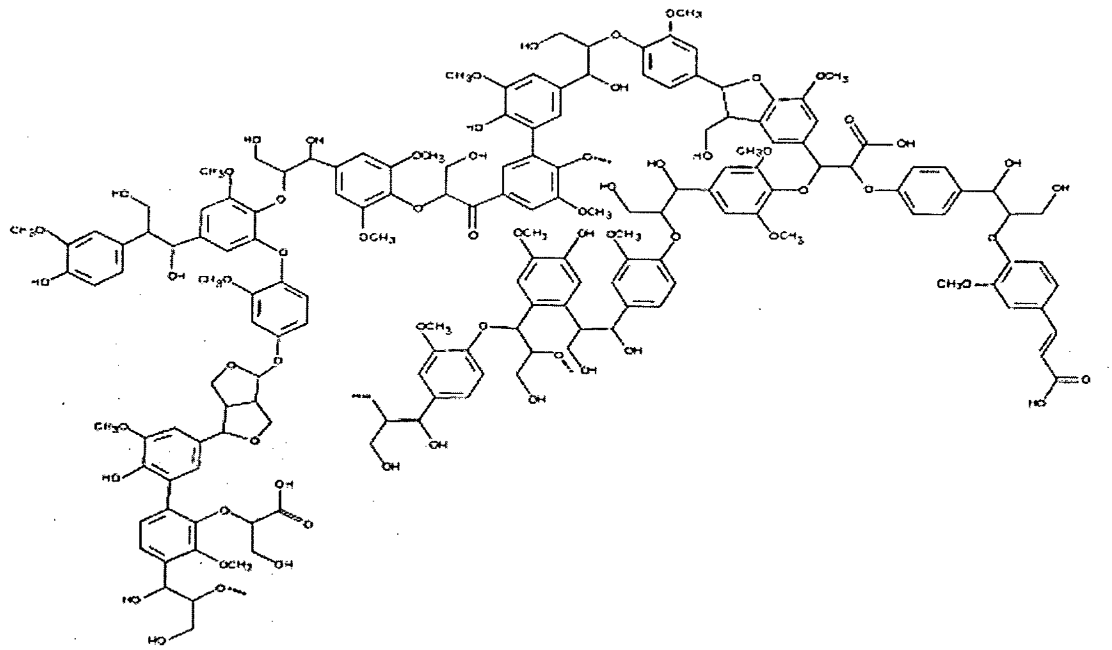
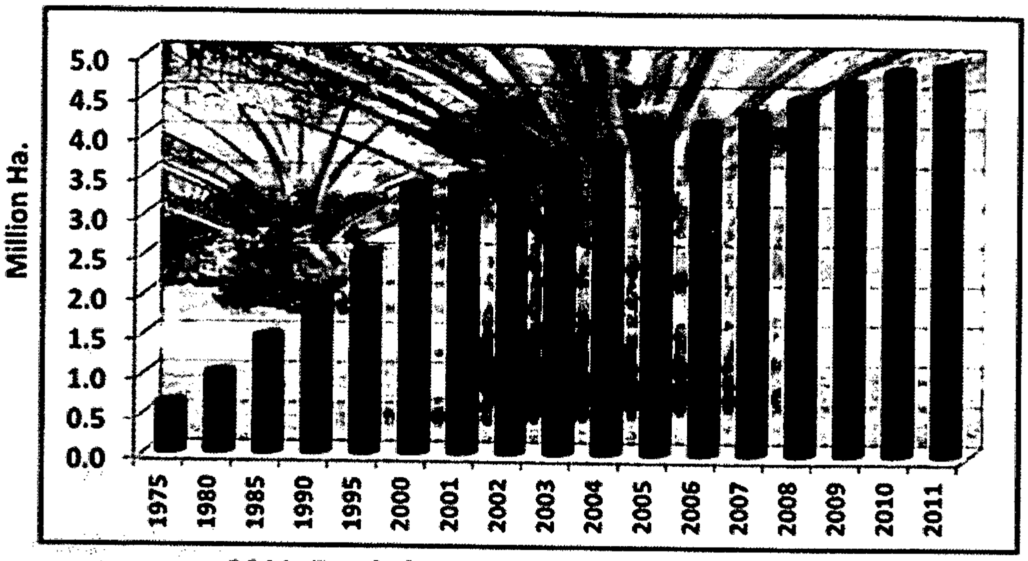


Figure 2-3: Illustration for Lignin.

(Sigma-Aldrich Director, 2014)

2.4 Oil palm in Malaysia

The first oil palm planted as ornamental plant in Malaysia was in year 1870. The planted area had increase at a rapid pace since 1960 and it had increased from 1.5 million hectares to 4.3 million hectares from year 1985 to year 2007. In year 2011, the total planted areas became 4.917 million hectares and it has become the most important commodity crop in Malaysia (MPOB Director, 2014).



2011: Total planted area = 4.917 million hectares
Mature area: 4.280 mil Ha (87.04%)
Immature area: 0.637 mil Ha (12.96%)

Figure 2-4: Planted Area of Palm Oil in Malaysia.

(MPOB Director, 2014)

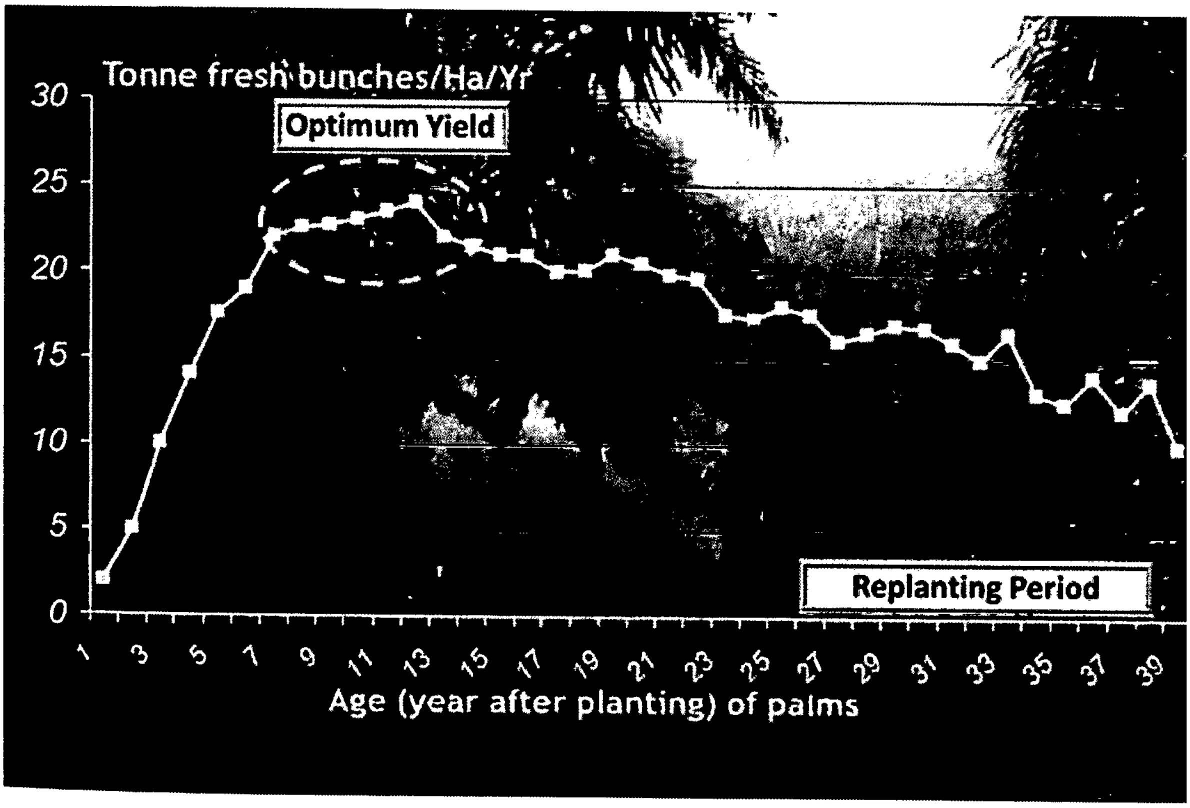


Figure 2-5: Yield of Palm Oil in Malaysia.

(MPOB Director, 2014)

The oil palm planted currently is the tenera hybrid which yields about 4.0 tons of palm oil per hectare, together with 0.5 tons palm kernel oil and 0.6 tons palm kernel cake. Oil palm has an economic life about 25 years and harvesting of palm could begin 30 months after field planting (MPOB Director, 2014).

Each palm oil fruit consists of a hard kernel within a shell and is surrounded by a fleshy mesocarp. Mesocarp is made up of about 49% oil and 50% kernel. A bunch of palm fruit is weighing between 10kg to 50 kg which can have up to 2000 fruits. There are different fatty acid compositions in palm oil. Palm oil which is from the mesocarp contains mainly palmitic acid (C_{16}:o) and oleic acid (C_{18}:1) while the palm kermel oil is more than 80 % saturated and contains mainly lautic acid (C_{12}:o) (MPOB Director, 2014).

Table 2-1: Fatty Acid Composition for Palm Oil.

(MPOB Director, 2014)

Fatty Acid	Palm Oil	Std. Palm Olein	Special Palm Olein	Palm Stearin
C14:0	1.1	1.0	1.1	1.3
C16:0	44.4	39.8	31.5	54.0
C18:0	4.5	4.4	3.2	4.7
C18:1	39.2	42.5	49.2	32.3
C18:2	10.1	11.2	13.7	7.0
C18:3	0.4	0.4	0.3	0.1
Iodine Value	53	58	66.4	39.9
Melting Pt. (°C)	36	21.6	12.0	51.3
Cloud Point (°C)	-	8.8	2.2	-

Note:

Standard palm olein = Single fractionated olein

Special palm olein = Double fractionated olein

FAC = Fatty acid composition:

16:0 = Palmitic acid 18:1 = Oleic acid 18:2 = linolenic acid

Table 2-2: Fatty Acid Composition for Palm Kernel Oil.

(MPOB Director, 2014)

Fatty Acid (%)	PKO	PKOo	PKOs
C6	0.3	0.3	0.1
C8	4.2	4.3	1.9
C10	3.7	3.6	2.7
C12	48.7	44.7	56.6
C14	15.6	14.0	22.4
C16	7.5	8.3	8.0
C18	1.8	2.3	1.8
C18:1	14.8	19.2	5.6
C18:2	2.6	3.3	0.8
Iodine Value	17.9	23.0	7.0
Slip Melting Point (°C)	27.3	23.6	32.2

PKO: palm kernel oil PKOo: palm kernel olein PKOs: palm kernel stearin

Malaysia is the second largest producer of palm oil in the world after Indonesia which is the largest producer from year 2006. Since 1985, soya bean oil is the most consumed oil in the world while the palm oil becomes the second most consumed oil in the world (MPOB Director, 2014).

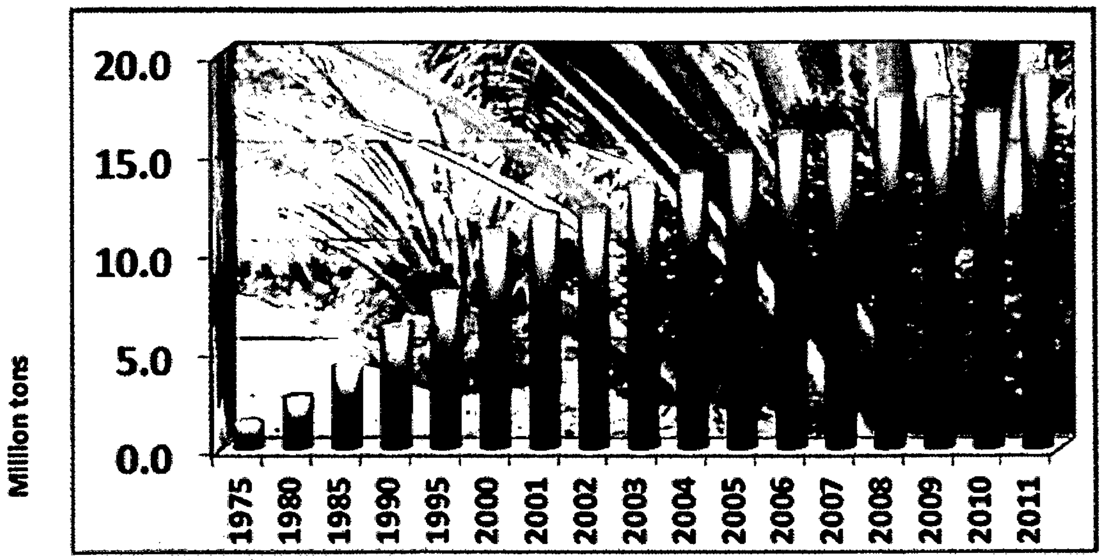


Figure 2-6: Production of Crude Palm Oil in Malaysia.

(MPOB Director, 2014)

Table 2-3: Table of Productivity of Various Major Oil Crops.

(MPOB Director, 2014)

Oil Crop	Oilseeds yield (t ha^{-1}yr^{-1})	Oil Content (%)	Calculated oil yield (t ha^{-1}yr^{-1})
Palm Oil (mesocarp)	19.03	20.1	3.82
Palm Kernel	0.999	45.4	0.45
Cottonseed	1.28	14.7	0.19
Groundnut	1.04	43.2	0.45
Sunflower	1.25	41.2	0.52
Rapeseed	1.75	39.7	0.69
Coconut	0.52	66.1	0.34

Table 2-3 shows the productivity of various oilseed crops in terms of their oil content and oil yield. It can be seen that the oil palm is the highest yielding oil crop and this is the reason why palm oil becomes important commodity crop in Malaysia (MPOB Director, 2014). Palm oil is one of the 17 major oils and fats produced globally. China is the largest consumer of oils and fats and followed by European Union, India and the United States. Global consumption for palm oil was 49.05 million tonnes in year 2011 (Sime Darby Director, 2013).

2.5 Empty fruit bunch (EFB)

Oil Palm is one of the most important economic plantation crops in Malaysia. The empty fruit bunches are harvested from oil palm tree and are sterilized in a horizontal steam sterilizer to inactivate enzymes present in pericarp and loosen fruits from bunches. Then, the sterilized bunches are fed into a rotary drum thresher in order to remove the sterilized fruit from bunches (Kerdsuwan & Laohalidanond, 2011). After the ripen oil palm fruits being yield, left the huge amount of biomass wastes in the form of empty fruit bunch. EFB is saturated with water due to the biological growth combined with the steam sterilization at the mill. Thus, EFB must undergo some process such as torrefaction and pelletization to produce better fuel (Zafar, 2013). The EFB was neutral in pH 7.2 and it contains 45.1% organic carbon. It was found that it contains 210.00 mg kg^{-1} Fe, 71.00 mg kg^{-1} Zn, 26.00 mg kg^{-1} Cu and 88.00 mg kg^{-1} Mn. Other than that, it also contains 33% cellulose, 34% lignin and 30% hemicelluloses. The EFB is hard to degrade because of the cellulose, hemicelluloses and lignin it contains (Kavitha *et. al*, 2013).

Table 2-4: Chemical Composition on Dry Basis of Empty Fruit Bunch.

Element	Chemical Composition (%)
H	6.3
C	48.8
S	0.2
N	0.2
O	36.7
Ash	8.4

Table 2-4 show that the composition of nutrient in EFB which contains 6.3% hydrogen, 48.8% carbon, 0.2% sulphur, 0.2% nitrogen, 36.7% oxygen and 8.4% ash which means that the EFB has high nutrient and is able to become useful material (Tabi *et. al*, 2008).

2.6 Pelletization process

Pelletization is a process in which biomass is dried and compressed under high pressure into cylindrical shaped fuel product. Pelletization consists of a series of unit operation of drying, size reduction, densifying, cooling, screening and warehousing. Before pelletization process, the EFB fibre which is the raw material from palm oil factory has the length of about 200mm which is too long and not suitable for pelletization process. Thus, the first step of pelletization process is to grind the EFB into shorted length of about 3mm or shorter. After that, the grinded fibre should be dried from moisture content of 50-60% to 10-15% of the moisture content. In order to produce quality pellet, the moisture content must maintain 10-15% moisture content. The pellet is in dense form, hard and high temperature after extruded from pelleting machine. The pellet is cooled in cooler machine and will send for drying.

A quality EFB pellets is hard, tough, smooth and shinny on the surface (Chuah *et. al*, 2012). The ash content of EFB pellet approximately 5%, it should have carbon content of 13% and it contains heat energy of 4000kcal/kg. The common diameters of pellet are 6,8 and 10 mm, while its length is less than 30mm (Biofuel Resource Director, 2012). Densified EFB is low and uniform in moisture content. It can be handled and stored cheaply and last longer (Mani *et. al*, 2006). Raw biomass is pelletized to increase the energy content of the biomass per unit weight. The pellets are categorized by their feedstock source, density, moisture level and ash content(Washington State University Director, 2012).

During the pelletization, the compression strength will affect the size and density of the pellet. Higher temperature will increase dry density of the pellets. Higher temperature and pressure in certain range throughout the pressure will produce better bonding observation. The composition of raw material and binding agent will also directly affect the particle bonding. The ratio of raw material and binding agent should be in an ideal range to hold the raw material together (Rahman *et. al*, 2013). The main advantages of EFB pellet towards the environment is EFB pellet will not generate smoke or fume during combustion which is environmental friendly because very minimum particulate is being discharge to the air. (Biofuel Resource Director, 2012)

Figure 2-7: Illustration of the Pellet.

2.7 Torrefaction process

Torrefaction is a thermochemical treatment process which is similar to roasting or mild pyrolysis under the absence of oxygen with low heating rate. The typical process temperature range is from 200 to 300℃. This process is to separate water, some hemicelluloses in biomass, leaving only cellulose and lignin to produce a charcoal-like carbonaceous residue which is the torrefied material. In this process, the biomass is dried and partially devolatilized, its mass will decrease but energy content will be preserved (Prabir, 2012). The main function of torrefaction is to improve the energy density, reduces the oxygen-to-carbon ratio, and reduces the hygroscopic nature of biomass for a better energy production (Dutta & Mathias, 2014).

After undergoing the torrefaction process, the biomass is in hydrophobic condition. This will make the storage of the biomass easier because the significant loss of energy due to re-absorption of moisture in biomass is saved. The torrefied biomass will have higher energy, lower moisture content and better grindability (Bourgois & Guyonnet, 1998). Pre-drying of biomass to reduce the moisture content is needed to torrefy the biomass efficiently. Higher moisture content will cause inefficient combustion of the wet torrefaction gas which it increases the residence time of torrefaction (Kleinschmidt, 2014). Torrefaction process will produce a biomass which is more friable and brittle because of the depolymerisation of hemicelluloses (Prabir, 2012).

Torrefaction will cause the energy content of the biomass decrease because of partial devolatilization, but there is higher reduction in mass given, the energy density of biomass increases. According to table 2-5, we lose only 11 to 17% energy, the biomass lost 31 to 38% of its original mass. Thus, there is a 29 to 33% increase in energy density of biomass. This increases its higher heating value to about 20 MJ/kg. There is still a net rise in the energy density of the fuel even if we take into account the energy used in torrefaction process (Prabir, 2012).

Table 2-5: Change in the Bagasse Properties after Torrefection at 250°C.

(Prabir, 2012)

Property	Torrefaction Time (min)		
	15	**30**	**45**
Mass yield (%)	69	68.33	62
Energy yield (%)	88.86	91.06	83.23
Energy density (% energy yield/% mass yield)	1.29	1.33	1.34
Energy required (MJ/kg product)	2.34	2.58	2.99
Higher heating value (HHV) (MJ/kg product)	19.88	20.57	20.72
Rise in HHV (%)	22.35	24.96	25.51
HHV (MJ/kg raw material)	15.44	15.44	15.44
Net energy (MJ/kg product)	17.54	17.99	17.73

Torrefied biomass performs better than the original raw biomass in gasification and combustion. The torrefied biomass had better performance in gasification efficiency because the oxygen to carbon ratio of the biomass is increased. Torrefaction process had reduced the power requirement for size reduction and it had improved handling because the torrefied biomass is hydrophobic which will not easily absorb moisture and it is not suitable for microorganism to grow. The torrefied biomass also offers cleaner-burning fuel with little acid in smoke which are environmental friendly and no pollution will occur. Torrefation can produce high quality biomass pellets with higher volumetric energy density (Prabir, 2012).

During torrefaction process, hemicelluloses decomposed and this cause the size of biomass reduced which will consume less energy after torrefied. The weight loss of biomass primarily is from the decomposition of the hemicelluloses constituents which will decompose within temperature range of 150°C to 280°C which is the temperature window of torrefaction. According to figure 2-8, hemicelluloses degrade the most at temperature within 200 to 300°C temperature window. Lignin starts softening above its glass-softening temperature at about 130°C which will helps in pelletization of torrefied biomass. While cellulose only show limited devolatization and carbonization when the temperature is above 250°C (Prabir, 2012).

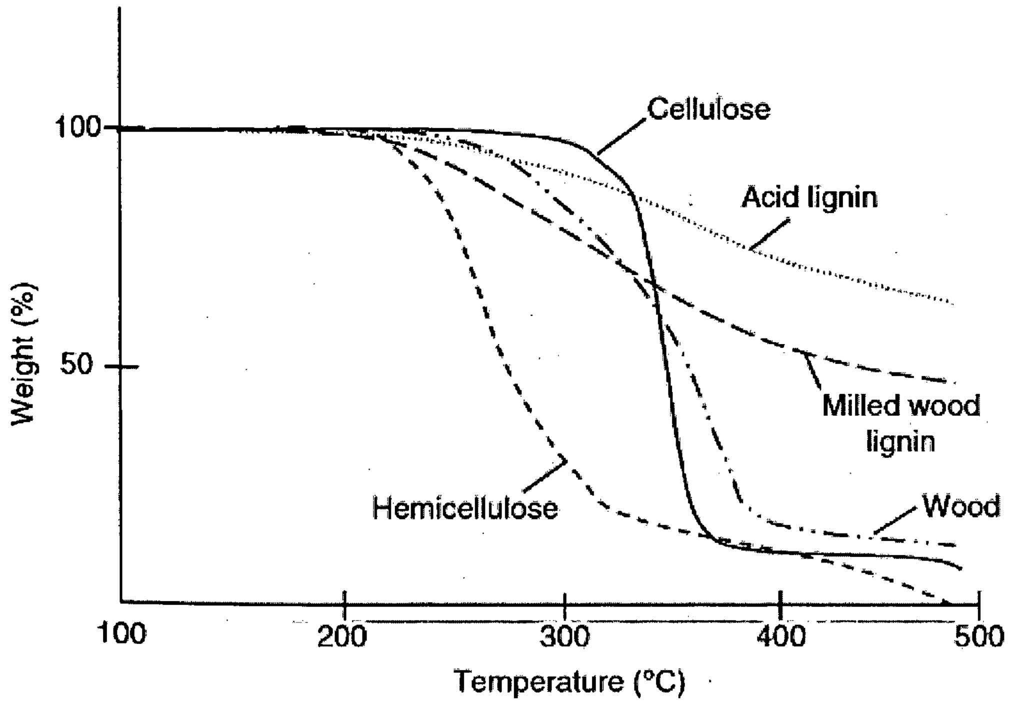


Figure 2-8: Weight Loss inWood Cellulose, Hemicellulose, and Lignin Durin Torrefaction.

(Prabir, 2012)