PROPERTIES AND THERMAL BEHAVIOR OF RAW AND TORREFIED EMPTY FRUIT BUNCH (EFB)

by

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DECLARATION

I declare that this thesis entitled "title of the thesis"is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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Properties and Thermal Behavior of Raw and Torrefied Empty Fruit Bunch

ABSTRACT

The torrefaction of an oil palm empty fruit bunch (EFB) which could be consider as the waste products from oil palm industry was carried out in this study. This process is carried out in two ways which are raw and torrefied sample inside a microwave with the presence of nitrogen gas and the components of peristaltic pump and temperature controller to hold the time, temperature and power given to the EFB. For raw sample, moisture content and colour changes is being analysis and the result show even it looks dry, there is quite high value of moisture content inside the EFB which is 9.7%. As for colour's observation, the colour change become darker colour from bright colour.

As for torrefaction process, the mass loss and mass yield were investigated right after the sample being torrefied. For the thermal behaviour of the sample, the torrefaction product is being analysed by using thermal gravimetric analysis (TGA) and also bomb calorimeter. Bomb calorimeter is used to identify the calorific value. For this study, the calorific value ration of the torrefied EFB in the presence of nitrogen gas is about 15.8 MJ/kg with its energy yield of 80.4% and while for torrefaction was 26.5337 MJ/kg. As for thermal behaviour of the sample, the process was carried out in a (TGA-DSC). The result showed that torrefaction is depended on the composition of lignocellulosic constituent and torrefaction increased the carbon content and decreased the hydrogen and oxygen content. Thus, it could be identified that the size of the sample, power and temperature influences the product of torrefaction.

Ciri-ciri dan Tingkah Laku Haba Tandan Buah Kosong Mentah Dan Pengeringan

ABSTRAK

Proses pengeringan daripada tandan buah kosong kelapa sawit yang boleh dipertimbangkan sebagai bahan buangan daripada industri kelapa sawit telah dijalankan dalam kajian ini. Proses ini dijalankan dalam dua cara yang sampel mentah dan yang telah dikeringkan dalam microwave dengan kehadiran gas nitrogen dan komponen pam peristalsis dan pengawal suhu untuk mengawal masa, suhu dan kuasa diberikan kepada tandan buah kosong kelapa sawit. Untuk sampel mentah, kandungan kelembapan dan perubahan warna yang analisis dan menunjukkan hasil walaupun ia kelihatan kering, ada nilai agak tinggi untuk kandungan lembapan dalam tandan buah kosong kelapa sawit yang merupakan 9.7%. Bagi pemerhatian warna, perubahan warna menjadi warna lebih gelap dari warna yang terang.

Bagi proses pengeringan, kehilangan jisim dan hasil masa telah dikenal pasti selepas sampel dikeringkan. Selaras dengan tingkah haba sampel, produk pengeringan itu sedang dianalisis dengan menggunakan analisis terma gravimetrik dan juga bom kalorimeter. Bom kalorimeter digunakan untuk mengenal pasti nilai kalori. Untuk kajian ini, nisbah nilai kalori dengan kehadiran gas nitrogen adalah kira-kira 15.8 MK / kg dengan hasil tenaga sebanyak 80.4% untuk sampel mentah manakala 26.5337 MK/kg bagi sampel yang telah dikeringkan. Bagi tingkah laku haba sampel, proses itu dijalankan di dalam analisis terma gravimetrik. Hasilnya menunjukkan bahawa proses pengeringan adalah bergantung kepada komposisi konstituen lignoselulosa dan pengeringan meningkatkan kandungan karbon dan mengurangkan kandungan hidrogen dan oksigen. Oleh itu, ia dapat dikenal pasti bahawa saiz sampel, kuasa dan suhu mempengaruhi hasil pengeringan.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF ABBREVIATIONS

EFB	Empty fruit bunch
TGA	Thermal gravimetric analysis
GHG	Greenhouse gas
EA	Elemental analysis
ASTM	American Standard Measurement
RSM	Response Surface Method
CCRD	Central Composite Rotational Design
PKS	Palm Kernel Shell

LIST OF SYMBOLS

%	Percentage
<	Less than
>	More than
H/C	Hydrogen-carbon ratio
kcal/kg	Heat value
kg m^{-3}	Bulk Density
kg	Kilogram
min	Minutes
MJ kg^{-1}	Energy density
mm	Milimeter
O/C	Oxygen-carbon ratio
^{o}C	Degree Celsius
^{o}C/min	Heating rates
W	Watt

CHAPTER 1

INTRODUCTION

1.1 Background of study

Generally, biomass is any organic material which are derived from plants or animals. It is also including gases and liquids gained from the decomposition of non-fossilized and biodegradable organic materials. It is being formed from the interaction of organism and sunlight, which will give a potential energy. However, this process will not lead to the addition of total carbon dioxide inventory of the earth. Biomass is any organic materials that could be one of the promising renewable energy sources and could be utilized as solid, liquid and gas fuels (Uemura et al., 2011).

Biomass is constantly formed from the interaction of carbon dioxide gas, air, water, soil and also sunlight. It is also undergoing the process of photosynthesis. There are also several biomasses that are comes from botanical plant species or from animal waste or we called it as carcass. In fact, biomass had already become one of the most regularly used as a renewable sources of energy few decades ago. Due to the huge amount of biomass generated from the oil palm industry, it will be a waste if the biomass is not utilized properly (Sabil, Aziz, Lal, & Uemura, 2013).

Moreover, Malaysia is located in high biomass productivity which can lead to supply the unlimited source of renewable energy resources to be used in the future. There are many sources of biomass whether it is in wood products, dried vegetation, crop residues and also from aquatic plants which are being grouped as secondary biomass. One of the most viable and sustainable biomass is from agricultural waste (Aziz et al., 2011). Besides, municipal solid waste is one of the biomass waste which most of them comes from renewable like food scraps, lawn clippings, leaves and papers. The example of the waste material from the agricultural waste is the oil palm. From the oil palm itself, the material that could be obtain is from the leaves to the trunk. The whole part of an oil palm tree could be used wisely such as empty fruit bunch (EFB), palm kernel shell, leaves, fruits, fronds and also trunks. Mostly, the part of oil palm tree could be used for a source of energy. Since Malaysia is the second largest producer of palm oil, its cultivation had been criticized for the cause of environmental issue such as greenhouse gas emission which lead to the climate change.

Besides, when talking about the biomass which could also act as energy source, this biomass could be used directly and indirectly through the process of combustion which will produce heat and also conversion to produce energy. It is also having the relation with bio-fuel energy. Bio-fuel energy is the solar energy from the photosynthesis of plants process. The sustainable of the availability of bio-fuel energy depends on the amount of energy that are derived from the growth of biomass that are being used for the production of food, clothes and also wood product.

In addition, due to the depletion of fossil fuels and serious environmental problems associated with the usage of fossil fuels, renewable energy sources which can be utilized as solid, liquid and gas fuels. In fact, the total extraction is the same as when the externality is ignored, but in the presence of the greenhouse effect, it will be optimal to slow the extraction and spread over a longer period (Hoel, 1996). The combustion process of biomass does not affect the total inventory of carbon dioxide of the earth. Thus, it is called as greenhouse gas neutral or GHG neutral. The effect of gas emission from fossil fuels call for sustainable energy sources such as biomass (Sabil et al., 2013). Thus, biomass is a promising renewable energy sources to replace fossil fuels in the future (Aziz et al., 2011).

Lastly, the presence of several hectares of land in Malaysia are fully occupied with oil palm plantation that are generating huge amount of biomass. Biomass from oil palm industries appears as an alternative source of raw materials that are renewable energy in Malaysia. Thus, the scenario of biomass in Malaysia had covered the issue of the sustainability of energy. Besides, it can also help to reduce the global warming because the renewable energy is a perfect solution to promote the sustainable development.

1.2 Problem statement

Oil palm is the product from Malaysia that already helped to change the scenario of the agriculture and economy of Malaysia. The lignocellulosic biomass that are being produced from the oil palm itself whether through its trunks, leaf, empty fruit bunches and also from the palm shells itself will undergo the different affect when energy heat are being applied onto it.

The main problem of this research is to minimise the disposal waste of the oil palm wastes especially from its empty fruit bunches (EFB) by determining the properties and thermal behaviour of the (EFB) biomass during torrefaction process in order to be used in energy section. According to this, torrefaction is suitable method to encounter the problem. Torrefaction is also suitable as a thermal treatment to improve the properties of biomass for energy generation.

1.3 Objectives

The main objectives are to study the properties and thermal behaviour of raw and torrefied empty fruit bunches derived from oil palm wastes. Below are the specific objectives regarding this study:

i. To determine the physical and elemental properties of raw and torrefied materials.

ii. To analyse the proximate analysis of raw and torrefied materials by using thermal gravimetric analysis (TGA).

1.4 Research scope

This study is focusing on torrefaction process onto oil palm wastes. The consideration that need to ensure is the chemical and physical properties of raw and torrefied sample of oil palm waste. As for chemical properties, the composition of the efb need to be identified. The calorific value of the sample need to be identified also by using bomb calorimeter. As for physical properties, the mass yield, the colour changes and the density of the empty fruit bunch sample is need to investigate. Moreover, the raw sample will be treated in the microwave with temperature 200-300 °C.

The torrefaction of the sample would increase the energy yield and reduce of its mass. The changes of the chemical compositions and elements could be detected by using thermal gravimetric analysis (TGA). Moreover, TGA is also used to detect the thermal behaviour during the torrefaction and combustion process. TGA is used to monitor the mass loss during torrefaction while applying variant of heat and continuous weight balance chemical which the output will be analysed in terms of proximate analysis

CHAPTER 2

LITERATURE REVIEW

2.1 Biomass

Biomass is the amount of living organism in certain habitat, or derived from the living organism itself. Usually it is whether from plant based material both comes from animal or plants. Biomass can also be categorized into four groups namely agricultural waste, wood residues, energy crops and also municipal solid waste (Aziz et al., 2011). In this study, we are more focusing on agricultural waste which is to convert the biomass to energy. The agricultural waste is a production of waste from agricultural operations. It is derived whether from farms, plantation, and also harvest waste. All these biomasses could be convert to become renewable energy. Thus, in order to utilize the raw biomass to be used as energy sources, there were many challenges due to its characteristic. This is because the raw biomass is usually high in moisture content, low energy density, difficult to store and poor grind ability (Aziz et al., 2011).

2.1.1 Biomass from empty fruit bunch (EFB)

Empty fruit bunch is a part of oil palm tree which is derived from its fresh fruit. It is the empty husks left over after oil had been extracted from the palm fruit, which is generated from palm oil industry as a waste material. It is also could be derived from any source of plant. Empty fruit bunch can be applied directly to the field or applied as bunch ash, which is especially good for acid sulphate soils. However, because of air pollution caused by burning of EFB, the current practice is direct application of EFB to the field ("Utilization of Organic Wastes and Natural Systems in Malaysian Agriculture H. A. H. Sharifuddin and A. R. Zaharah University of Agriculture, Serdang, Malaysia," 1987). In this study, it is more focused on oil palm waste due to large amount of EFB that are generated in Malaysia could be utilized as big potential of lignocellulosic biomass in order to generate energy and power. At the oil palm mill, the fresh fruit bunches will be sterilized through a threshing process to separate the fruit nuts from its bunches. EFB from oil palm is one of the potential biomass to produce biofuels like bio-oil due to its abundant supply and favourable physicochemical characteristics (Chang, 2014). EFB is a bulky and voluminous brown bunch left over at palm oil mills after the removal of sterilized fruit by a rotary thresher drum. It is irregular in shape, weighs about 3.5 kg and has a thickness of 130 mm [20], and can vary from 170 to 300 mm long and 250 and 350 mm wide (Chang, 2014).

2.2 Energy

Energy is the potential of chemical substance to undergo transformation through chemical reaction. There are renewable and sustainable energy which are being used as the energy supply for the country. Renewable energy has become more important globally especially with the current fuel and economic crisis (Idris et al., 2010). The world needs an enormous amount of energy to maintain the future economic development which as for example India has easy way to overcome the immediate demand of energy supply by renewable energy resources. It has a big potential of biomass resources to reduce the dependence on fossil fuels in order to produce electrical and heat energy (Herbert & Krishnan, 2016). However, biomass energy will also deal with environment of the bio-energy for the future development.

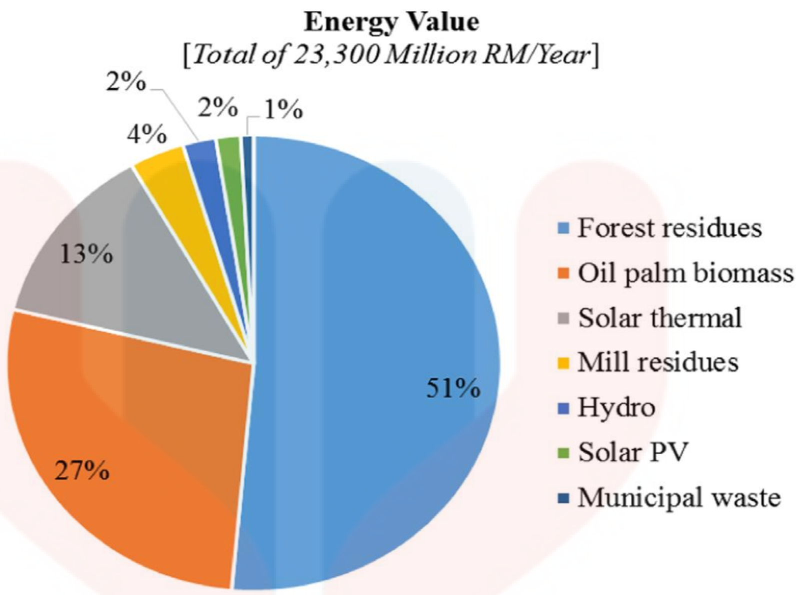


Figure 1 : Renewable energy sources in Malaysia (Fazeli et al., 2016)

2.3 Microwave technique

Generally, microwave is the electrical instrument which people are mostly used to cook something inside it or used microwave energy to heat food or other items placed within it. In a nouns form, microwave is a non-ionising electromagnetic wave that comes with wavelength between the infrared light and radio waves. On the other words, microwaves are electromagnetic waves with frequencies between 300 MHz and 300 GHz, and thus the corresponding wavelengths are between 1 m and 1 mm, respectively (Huang et al., 2016). Microwave heating includes two mechanisms: dipole rotation and ionic conduction which both of these mechanism is able to heat materials quickly and uniformly. Most people are preferring to use a microwave in this fast-paced world because compared with conventional heating, microwave heating can be more efficient due to its rapid, selective, volumetric, and uniform heating (Y. Huang et al., 2016). Besides, microwaves help to save time and easy to clean after use it and more important is that it can conserve energy by reducing the energy consumption as an alternative way to a conventional oven. This is because microwave is eco-friendly and save 50% of energy cost without causing the indoor air pollution.

Usually, the typical microwave ovens or reactors work at a frequency of 2.45 GHz. Microwave heating is the direct conversion of microwave energy into thermal energy for conventional heating. The advantages of the performance of microwave is that it is rapid heating, quick start-up and reduced time. Besides, the microwave is being applied in industrial process because of non-contacting heating, high level of safety automation and high flexibility of certain materials. However, as for microwave reactor, it is different from usual microwave because of the condition of heating itself. The influence of microwave power level on both maximum temperature and heating rate was substantial. Both reaction tube (40 cm length, 5 cm outer diameter) and sample holder (3 cm height, 4 cm outer diameter) were made of quartz (Y. Huang et al., 2016).

2.3.1 Effect of power level towards torrefied products

As for this study, the power that would be used will be varies to see the variance of study from torrefaction effects. The power used as parameter in this study are 385 watts, 540 watts and 700 watts. Different parameter of power will give different effect of result. This study is also want to verify the optimization between all the involved parameter which gives the best result of torrefaction process. The power value is also need to be suitable with the amount of sample to avoid from overheated. Therefore, the microwave power level should be the most important parameter affecting the performance of microwave heating (Y. Huang et al., 2016).

2.4 Torrefaction

The process of torrefaction is quite similar to that process of roasting the coffee beans which the price and taste of the roasted coffee depends on the degree of the roasting temperature. Specifically, torrefaction is one of the thermal process that are coverting biomass into charcoal-like material that will have a better fuel characteristic and becomes them more brittle, easy grindability and also less energy demand. This pre-treatment method called ‘torrefaction’ is found to be effective process to improve the limitation properties of raw biomass (Aziz et al., 2011). Usually, the torrefaction process may sometimes confused with the related process which is carbonization, pyrolysis, roasting and wood cooking but actually the process condition is differ from each other. Torrefaction is a thermal pretreatment process which material are being heated with temperatures (200 °C-300 °C) within less than 60 minutes in an inert atmosphere which those process will reduces the moisture in biomass and lower the affinity of water in torrefied biomass (Chen, Kuo, Liu, & Wu, 2014). There are many variables that can be attributed to the torrefaction process which the idea that a range of temperatures can be used in torrefaction and also the time which could be vary (Mitchell, 2010).

2.4.1 Effect of torrefaction to physical of empty fruit bunch

The torrefied products is the products obtained from the process of torrefaction. The product obtained are strongly depends on the applied process condition, time consuming and the temperature setting. In spite of the fact that 30 % wt of biomass is lost during torrefaction the recovered solid may retain up to 90 % of the initial biomass energy content. From this torrefied products, the physical properties such as the colour, the density and also the mass yield need to be identified. For the colour, the changes of the efb from raw to torrefied will be observed. Different temperature of torrefaction process will give different colour to efb. The effect from the density aspect will give the efb low density since the torrefaction process will remove the moisture content inside the efb. And for mass yield, this process will lower the value of mass yield.

2.4.2 Effect of torrefaction on elemental composition of empty fruit bunch

Elemental analysis of air dried biomass samples was carried out using CHN-O Elemental Analyzer. In terms of ultimate analysis, biomass is mainly composed of C, H, and O, which define, for the most part, its heating value. It also contains small quantities of N, S, Cl. These six elements make up the organic phase of biomass (Peduzzi, Boissonnet, & Maréchal, 2016). The carbon content increase with the increasing of torrefaction temperature. While the o/c, hydrogen and also the oxygen content of an efb are decreasing.

2.5 Thermal behaviour during torrefaction process

Thermal behaviour is the process involving increasing in heat that are caused by uneven heating. Thermal behaviour of biomass in the process of torrefaction is related to the pre-treatment control and torrefaction performance. Thermal behaviour of biomass in torrefaction plays an important role in the operation of pre-treatment to understand the endothermic and exothermic characteristic of biomass in the course of torrefaction (Chen et al., 2014). TGA has been demonstrated to be a very valuable technique for studying the combustion of a wide range of solid samples (Parshetti, Quek, Betha, & Balasubramanian, 2014). It is also being used to determine proximate analysis of the biomass. Moreover, the mass loss of the biomass sample is correlate with the temperature of the torrefaction process. As for torrefaction process, the mass loss distributions for all type of biomass have been monitored by TGA (Sabil et al., 2013). Thus, this study concludes that the mass and energy yield are depending on the torrefaction temperature and biomass type (Sabil et al., 2013).

2.6 Torrefaction temperature

Torrefaction processes are usually conducted by following operating parameters; reaction temperature ranging from 200-300 °C, heating rate below than 50 °C, residence time within 30 minutes, ambient pressure and various feedstock (Hisham, Uemura, & Tazli, 2016). Recently, a low temperature treatment at 200–300 °Cunder an inert atmosphere has been found to be effective for improving the energy density and the shelf life of biomass. In addition, temperature is also one of the important parameter in order to undergo torrefaction process. Thus, the temperature will give the huge effect to the sample and this parameter must be set up correctly to avoid unwanted condition of the sample. The temperature of torrefaction will also give the effect towards energy value. The activation energy for torrefaction of empty fruit bunches was 30.81 kJ/mol (Hisham et al., 2016). As known, efb is from biomass that contain fibre inside it. Thus, the temperature of the torrefaction process were also gives effect. Lignocellulosic biomass consists of three major components which made up of hemicellulose, cellulose and lignin. When EFB was treated with torrefaction process, these components were started to decompose (Hisham et al., 2016).

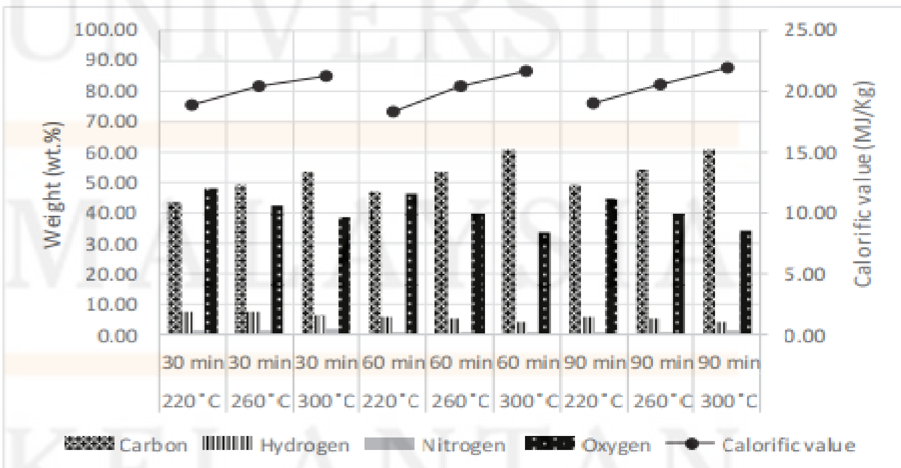


Figure 2. Effect of temperature and time on elemental composition and calorific value (Hisham et al., 2016)

2.7 Residence time

Residence time is also called removal time which is the definition is defined as the average amount of time that a particle spends in a particular system. It is also called as holding time. The time taken when the torrefaction process start to occur. The measurement is varying directly with the amount of the substance which present in a system. In other words, residence time is defined as the average time a particular molecule of water will remain in the body of water. Results indicated that a high temperature and long holding time produced the torrefied sample with low mass and energy yields (Li et al., 2015).

CHAPTER 3

MATERIALS AND METHODS

3.1 Materials

The materials that are being used in this study is the empty fruit bunch (EFB) derived from oil palm wastes. The EFB have been collected from oil palm plantation located at Felda Kemahang, Jeli. Firstly, the raw sample will be put inside the oven at 105 °Cfor 24 hours. After that, the dried sample will be grinding by using the grinder machine. The time taken for grinding process is about 2-3 hours for 1 kilogram of sample. This is because the sample need to become as smaller as it could to undergo several heat treatment and torrefaction process. After that, the grinded sample were sieved and grouped to the size of 250, 500 and 750 microns to ensure the uniformity of the heat treatment. The size of the sample is also play an important role because different instrument used different size of sample.

Figure 3.1: Empty Fruit Bunch (EFB)

Figure 3.2: Grinding Machine

Figure 3.3: Grinded Sample

3.2 Methodology

3.2.1 Properties of Raw Materials

The 10g of fresh EFB was weighed and put inside the oven to determine the moisture content of the sample before getting through the torrefaction process. The EFB were dried inside the oven by using the temperature value of 105 °Cfor 1 hour. After that, the weight was determined until the constant weight was obtained. The formula for moisture content is as follow:

$$Moisture\ Content,\ MC\ (\%) = \frac{weight\ of\ original\ efb - weight\ of\ dried\ efb}{weight\ of\ original\ biomass} \times 100$$

Equation 1

The colour of the sample was determined by using naked eyes at this stage to show the difference of the sample before and after torrefaction process. At this stage, all the physical properties were determined.

3.2.2 Optimization of Torrefaction Process

The microwave system had been developed by Faculty of Earth Science which is located at Environmental Lab at University Malaysia Kelantan (UMK). This microwave system consists of nitrogen gas tank, gas cooling system, peristaltic pump, and also temperature controller to achieve the desired torrefaction temperature. This microwave system will be able to carry out the required torrefaction temperature.

The EFB samples were placed inside the microwave which the sample will undergo minor pyrolysis through microwave radiation. Three experimental parameter were used to characterize the torrefaction process which were the temperature, power input and residence time. The temperature was varied from 200, 225, 250, 275 and 300 °C. The residence time which the EFB was allowed to undergo was for 20.30,40 and 60 minutes. From this process, the optimum value for all the parameter were obtained by using response surface method (RSM).

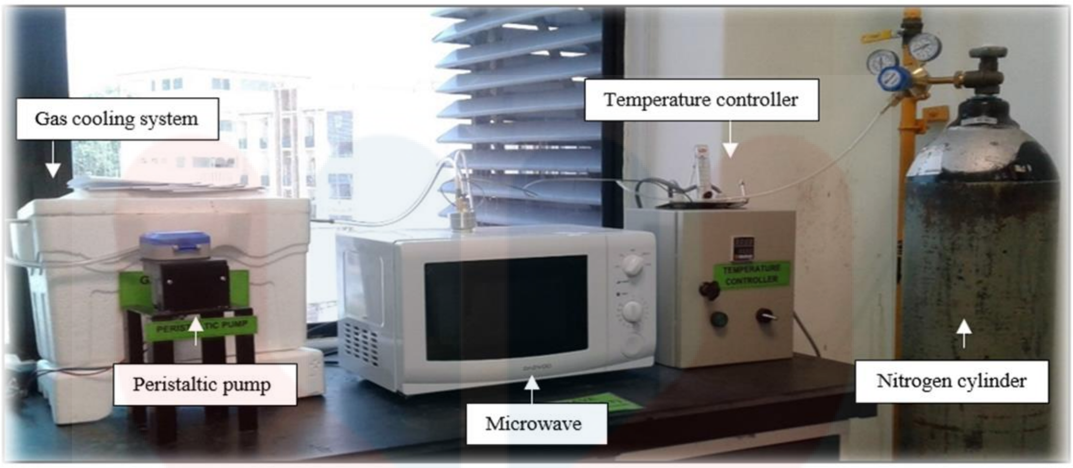


Figure 3.4: Microwave reactor

3.2.3 Characeristic of Torrefied Materials

To achieve the optimum output from the microwave setting, RSM will introduced to correlate all the parameter. The value of mass input, nitrogen flow, time and power needed will be analysed.

a) Thermal Behaviour Test – Proximate Analysis

The torrefied EFB samples were undergo proximate analysis process. This analysis was to determine the moisture content, volatile matter, ash content and fixed carbon in the samples. This testing could also verify the constituent obtained from chemical reactions or could be conducted manually by using TGA instrument. Firstly, the sample will be weight by using electronic balance. The weight of the sample that is being used is about 10mg and this weight must be standardized for all the sample both raw and torrefied. Once the preferred weight had been obtained, the sample will be insert to TGA machine. The rate of gas flow for the sample will be 10 °Cper min, 50ml nitrogen gas per minute and the starting temperature will be 30 °C-1000 °C. The TGA will run each sample for about 1 hour and 48 minutes. Then, the result will be in graph form and could be analyse by using the STARe Evaluation Software.

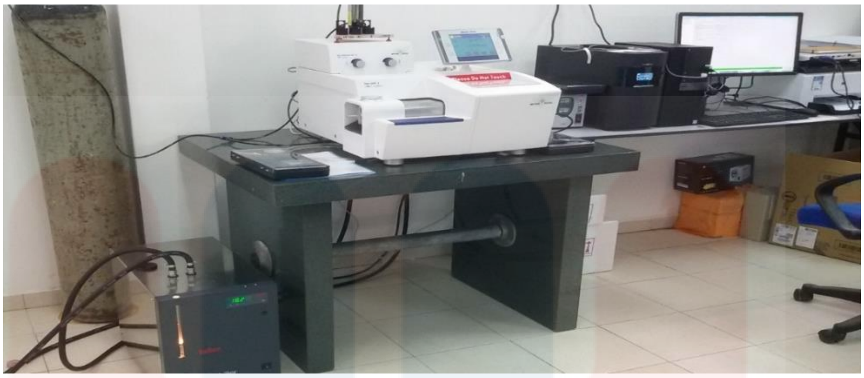


Figure 3.5: TGA Machine

b) Calorific value test

Calorific value was used to determine the energy released from the fuel pellets of oil palm fronds. Calorific value is very important for fuel pellets production. The instrument that used to measure calorific value is bomb calorimeter using the standard ASTM D58565-07. Fig. 3.11 the bomb calorimeter AC 500. The weight of the tested sample was preferred more than 1 g in order to avoid invalid combustion (misfire) from occurs as the sample might be burned out before the computer was able to obtain the data. The combustion chamber must be ensuring in the dry condition and then the wood samples were putted into the holder crucible. A 10 cm wire fuse was install on combustion chamber. The oxygen gases at 300 Pascal were pumped into the station with the combustion chamber. The station was immersed into distilled water before analysing by using automatic calorimeter. The data was recorded on the main computer after 15 minutes of analysing.

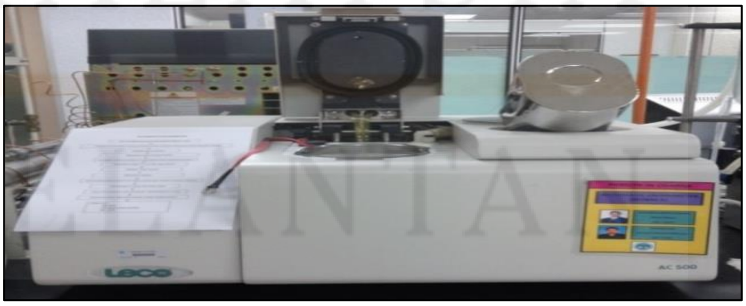
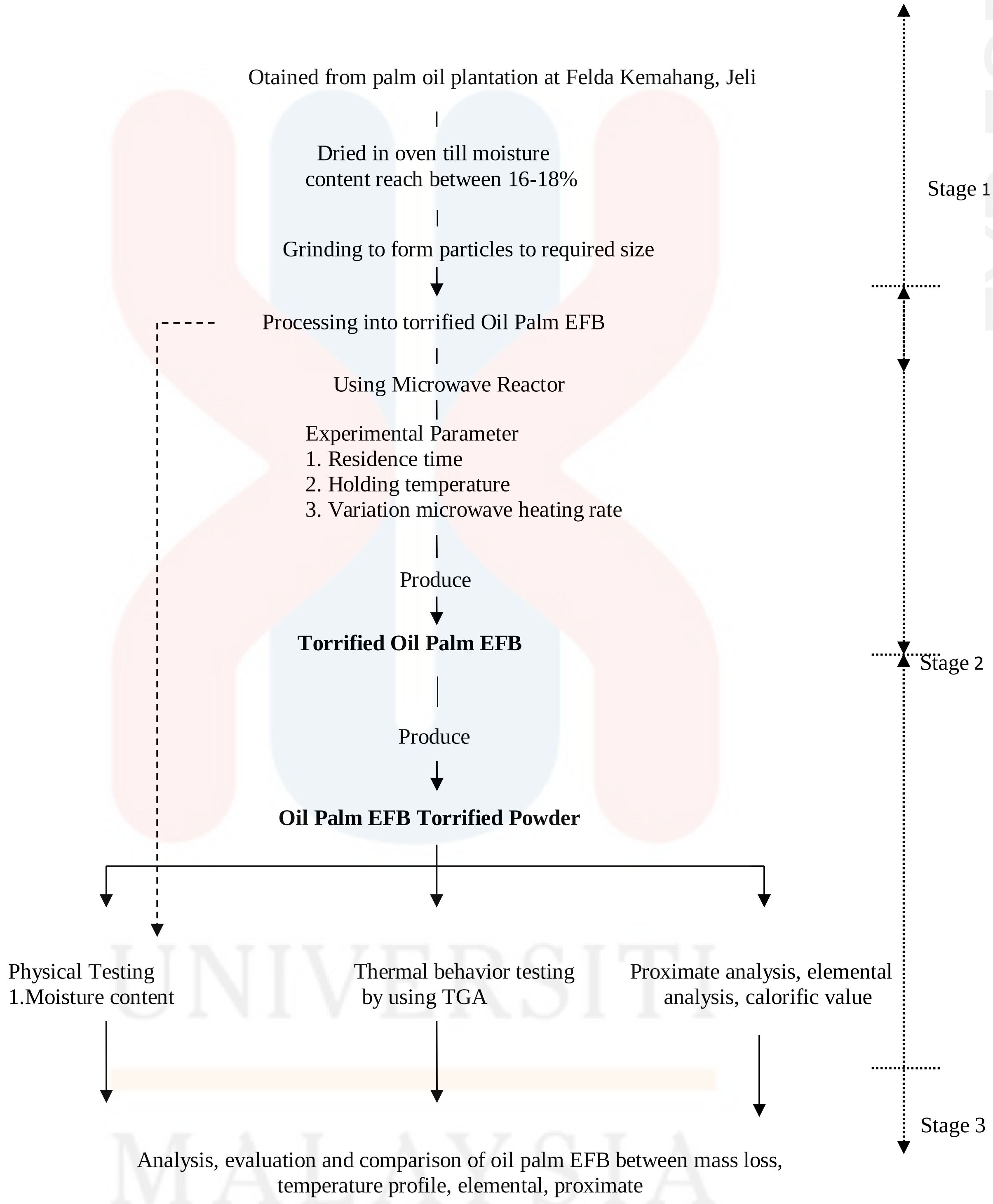


Figure 3.6: Bomb calorimeter, Leco brand, AC 500 series

Flow chart of Research Activities



Note:

Stage 1: Material preparation (Process takes place including collecting, crunching, drying followed by experimental setup for microwave reactor)

Stage 2: Processing the oil palm EFB in microwave reactor with variable parameter such as temperature, holding time and heating rate.

Stage 3: Processing the torrified empty fruit bunch and conduct several testing.

Stage 4: Analysis, evaluation and comparison of the obtained experimental data

Figure 3.7: Flow chart of research activities

CHAPTER 4

RESULTS AND DISCUSSION

4.0 Result overview

Basically, the study was about the identification of physical and thermal behaviour of raw and torrefied empty fruit bunch (EFB). The chosen mass of the sample was 500 microns. The power consumption to undergo torrefaction process was 385 W. The holding time were 20, 40 and 60 minute. The selection temperature was between 200 °Cuntil 300 °C. For physical testing, the colour and moisture content of EFB was identified. The colour of EFB turned darker when the temperature increased. For moisture content, the value obtained was 9.7%. For thermal behaviour analysis, the instrument used were TGA, bomb calorimeter and CHNOS analyser. TGA gave the proximate analysis of the EFB. The graph trend for moisture content and volatile matter were decreased with increasing time and temperature. While for the fixed carbon and ash content, the graph trend was increased. Calorific value that was tested by using bomb calorimeter, the low heating value (LHV) value was obtained. The lowest calorific value was for raw EFB with 15.8 MJ/kg while the highest was for torrefied EFB at 300 °Cfor 60 minutes with 26.5377 MK/kg. Lastly, for CHNOS analyser, the elemental analysis that was being tested were increased in this study. Enthalpy of C, H and O showed different trend. For C and O, there were an increasing trend while for H, the trend was decreased.

4.1 Moisture content

The moisture content test had been undergoing to identify the percentage value of moisture content of the sample. From the calculation above, it can be concluded that the EFB which allowed to be sundried before put inside the furnace to dry is more efficient to get the required moisture content which is suitable to be used in torrefaction process. The value of moisture content of the EFB was 9.7%. This value could be accepted since the range value for the best torrefaction is below than 10%. The moisture content value in materials is suitable for commercial purpose with 10% moisture content (Hasibuan & Daud, 2004). The higher value of moisture content will prolong the time taken for the torrefaction process. The sample will not torrefied properly due to the condition of the sample. The mass obtained for the sample will not as much since the sample was not fully dried.

Calculation for moisture content are as follow:

Data collection; weight of original and dried EFB is 10g and 9.03g respectively.

$$\textbf{MC of EFB (\%)} = \frac{10g - 9.03g}{10g} \times 100 \quad = 9.7\%$$

4.2 Effects of heating rate towards microwave power selection

Below are the data for thermal expansion for alumina crucible. When the power value of 100 W, 230 W, and 385 W was used, the alumina did not crack due to the thermal expansion not exceed the supposed value. But, for 385 W, the crucible could be cracked due to repeated heating.

Table 4.2: Heating rate and thermal expansion of alumina crucible for different power

Power (watt)	Heating rate (°C/min)	Thermal Expansion(K^{-1})	Condition
100	2.86	6.94×10^{-6}	Not crack
230	4.54	7.34×10^{-6}	Not crack
385	20.90	7.74×10^{-6}	Not crack
540	29.00	27.8×10^{-6}	*Crack
700	41.60	37.7×10^{-6}	*Crack

*Note $7.0-8.0\times 10^{-6}$ K^{-1} was the maximum value of thermal expansion alumina to retain the cracking issue. (cited)

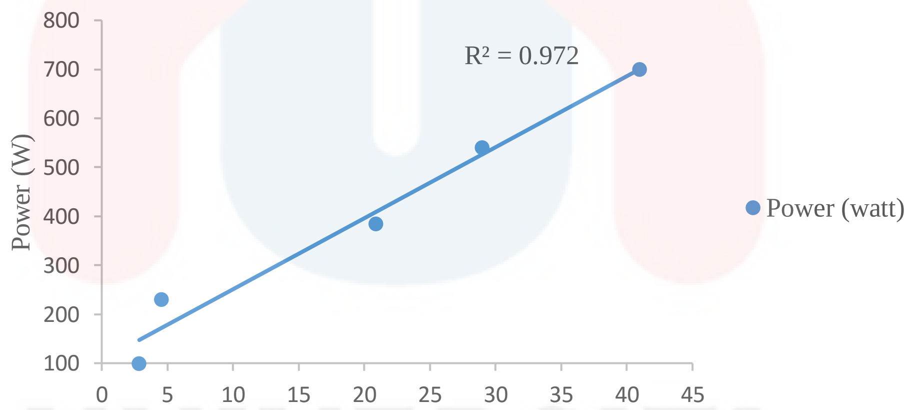


Figure 1: Heating rate (°C/min) value due to microwave power selection (W)

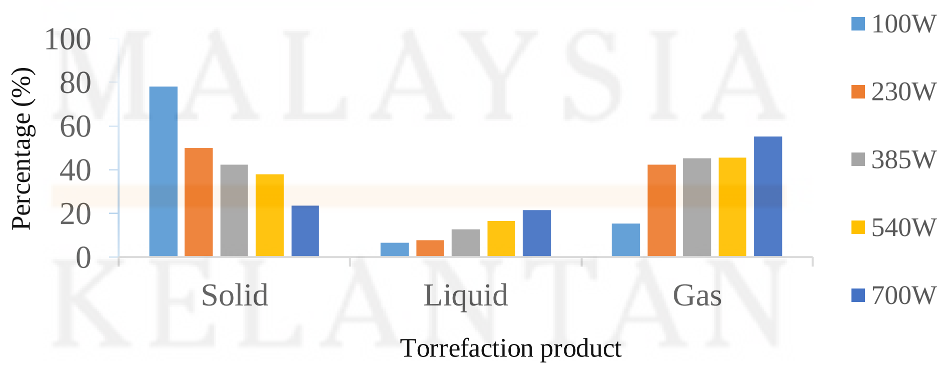


Figure 2: percentage of fractional mass

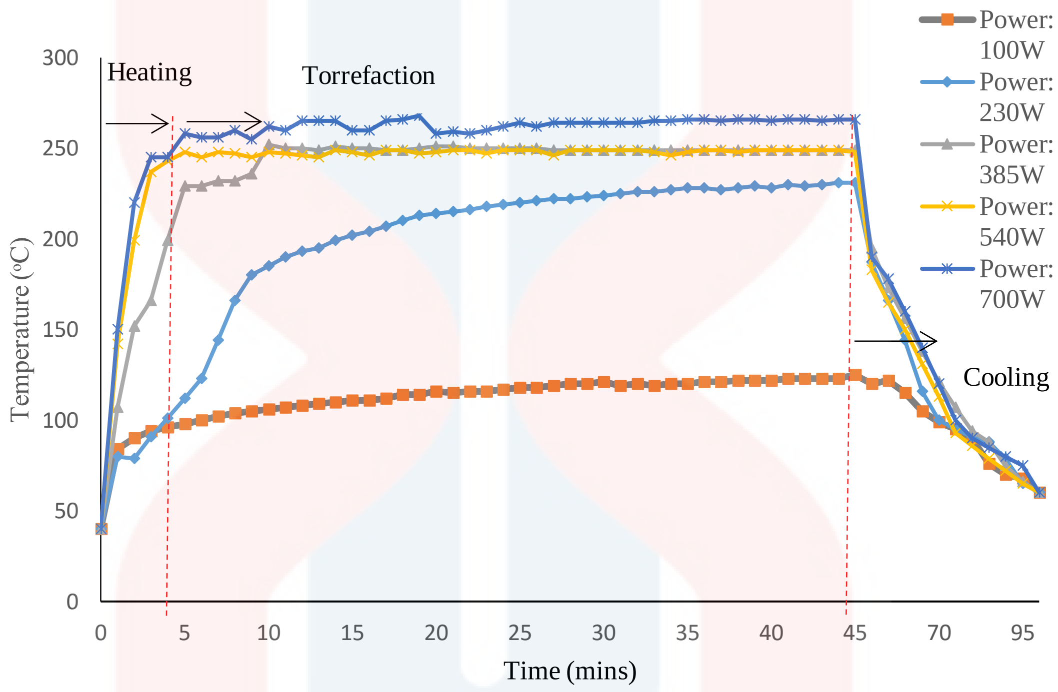
The figure 1 above shows the heating rate of the sample sized of 500 microns. The power used influenced the final percentage of the solid, liquid and gas. The value of 100 W until 700 W was reflecting to the heating rate used in this study. In this study, we need to identified which value of power reached the desired temperature of 250°C. The desired temperature was chosen according to torrefaction range which were from 200°C– 300°C.

The first power used to run the sample was 385 W. The heating rate for the sample that run at 385 W produce heating rate at 20.90°C/min. It shows that this power selection was good in order to reached desired temperature. This heating rate was suitable because it showed that there was a less expansion inside the crucible to reduce the thermal shock of the crucible which was made from alumina. The alumina crucible able to retain their strength when thermal shock at 14.51 MPa, maximum temperature 500°C and the maximum thermal expansion of alumina crucible was 7.2 x $10^{-6}K^{-1}$ (Kuscer, Bantan, & Hrovat, 2016). As figured in table 4.2, when used 100 W-300 W, the thermal expansion did not exceed the range for accepted thermal expansion. While for 540 W and 700 W, the value exceeded the thermal expansion range and caused crack.

For 540 W and 700 W, the power used was not suitable for the EFB since the end fibre would produce more ash. Ash content and ash-forming elements produced in the temperature range of 150°C – 500°C (Saleh, 2013). When this kind of power was used, ash will produce in large amount. Besides, the high value of heating rate had cause the huge amount of mass loss of the sample. The important thing that need to be considered in this study was the weight loss after the torrefaction process that can be referred in figure 2 chapter 4. The larger amount of mass retained left after the process showed good choice of power consumption. Reaction temperatures of 100°C and 250

°C provided weight loss of around 10 and 50%, respectively (Y. F. Huang, Chen, Chiueh, Kuan, & Lo, 2012).

4.3 Temperature profile



Graph 4.3: Torrefaction temperature against time

The above graph shows the temperature profile of the torrefaction process with different power value. For 100 W, the sample reached 107°C at minutes of 2 and started constant unti1 minute of 45. The power value did not reach the desired temperature at all. This was not suitable as the heating rate will be smaller. For 230 W, the temperature increased. This value of power will not also be accepted since it did not reach the desired temperature. The highest temperature that it could be reach was at 195°C which at that moment was at minute of 45.

This setting temperature was just to dried up the sample. In addition, based on the graph above, it can be concluded that at the heating rate of 20.90°C/min, it could be concluded that the suitable power selection for torrefaction process to occur was at

385 W. This was because when time reach at 5 minutes, the temperature of the sample had already reached 249°C compared to other sample which took longer time. This was important due to determination of heating rate that need to be considerate to choose the best optimum selection to proceed with response surface method (RSM).

For the power of 540 W, the temperature started to reach 250°C at the minute of 15 and started to maintain its temperature. This value of power could not be chosen as selection since the heating rate was low. This was because the time taken for the temperature to reach desired temperature was longer. It could be defined that the process of torrefaction started to happen was slow. Lastly, for power of 700 W, the temperature mostly exceeds desired temperature. The temperature nearly reached 250°C, but after that it fluctuated more than 250°C. This value cannot be used since the sample will torrefied at high temperature and would produce more ash content than fixed carbon.

4.4 Magnetron study

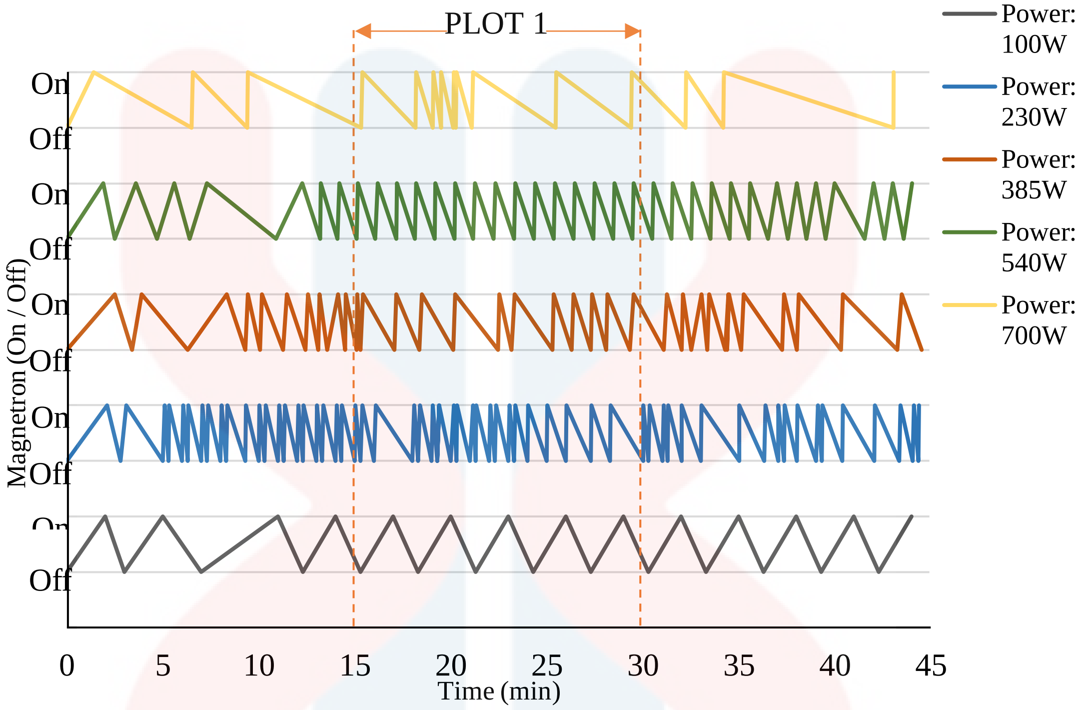


Figure 4.4: magnetron against time

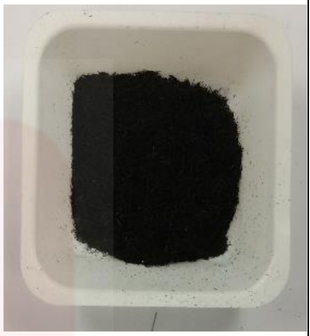
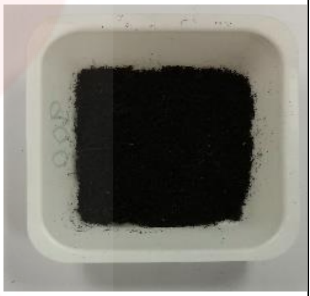
Based on magnetron graph in figure 4.4 above, it shows that how frequent electron was being released when the torrefaction process was on going. The time taken for the releasing of electron was taken starting from the first 5 minutes. For 100 W of power used, there was a huge gap between the peak. This shows that electron was not being released frequently when the process of torrefaction happened due to the low power consumption used.

As for 230 W, the electron released was not consistent with a huge gap at the minutes of 15, but after that the magnetron became frequent. This showed that the electron was not released consistently. For 385 W and 540 W, the peak started to frequent and there was not so much gap during the interval minute. Thus, the heating rate for 385 W and 540 W had no so much different due to the less gap between the peak of the magnetron.

4.5 Appearance of torrefied Empty Fruit Bunch (EFB)

Table 4.5: Table of raw and torrefied EFB (500 microns)

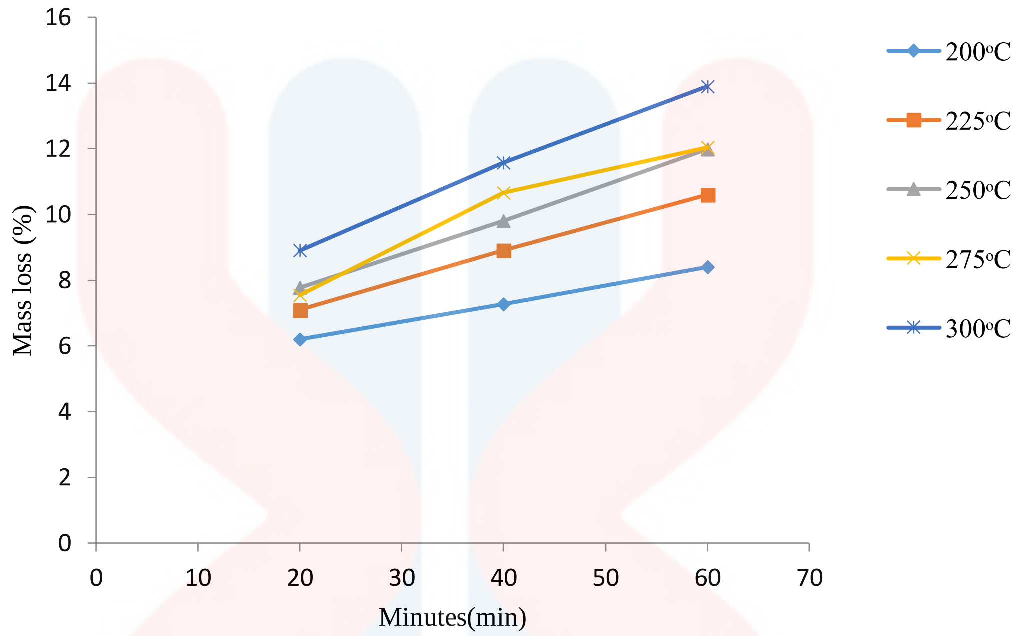
Holding time	20 minutes	40 minutes	60 minutes
Temperature			
Raw			
200 °C			
225 °C			
250 °C			

275 °C			
300 °C			

In this study, all of EFB sample were torrefied. From the table 4.1, there were a comparison between raw and torrefied sample. The colour of the EFB had changed from lighter colour to darker. The EFB which was torrefied at temperature of 300°C for 60 minutes exhibited almost darker colour. The progressive change in colour EFB is primarily due to the feedstock devolatization and increase in carbon content with increasing temperature during torrefaction (Bevan, Ahmad, Johari, Amran, & Abdullah, 2015).

Besides, there were a reduction of mass occurred from the sample. This is because, it could be seen from the observation that there was shrinkage of solid happen. The mass loss of the sample occurred due to the increasing temperature used to torrefied the sample. Even though torrefied biomass retains the shape and dimensions of raw biomass, it has a lower bulk density due to devolatilization and drying (Medic, 2012) Previous reports observed a similar trend. The mass retained also decreased with increasing oxygen concentration.

4.6 Mass loss of EFB



4.6: Graph of percentage of mass loss against temperature

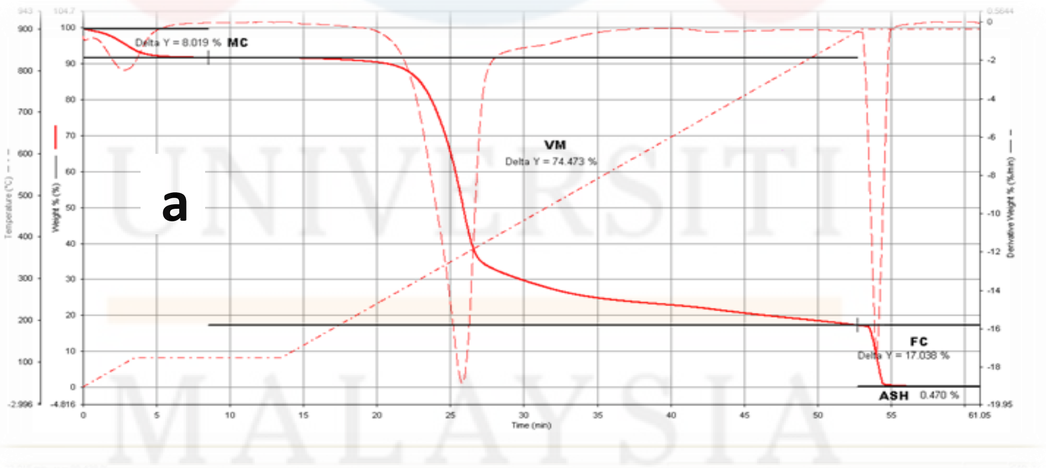
Based on graph 4.6 above, the graph was about the percentage of mass loss and temperature. The characteristics of the mass loss during the torrefaction process are in agreement with results of other studies for different type of biomass (Sabil et al., 2013). The graph showed that when temperature increased, the percentage of mass loss increased. For 200°C, the percentage of mass loss increased from 6.2% until 8.4% with the increasing time. This was maybe due to low temperature being applied towards the sample. The samples were not fully torrefied, thus the percentage of mass loss was less. But, for 300°C, the graph showed that the percentage of mass loss increased from 8.9% up to 13.9%. This was due to the duration time of torrefaction that was longer and also the increasing temperature used for the sample. Thus, from this affect, there were a shrinkage of solid or the EFB fibre that influenced the percentage of mass loss of the sample. The mass reduction occurred between the solid.

It is caused by degradation of the chemical components of wood, especially hemicelluloses which are the components most sensitive to thermal degradation, and produces volatiles (Almeida, Brito, & Perré, 2010).

4.7 Effects of torrefaction towards thermal behaviour of EFB

a) Thermal Gravimetric Analysis

TGA used to observe the mass loss during torrefaction process. It was observed that TGA analyses for all samples shown two significant regions of mass loss which corresponded to moisture loss during the first holding temperature of 100 °Cand followed by subsequent volatile release during the second holding temperatures for torrefaction (Daud, Rahman, & Shamsuddin, 2013). In this study, TGA measured the amount of moisture content (MC), volatile matter (VM), ash content (AC) and fixed carbon (FC) simultaneously of empty fruit bunch (EFB). These three aspects are the important components in observing the thermal behaviour of the EFB.



Every peak of the graph indicates the state of the sample. The first stage is mainly due to the dehydration process where the remaining moisture. The moisture may be absorbed from the atmospheric condition during storage (Sabil et al., 2013). Based on the above figure, as temperature furnace increase, the EFB degraded. The temperature range was associated with the decomposition of EFB component. For raw EFB, when temperature was at 900°C, the percentage of moisture content was 8.019 %.

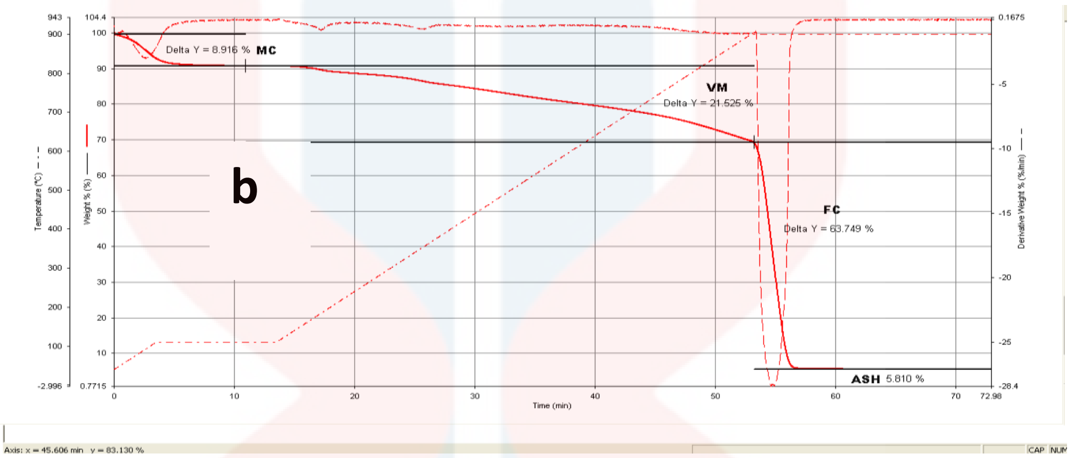


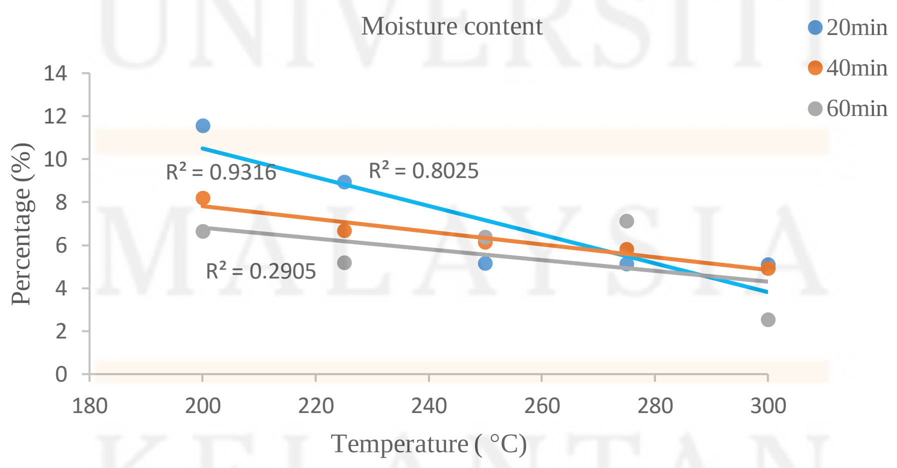
Figure 4.7: Thermal behaviour of a) raw EFB, b) torrefied EFB

During torrefaction process, the EFB loses its moisture content. The moisture content of EFB is the quantity of water inside the sample which also referred to the percentage of the sample's weight. As for percentage of volatile matter (VM), it was referred to the component of coal which the moisture that obtained when reached high temperature without the presence of air. During each torrefaction experiment, collection of volatile substances generated from the reactor was attempted by an iced trap (Uemura et al.,). The VM for raw RFB was 74.473%. This percentage value was high because this was for untreated EFB. For fixed carbon (FC), the percentage value was 17.038%. Lastly, for ash content, the percentage amount was 0.470%. Ash varies in different forms of biomass. The ash content in biomass will give a significant effect on biomass energy conversion such as in the pyrolysis process (Abdullah & Sulaiman, 2013). Ash content which was a mineral that was produced by the burning process for untreated EFB.

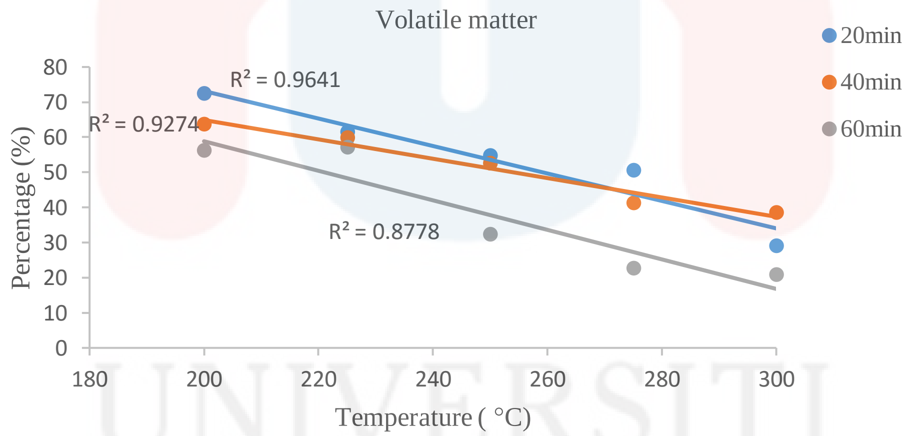
Based on figure 4.7 above, it was a graph of torrefied EFB. This graph indicates for the EFB that was being torrefied for 300°C for 60 minutes. Each peak pf the graph shows the proximate analysis of the EFB. The proximate analysis that was being analysed for this study was moisture content, volatile matter, fixed carbon and also ash content. The pattern of the graph was quite same like raw EFB, but the difference was due to the torrefaction process.

b) Proximate Analysis

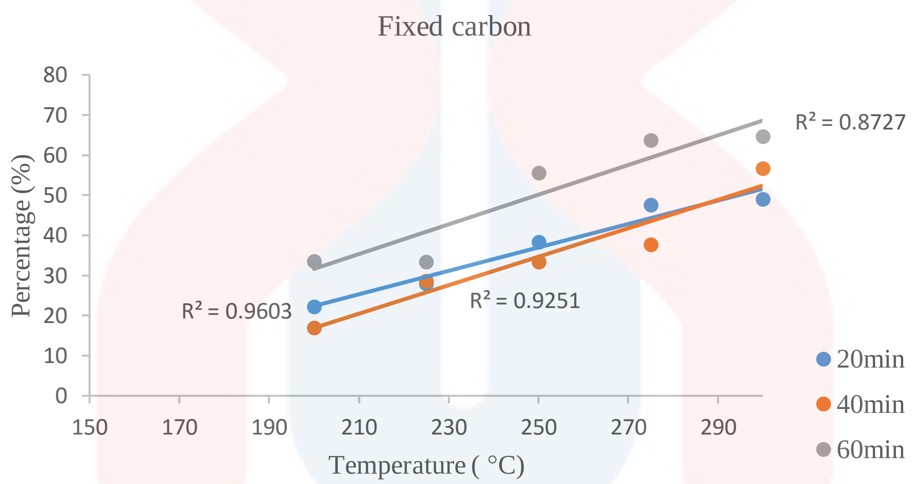
Based on the percentage of moisture content below, there was a high value of moisture content (MC) at temperature of 250°C for 60 minutes. The value was 11.258% compared to the lowest value was when temperature of 200°C. During the first stage, all three cases shown an average of 96.64% of all moisture was lost when compared to the initial moisture from the proximate analysis results. It can be assumed that the samples were fully dried during this stage as mass loss stop occurring within the 30 minutes holding period. The very small difference observed could be due to the samples had actually dried very slightly while in storage (Daud et al., 2013)



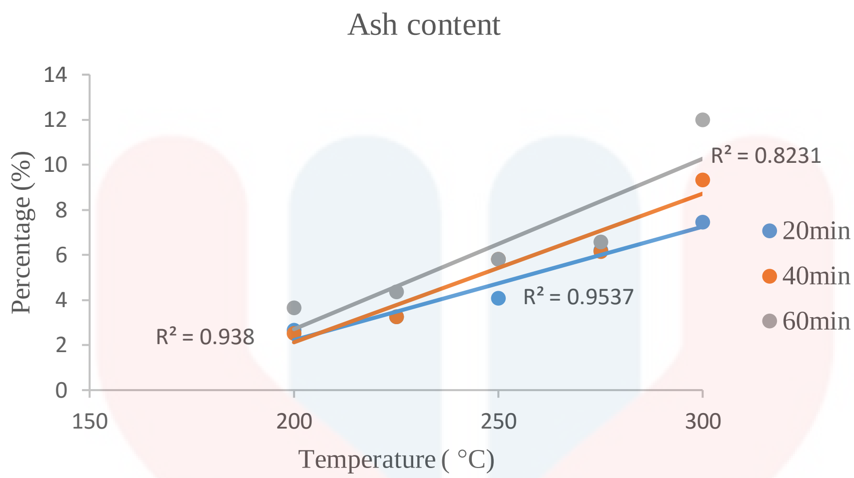
Besides, for the percentage of volatile matter (VM) against temperature below, VM was obtained when there was no moisture and ash content inside the sample. This volatile matter is constituted of about one third of gas mostly carbon monoxide and carbon dioxide (Nocquet et al., 2014). For 20 minutes, the percentage of VM was fluctuated. The higher content of VM was at temperature of 250 °C which the value for 40 minutes was 74.507%. The volatile matter content was > 70 % which is comparable with the findings of Lahijani and Zainal [4] and Mohammed et al. [6] for EFB (Nyakuma, Johari, Ahmad, & Abdullah, 2014). For 40 minutes, the lower percentage was when the temperature reached at 225 °C. Both of percentage of VM was higher at temperature of 250 °C at 20 and 40 minutes.



For percentage of fixed carbon, the solid carbon found in char obtained after the devolatization or pyrolysis of biomass. It is not a static property of biomass fuels since the conversion of volatile matter (VM) in biomass into char is largely dependent on the heating rate (Nyakuma et al., 2014). Based on the percentage value above, fixed carbon (FC) was higher for the temperature of 275°C and 300°C for 60 minutes. This was due to the torrefaction process towards the sample. The torrefaction process would also increase fix char and decrease volatile matter content, because of devolatilisation (Suwono, Hardianto, P, & Bandung, 2008). The presence of the oxygen gives more combust air towards the sample. Thus, the carbon content was higher caused from the torrefaction reaction. Since all the oil palm biomass were considered as high fixed carbon and volatile matter content, low ash and moisture content, they were suitable feed for torrefaction. (Aziz et al., 2011).



Lastly, based on percentage of ash content below, the graph indicates the fractional loss of ash content for torrefied EFB as a function of temperature. The ash content in biomass will give a significant effect on biomass energy conversion such as in the pyrolysis process. The high ash content in biomass promotes secondary reaction of the thermochemical process, thus producing non-homogenous liquids (Abdullah & Sulaiman, 2013). Ash content is not measured but average values are taken in order to not over-evaluate the oxygen content, calculated by difference (Doassans-carrère, Muller, & Mitzkat, 2014). In this study, the higher percentage loss of ash was at minute of 60 for temperature of 250 °C while the lower percentage was at the minute of 20.



4.8 Calorific value of EFB

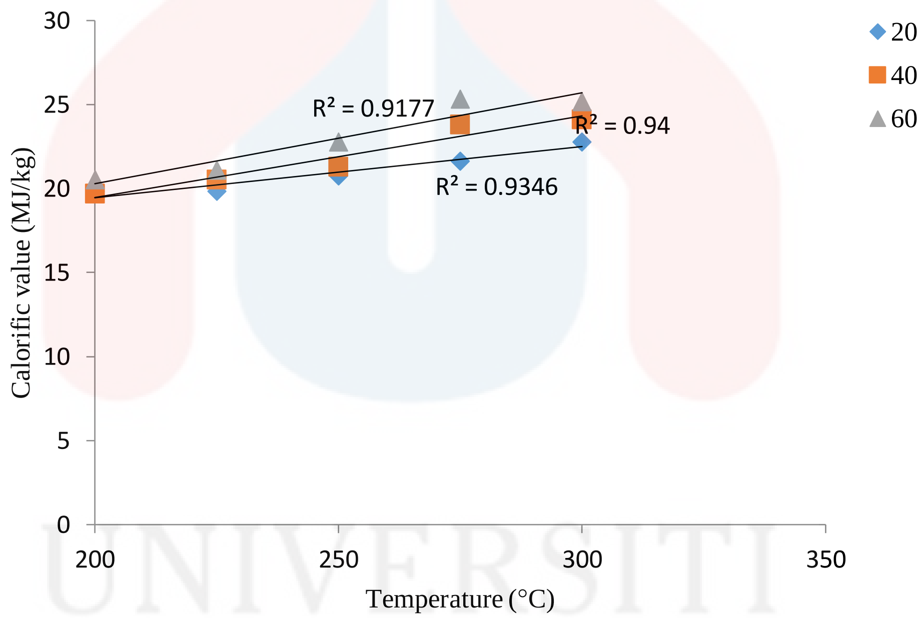


Figure 4.8: calorific value against temperature

Based on the figure above, calorific value was being measured by using bomb calorimeter. For raw EFB, the value was 15.8 MJ/kg because there was no torrefaction process occurred. The highest value for torrefied EFB was at 300 °C for 60 minutes which was 26.5337 MJ/kg. The calorific value obtained from the bomb calorimeter was the low heat value (LHV) because amount of heat released initially at 25 °C. The net calorific value changed between the range of 15.8 MJ/kg until 26.5337 MJ/kg. The study reveals that carbon mass fraction and gross calorific value increase with the increase of torrefaction temperature but the O/C ratio, hydrogen and oxygen mass fractions decrease for all biomass (Sabil et al., 2013). The higher torrefaction temperatures resulted in higher calorific values of the torrefied biomass (Yaacob, Rahman, Matali, Idris, & Alias, 2016). The torrefied solid had lower moisture and O/C ratio with higher carbon mass fraction and calorific value compared to the raw biomass.

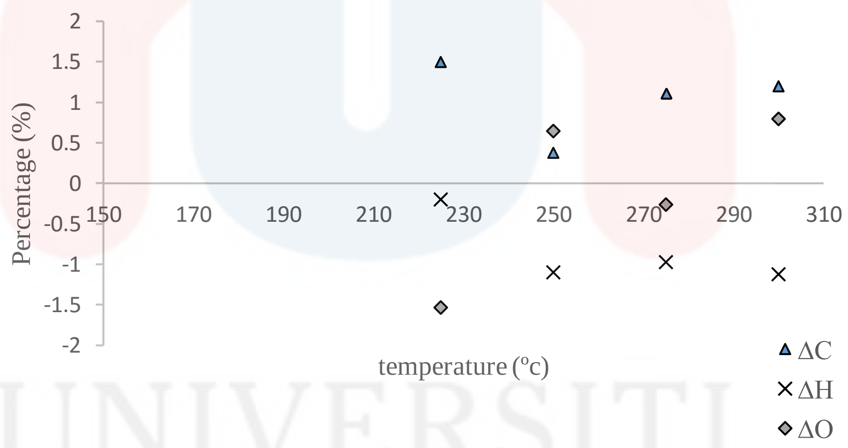
4.9 Effect of torrefaction towards elemental analysis

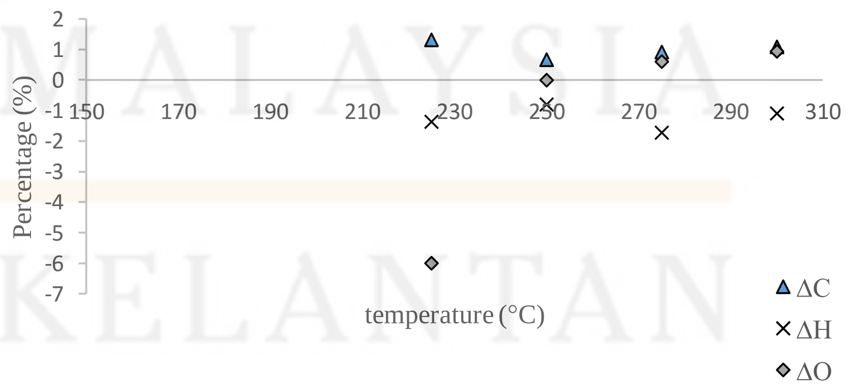
a) CHNS Analyser

Time (min)	T(°C)	%C	ΔC	%H	ΔH	%N	% O	ΔO	%S
raw		32.65	-	12.3	-	0.26	53.75		1.04
20	200	41.35		7.17		0.4	50.38		0.7
	225	42.85	**1.5**	6.97	-0.2	0.62	48.85	-1.53	0.71
	250	43.23	**0.38**	5.87	-1.1	0.75	49.5	0.65	0.65
	275	44.34	**1.11**	4.9	-0.97	0.86	49.24	-0.26	0.66
	300	45.54	**1.2**	3.78	-1.12	1.24	50.04	0.8	0.4
40	200	46.23		7.9		0.48	45		0.39
	225	47.56	**1.33**	6.54	-1.36	0.64	44.94	-0.06	0.32
	250	48.23	**0.67**	5.75	-0.79	0.71	44.95	0.01	0.36
	275	49.15	**0.92**	4.03	-1.72	0.87	45.55	0.6	0.4
	300	50.25	**1.1**	2.94	-1.09	1.02	46.50	0.95	0.3
60	200	50.9		7.85		0.79	37.97		0.49
	225	51.08	**0.18**	6.72	-1.13	0.75	38.96	0.99	0.49
	250	51.78	**0.7**	5.24	-1.48	0.66	39.89	-0.07	0.43
	275	52.06	**0.28**	4.31	-0.93	0.97	40.24	0.35	0.42
	300	52.67	**0.61**	3.63	-0.68	1.05	41.20	0.96	0.45

Table 4.9: Results of CHNOS analyser

The main composer elements of biomass and other solid fuels are carbon (C), hydrogen (H) and oxygen (O). While nitrogen (N), sulphur (S) and minerals (ash) are possibly found in small amount. C, H and S have positive impact on the heating value, while O, N and ash content decreases the heating value (Suwono et al., 2008). Based on figure 4.4 above, it was the percentage value of C, H, N, O and S inside the EFB. For percentage of carbon, the graph showed an increasing trend with the increasing of temperature. While for hydrogen content, the graph showed the decreased trend. This decrease in hydrogen and oxygen was due to dehydration and de-carbon dioxide from the biomass during the torrefaction (Uemura et al., 2011).





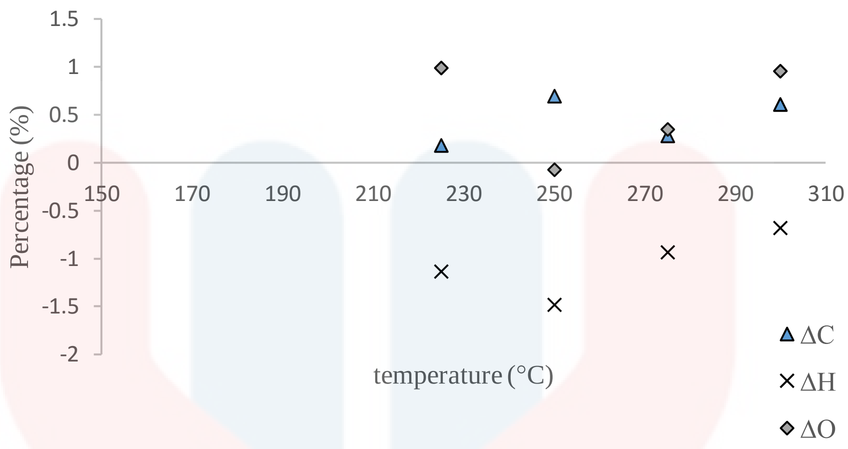


Figure 4.9: Difference of C, H, and O

The results for elemental analysis for torrefied EFB was listed as above figure. To discuss more specifically, the CHO contents and the difference were plotted as above. For 20, 40 and 60 minutes, the graph showed decreasing and increasing trend when tested with CHNOS analyser. The percentage of C increased with the increasing of time and temperature. From figure 4.9. it was found that the increasing of carbon and oxygen content also influenced the value of LHV.

Besides, the difference of hydrogen was also decrease until -1.48 for 60 minutes. The hydrogen decreased when the temperature increased. This decrease in hydrogen and oxygen is due to dehydration and de-carbon dioxide from the bio- mass during the torrefaction. The decreasing tendency observed for EFB in this study, therefore, may be attributed to the inhomogeneity of the biomass (Uemura et al., 2011). Since all part of the oil palm biomass were considered as high carbon content and low sulphur and nitrogen content, they were suitable feed for torrefaction (Aziz et al., 2011).

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

Conclusion

In this study, the torrefaction of empty fruit bunch (EFB) that was carried out with the presence of oxygen to identified the effects of torrefaction towards the thermal behaviour of EFB. The effect of torrefaction were influenced by several parameters which were residence time, holding temperature, power consumption and size of sample. The effect of torrefaction gave the different percentage value towards proximate analysis. The proximate analysis that were being analysed were moisture content (MC), fixed carbon (FC), volatile matter (VM) and also ash content. The trend of graph showed that MC and VM decreased while FC and Ash increased with the increasing of temperature.

The elemental analysis also showed an increase trend of graph in carbon, and oxygen content when temperature up to 300 °C. The CHNOS analyser showed the value of element inside the sample. The value of C and O increase with the increasing of time and temperature while the O content decrease. The calorific value for raw EFB was at 15.8 MJ/kg and 26.5337 MJ/kg for torrefied EFB.

Thus, the product from microwave torrefaction process could be used as energy production for industry that could be used as to decrease the emission of net power plant.

Recommendations

There are few recommendations for the further improvement of microwave torrefaction process.

i. The usage of instrument to identified moisture content to get accurate value

ii. The type of materials uses for crucible to withstand high temperature even when the process of torrefaction repeated.
iii. Torrefaction process need to be done in convenient surrounding to avoid any error during sample preparation.
iv. Exploration of heating rate by changing the temperature controller to heating rate controller.

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APPENDIX A

APPENDIX – A

Data for heating rate

Power (watt)	Heating rate (°C/min)
100	2.86
230	4.54
385	20.90
540	29.00
700	41.00

Data for temperature against time

Power: 100W		Power: 230W		Power: 385W		Power: 540W		Power: 700W	
Time (min)	T (°C)	Time (min)	T (°C)	Time (min)	T (°C)	Time (min)	T (°C)	Time (min)	T (°C)
0	40	0	40	0	40	0	40	0	40
1	84	1	80	1	107	1	142	1	150
2	90	2	79	2	152	2	199	2	220
3	94	3	91	3	166	3	237	3	245
4	96	4	101	4	199	4	243	4	245
5	98	5	112	5	229	5	248	5	258
6	100	6	123	6	229	6	245	6	256
7	102	7	144	7	232	7	248	7	256
8	104	8	166	8	232	8	247	8	260
9	105	9	180	9	236	9	245	9	255
10	106	10	185	10	252	10	248	10	262
11	107	11	190	11	250	11	247	11	260
12	108	12	193	12	250	12	246	12	265
13	109	13	195	13	249	13	245	13	265
14	110	14	199	14	251	14	249	14	265
15	111	15	202	15	250	15	248	15	260
16	111	16	204	16	250	16	246	16	260
17	112	17	207	17	249	17	249	17	265
18	114	18	210	18	249	18	249	18	266
19	114	19	213	19	250	19	247	19	268
20	116	20	214	20	251	20	248	20	258
21	115	21	215	21	251	21	249	21	259
22	116	22	216	22	250	22	249	22	258
23	116	23	218	23	250	23	247	23	260
24	117	24	219	24	250	24	249	24	262
25	118	25	220	25	250	25	249	25	264

26	118	26	221	26	250	26	249	26	262
27	119	27	222	27	249	27	246	27	264
28	120	28	222	28	249	28	249	28	264
29	120	29	223	29	249	29	249	29	264
30	121	30	224	30	249	30	249	30	264
31	119	31	225	31	249	31	249	31	264
32	120	32	226	32	249	32	249	32	264
33	119	33	226	33	249	33	248	33	265
34	120	34	227	34	249	34	246	34	265
35	120	35	228	35	249	35	248	35	266
36	121	36	228	36	249	36	249	36	266
37	121	37	227	37	249	37	249	37	265
38	122	38	228	38	249	38	248	38	266
39	122	39	229	39	249	39	249	39	266
40	122	40	228	40	249	40	249	40	265
41	123	41	230	41	249	41	249	41	266
42	123	42	229	42	249	42	249	42	266
43	123	43	230	43	249	43	249	43	265
44	123	44	231	44	249	44	249	44	266
45	125	45	231	45	249	45	248	45	266
50	120	50	187	50	195	50	183	50	190
55	122	55	166	55	173	55	165	55	178
60	115	60	144	60	156	60	150	60	160
65	105	65	116	65	138	65	131	65	140
70	99	70	100	70	121	70	113	70	120
75	95	75	95	75	107	75	93	75	100
80	90	80	91	80	94	80	86	80	90
85	76	85	88	85	88	85	79	85	85
90	70	90	79	90	75	90	72	90	80
95	68	95	65	95	66	95	65	95	75
100	60	100	60	100	60	100	60	100	60

Data for percentage mass loss

Time (min) / Temperature (°C)	20	40	60
200	6.200	7.271	8.4
225	7.1	8.9	10.60
250	7.771	9.8	11.99
275	7.544	10.67	12.0396
300	8.900	11.583	13.900

Data for moisture content (torrefied EFB)

Time (min)	Temperature (°C)	Percentage (%)

20	200	11.528
	225	8.916
	250	5.1445
	275	5.106
	300	5.082
40	200	8.186
	225	6.645
	250	6.124
	275	5.780
	300	4.91
60	200	6.632
	225	5.159
	250	6.362
	275	7.101
	300	2.526

Data for volatile matter (torrefied EFB)

Time (min)	Temperature (˚C)	Percentage (%)
20	200	63.605
	225	59.84
	250	52.5
	275	41.159
	300	38.489
40	200	72.4
	225	61.445
	250	54.66
	275	50.457
	300	29
60	200	56.168
	225	57.144
	250	32.345
	275	22.569
	300	20.88

Data for fixed carbon (torrefied EFB)

Time (min)	Temperature (˚C)	Percentage (%)
20	200	22.21
	225	27.978
	250	38.2795
	275	47.527
	300	48.953
40	200	16.881
	225	28.641
	250	33.401
	275	37.61
	300	56.754

60	200	38.54
	225	33.329
	250	55.483
	275	63.749
	300	64.582

Data for ash content (torrefied EFB)

Time (min)	Temperature (˚C)	Percentage (%)
20	200	2.657
	225	3.266
	250	4.076
	275	6.208
	300	7.476
40	200	2.533
	225	3.269
	250	5.815
	275	6.153
	300	9.336
60	200	3.66
	225	4.368
	250	5.81
	275	6.581
	300	12.012

Data for bomb calorimeter

Sample	Temperature/time	MJ/kg
Raw	40	15.8
Torrefied		
20min	200	19.8476
	225	19.8704
	250	20.7688
	275	21.6279
	300	22.7754
40min	200	19.6908
	225	20.554
	250	21.2928
	275	23.8019

	300	24.1407
60min	200	20.5585
	225	21.0945
	250	22.7889
	275	25.3377
	300	25.2028

Data for CHNS Analyser

Type of Samples	Weight (mg)	% C	% H	% N	%O	% S
Raw	2.208	32.65	12.30	0.26		1.04
20min/200°C	2.594	41.35	7.17	0.40	50.38	0.70
20min/225°C	2.152	42.85	6.97	0.62	48.85	0.71
20min/250°C	2.652	43.23	5.87	0.75	49.5	0.65
20min/275°C	2.565	44.34	4.9	0.86	49.24	0.66
20min/300°C	2.781	45.54	3.78	1.24	49.04	0.40
40min/200°C	2.306	46.23	7.9	0.48	45	0.39
40min/225°C	2.654	47.56	6.54	0.64	44.94	0.32
40min/250°C	2.678	48.23	5.75	0.71	44.95	0.36
40min/275°C	2.916	49.15	4.03	0.87	45.55	0.40
40min/300°C	2.815	50.25	1.93	1.02	46.5	0.30
60min/200°C	2.330	50.9	7.85	0.79	39.97	0.49
60min/225°C	2.200	51.08	6.72	0.75	40.96	0.49
60min/250°C	2.346	51.78	5.24	0.66	41.89	0.43
60min/275°C	2.597	52.06	4.31	0.97	42.24	0.42
60min/300°C	2.872	52.67	3.63	1.05	42.2	0.45

Difference in C, H and O

Time (min)	temperature (ºc)	% C	ΔC	% H	ΔH	% N	% O	ΔO	% S
20	200	41.35		7.17		0.4	50.38		0.7
	225	42.85	1.5	6.97	-0.2	0.62	48.85	-1.53	0.71
	250	43.23	0.38	5.87	-1.1	0.75	49.5	0.65	0.65
	275	44.34	1.11	4.9	-0.97	0.86	49.24	-0.26	0.66
	300	45.54	1.2	3.78	-1.12	1.24	50.04	0.8	0.4

Time (min)	temperature (ºc)	% C	ΔC	% H	ΔH	% N	% O	ΔO	% S

40	200	46.23		7.9		0.48	45		0.39
	225	47.56	1.33	6.54	-1.36	0.64	44.94	-6	0.32
	250	48.23	0.67	5.75	-0.79	0.71	44.95	0.01	0.36
	275	49.15	0.92	4.03	-1.72	0.87	45.55	0.6	0.4
	300	50.25	1.1	2.94	-1.09	1.02	46.5	0.95	0.3

Time (min)	temperature (°C)	% C	ΔC	% H	ΔH	% N	% O	ΔO	% S
60	200	50.9		7.85		0.79	37.97		0.49
	225	51.08	0.18	6.72	-1.13	0.75	38.96	0.99	0.49
	250	51.78	0.7	5.24	-1.48	0.66	39.89	-0.07	0.43
	275	52.06	0.28	4.31	-0.93	0.97	40.24	0.35	0.42
	300	52.67	0.61	3.63	-0.68	1.05	41.2	0.96	0.45

APPENDIX – B

(a)

(b)

Empty fruit bunch (EFB): a) raw bunch & b) grinded

c)

d)

c) sieve to 500 micron & d) ready sample