Torrefaction of Palm Kernel Shell Into Value-Added Solid Fuels

by

Mohd. Amin bin Aziz Jaafar

Dissertation submitted in partial fulfillment of
the requirement for the
Bachelor of Engineering (Hons)
(Chemical Engineering)

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Universiti Teknologi PETRONAS
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CERTIFICATION OF APPROVAL

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Approved by,

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(Dr. Murni Melati)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
May 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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MOHD. AMIN BIN AZIZ JAAFAR

ABSTRACT

The use of renewable energy sources is becoming increasingly necessary due to the impacts of global warming from fossil fuel usage. Wood and other forms of biomass including energy crops and agricultural and forestry wastes are some of the main renewable energy resources available to provide liquid, gaseous and solid fuels. However, several major weakness of biomass, limit its wider application in energy generation i.e. low heating value, high moisture content, hygroscopic nature, smoke during combustion, low energy density, and low combustion efficiency. Torrefaction can help to overcome the limitations of biomass to be a more efficient energy sources. Malaysia was the second largest producer of oil palm waste, and thus palm kernel shell (PKS) has been selected to be a biomass that will be used in this study because of its good availability which is about 4.5 million tonnage-wet/year. PKS has a good potential as a fuel because of its carbon neutrality, low moisture content and high calorific value. This project aims to investigate the fundamental of torrefaction to improve the properties of PKS as a solid fuel. A study towards torrefaction of PKS will be done under varying temperature and residence time of 240, 260, and 280^{o}C and 30, 60, and 90 minutes respectively. The changes of the torrefied PKS were characterized by the mass yield, energy yield, elemental composition analysis, calorific value analysis and proximate analysis. The mass and energy yield changes of torrefied PKS was shown to prove that the temperature has more effect compare to residence time in torrefaction. The C contents of torrefied PKS increase while H and O contents decrease, thus C:C bond proportion of the torrefied PKS increased which resulted in higher calorific value. The higher heating value (HHV) of torrefied PKS increased in the range of 5-16%. The ash and fixed carbon content of torrefied PKS increased, while the moisture and volatile matter decrease.

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Biomass is considered as a sustainable and renewable energy sources with the highest potential to contribute to the energy needs of modern society and to replace the existing conventional fuel which is subject to depletion as they are consumed. However, several weakness of biomass had limits its wider application in energy generation. On the other hand, torrefaction is a treatment process which serves to improve the properties of biomass in relation to the thermal conversion technologies for more efficient energy generation. This project entitled as "Torrefaction of Palm Kernel Shell into Value-Added Solid Fuels" will study on how to conduct torrefaction towards biomass, namely palm kernel shell which will upgrade its properties to be a better solid fuel.

1.1.1 Biomass as an alternative energy sources

In the context of biomass for energy this is often used to mean plant based material. Biomass is the plant material derived from the reaction between CO_2 in the air, water and sunlight, via photosynthesis, to produce carbohydrates that form the building blocks of biomass (Peter McKendry,2002). Man for millennia has exploited the energy stored in these chemical bonds, by burning biomass as a fuel. Burning new biomass contributes no new carbon dioxide to the atmosphere, because replanting harvested biomass ensures that CO_2 is absorbed and returned for a cycle of new growth.

1.1.2 Torrefaction

Torrefaction is a thermochemical treatment method that is maintained by an operating temperature ranging from 200-300°C. It is carried out at under atmospheric pressure and in the absence of oxygen and in the flow of nitrogen gas. The process is characterized by low particle heating rates and by relatively long residence time, typically 1-3 hours.

1.1.3 Palm kernel shell in Malaysia

In 2008, Malaysia was the second largest producer of oil palm waste with 17.7 million tonnes or 41% of the total world supply (Uemura et al., 2010). Palm kernel shell (PKS) is a part of oil palm waste produced by the oil palm industry. Because of its good availability in Malaysia, with the annual production of 4.5 million tonnage-wet/years (Yusup et al., 2009), PKS has been selected as a biomass sources in this study.

1.2 PROBLEM STATEMENT

As been mentioned in section 1.1, several weakness of biomass had limits its wider application in energy generation. These include low heating value, high moisture content, high alkali metal content, hygroscopic nature, degradation and self-heating, smoke during combustion, low energy density, low combustion efficiency and low grindability properties (Bergman et al., 2005; Bridgeman et al., 2008; Pimchuai et al., 2010). Biomass, being a high moisture fuel, consumes a considerable amount of energy during drying. Furthermore, the dried biomass again picks up moisture due to its hygroscopic (water-absorbing) nature that leads to biomass degradation and self-heating, thus raising complications in storage. Also, a high oxygen content of biomass does not make it an ideal fuel for gasification (thermochemical conversion technology) (A.V. Bridgwater, 2003). The size reduction of biomass to produce a powder that can be burned in a coal-fired power station has been identified to be problematic because of its low grindability properties (Bergman et al., 2005). Thus, a process called torrefaction can help to overcome the above limitations of biomass to be a more valuable solid fuels and preferred energy sources.

1.3 OBJECTIVES

- To perform characterization of Palm Kernel Shell potential as a solid fuel
- To perform torrefaction towards Palm Kernel Shell under different torrefaction conditions (i.e. temperature & residence time)
- To characterize the properties of torrefied Palm Kernel Shell and show the improvement of its properties as a solid fuel

1.4 SCOPE OF STUDY

- Study on the concept of biomass as an alternative energy sources and its importance towards modern society.
- Study on the characteristics and properties of palm kernel shell as a potential material to be selected as an energy sources in this country.
- Study on the concept and experimental procedure of torrefaction process.
- Study on the principle and parameters of torrefaction and possibility of applying the process to improve the properties of palm kernel shell.
- To conduct torrefaction process with different parameters towards palm kernel shell and investigating their properties respectively.

CHAPTER 2
LITERATURE REVIEW

2.1 BIOMASS PROPERTIES

Dependent on the energy conversion process selected, particular biomass properties become important during subsequent processing. According to Peter McKendry (2002), the main material properties of interest during subsequent processing as an energy sources relates to:

- Moisture content
- Calorific value
- Proportions of fixed carbon and volatile matter
- Ash content
- Elemental composition
- Cellulose/lignin ratio
- Alkali metal content
- Bulk density

2.1.1 Moisture content

Two forms of moisture content are of interest in biomass:

- Intrinsic moisture
  - The moisture content of the material without the influence of weather effects.
- Extrinsic moisture
  - The influence of prevailing weather conditions during harvesting on the overall biomass moisture content.

For thermochemical conversion technologies, low moisture content of biomass, typically below 50% is required (Peter McKendry, 2002). Thermochemical conversion technologies can also utilize biomass with high moisture content but the overall energy balance for the conversion process is adversely impacted.

2.1.2 Calorific value

The calorific value (CV) of a material is an expression of the energy content or heat value that was released when burnt in air. The CV of a fuel can be expressed in two forms, higher heating value (HHV) and lower heating value (LHV). HHV is the total energy content released when the fuel is burnt in air, including the latent heat contained in the water vapour and therefore represents the maximum amount of energy potentially recoverable from a given biomass source. While LHV is the total energy content released when the fuel is burnt in air, excluding the latent heat contained in the water vapour. Usually, when quoting a CV, the moisture content needs to be stated, as this reduces the available energy from the biomass.

2.1.3 Proportion of fixed carbon and volatile matter

Fuel analysis has been developed based on solid fuels such as coal, which consists of chemical energy stored in two forms, fixed carbon and volatile matter. The volatile content or volatile matter of a solid fuel is a portion of a driven-off as a gas (including moisture) by heating. The fixed carbon (FC) content is the mass remaining after the releases of volatiles, excluding the ash and moisture content. Dependent on the magnitude of the FC content, the available energy of the fuel is increase proportionately. Fuel analysis based upon the volatile matter, ash and moisture content, with the fixed carbon content determined by difference, is termed the proximate analysis of a fuel.

2.1.4 Ash content

Ash is a solid residue left after the combustion of biomass in air. The ash or solid residue content forms a standard measurement parameter for solid and liquid fuels. The ash content of biomass affects both the handling and processing costs of the overall biomass energy conversion cost (Peter McKendry, 2002). Dependent on the magnitude of the ash content, the available energy of the fuel is reduced proportionately. In a thermochemical conversion process, the chemical composition of the ash can present significant operational problems. This is especially true for combustion processes, where the ash can react to form a ‘slag’, a liquid phase formed at elevated temperatures, which can reduce plant throughput and result in increased operating costs.

2.1.5 Elemental composition

The determination of the elemental (C, H, N, S, and O) composition amount in a sample of biomass is termed the ultimate analysis of a fuel. The amount of C, H, N and S content is obtained from the analytical experiment. While the O content is calculated by subtraction (Yang et al., 2006) which follows the equation:

$$O(\%) = 100 - C(\%) - H(\%) - N(\%) - S(\%) - ash\ (dry)(\%)(1)$$

The significance of the carbon-oxygen (C:O) and carbon-hydrogen (C:H) ratios on the calorific value or heating value of solid fuels can be explained using a Van Krevelen diagram *(Figure 2.1).* Comparison of biofuels with fossil fuels such as coal shows clearly that the higher proportion of oxygen and hydrogen, compared with carbon, reduces the energy value of a fuel, due to the lower energy contained in C:O and C:O bonds, than in carbon–carbon (C:C) bonds (Peter McKendry, 2002).

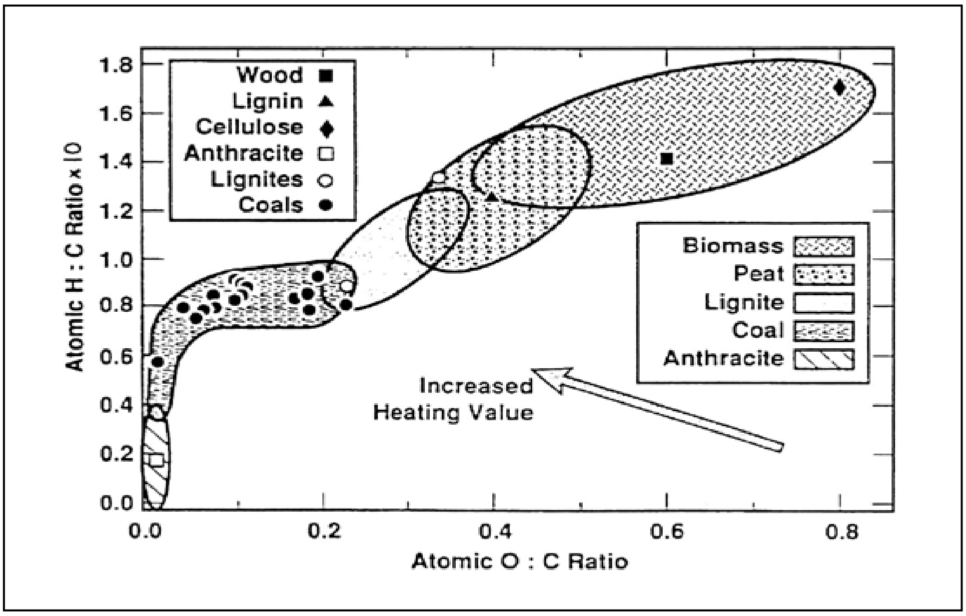

Figure 2.1: Van Krevelen diagram for various solid fuels

2.1.6 Cellulose/lignin ratio

Biomass contains varying amounts of cellulose, hemicellulose, lignin and a small amount of other extractives. Lignin, which binds together the cellulosic fibres, is an example of polysaccharides structure, which are the long-chain natural polymers contained in the biomass which are also the factor for its tenacious behaviour

(Bergman and Kiel, 2005). Cellulose is generally the largest fraction, representing about 40 to 50% of the biomass by weight while hemicelluloses portion represents 20 to 40% of the material by weight. The remaining fraction is predominately lignin with lesser amount of substances called extractives (Chen and Kuo, 2010). In general, the HHVs of lignocellulosic (biomass) fuels increase with increase of their lignin contents and the HHV is highly correlated with lignin content (A. Demirbas, 2001).

2.1.7 Alkali metal content

The alkali metal content of biomass (i.e. Na, K, Mg, P and Ca) is especially important for any thermochemical conversion processes. The reaction of alkali metals with silica present in the ash produces a sticky, mobile liquid phase, which can lead to blockages of airways in the furnace and boiler plant (A.V. Bridgewater, 2003). It should be noted that while the intrinsic silica content of a biomass source may be low, contamination with soil introduced during harvesting can increase the total silica content significantly, such that while the content of intrinsic silica in the material may not be a cause for concern, the increased total silica content may lead to operational difficulties (Peter McKendry, 2002).

2.1.8 Bulk density

The importance of bulk density or volume of biomass is in relation to transport and storage costs. The density of the process product impacts on fuel storage requirements, the sizing of the material handling system and how the material is likely to behave during subsequent thermochemical/biological processing as a fuel or feedstock.

2.2 WHAT HAPPEN DURING TORREFACTION

During the process, the biomass partly decomposes giving off various types of volatiles (Bergman et al., 2005). The final product is the remaining solid, which is often referred to as torrefied biomass or char. Figure 2.2 provides a typical mass and energy balances of torrefaction. Typically, 70% of the mass is retained as a solid product, containing 90% of the initial energy content. 30% of the mass is converted into torrefaction gases, but containing only 10% of the energy content of the biomass.

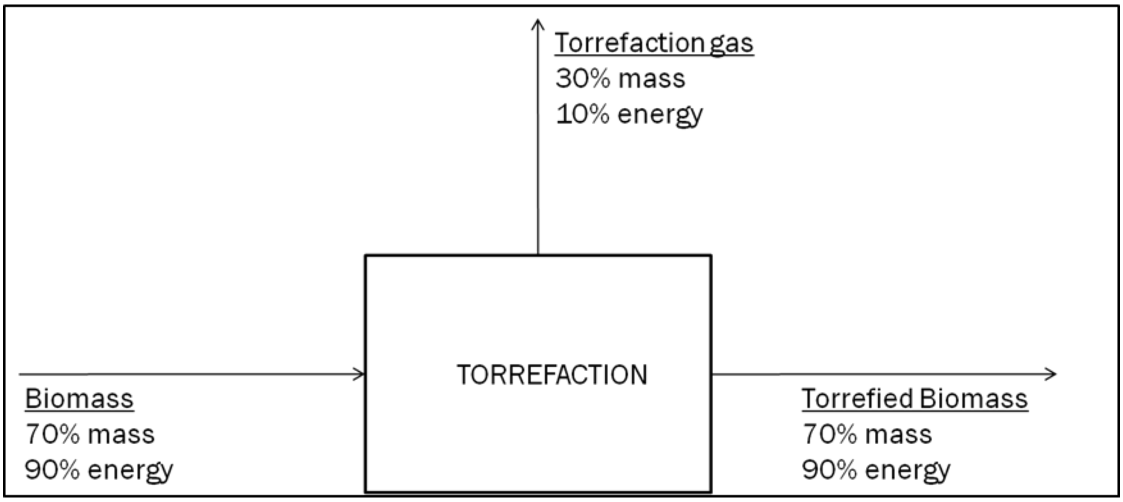

Figure 2.2: Typical mass and energy balance of torrefaction process.

According to Bergman et al. (2005), biomass is completely dried during torrefaction and after torrefaction the uptake of moisture is very limited. Depending on the torrefaction conditions this varies from 1-6% wt. The main explanation for this is that by the destruction of many OH groups in the biomass through dehydration reactions, torrefied biomass has lost the capability to form hydrogen bonds with water. In addition, more unsaturated structures are formed which are non-polar and hence it has become hydrophobic to a certain extend. It is likely that this property is also the main reason that torrefied biomass is practically preserved and rotting, which is often observed for untreated biomass, does not occur anymore.

2.2.1 Torrefaction decomposition mechanisms

Biomass consists of three main polymeric structures, which are cellulose, hemicellulose and lignin. During torrefaction numerous reactions occur and different reaction pathways can be defined. All these reaction pathways can be grouped to a few main reaction regimes, where similar decomposition regimes can be defined for each polymer, as shown in Figure 2.3.

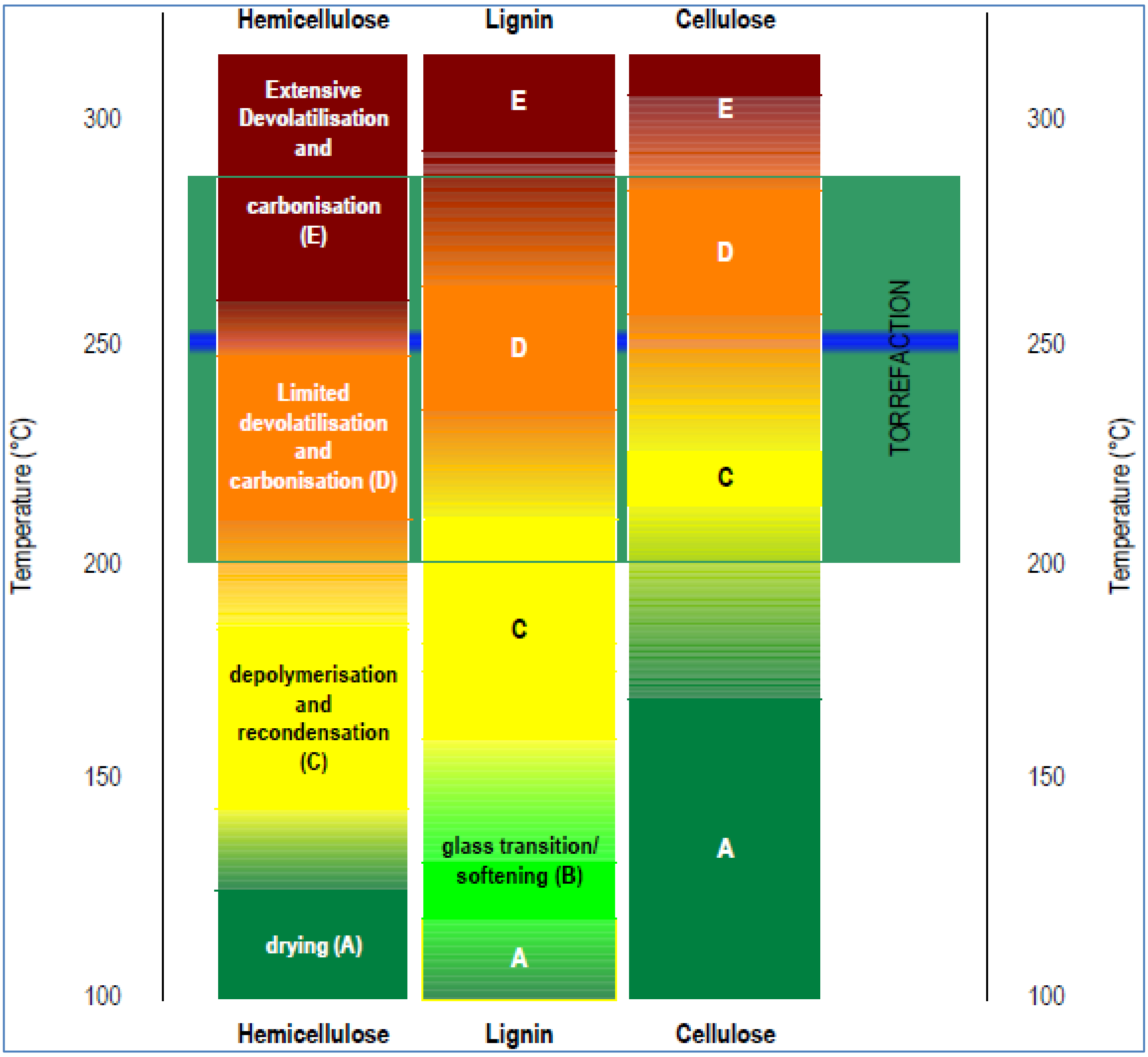

Figure 2.3: Main decomposition regimes of torrefaction (Bergman et al., 2005)

According to Bergman et al. (2005), in temperature regime A, physical drying of biomass occurs. When the temperature is increased to regime C, depolymerisation occurs and the shortened polymers condense within the solid structure. A further increase of temperature to regime D leads to limited devolatilisation and carbonisation of the intact polymers and the solid structures formed in the temperature regime C. Again a further increase of temperature to regime E leads to extensive devolatilisation and carbonisation of the polymers, and of the solid products that were formed in regime D. For lignin also a temperature regime B is defined in which softening of this biomass constituent occurs, a phenomenon very beneficial in the densification of biomass, as softened lignin is a good binder.

Figure 2.3 also includes the torrefaction temperature regime and the blue line splits it into a low (<250^{0}C) and high temperature regime (>250^{0}C). In general hemicellulose is the most reactive polymer followed by lignin and cellulose is most thermostable. In the lower torrefaction temperature regime the main biomass decomposition comes from the limited devolatilisation and carbonisation of hemicellulose. Minor decomposition is to be expected for lignin and cellulose except for chemical changes in their structure, which however do not lead to a significant mass loss. In the higher torrefaction temperature regime, decomposition becomes more vigorous as hemicellulose extensively decomposes into volatiles and a char-like solid product and also lignin and cellulose show limited devolatilisation and carbonisation.

2.2.3 Mass and energy yield

The mass and energy yield are main parameters in the evaluation of the torrefaction process. They describe the transition of mass and chemical energy from the biomass to the solid product. Analogous to Bergman et al. (2005), the following definitions of mass and energy yield have been applied:

$$Mass\ Yield\ (\%) = \frac{torrefied\ product\ \ weight}{raw\ material\ (dry)\ weight} \times 100\% \qquad (2)$$

and

$$Energy\ yield\ (\%) = \frac{torrefied\ product\ weight}{raw\ material\ (dry)\ weight} \times \frac{HHV_{product}}{HHV_{raw\,(dry)}} \times 100\% \qquad (3)$$

2.3 BIOMASS AFTER TORREFACTION

The changes of the biomass properties after being treated with torrefaction process can be found in previous papers, regardless of the biomass types.

2.3.1 Mass and energy yield

A study done by Pimchuai et al. (2010) had focused on the mass and energy balance of torrefied rice husks, sawdust, peanut husks, bagasse, and water hyacinth under varying temperature and residence time of 250, 270, and 300^{o}C and 1, 1.5, and 2 hours respectively. Based on the study, the percentage of mass and energy yield decrease with the increase in the temperature and residence time. It is also noted in the study that the temperature has more effect on torrefaction process than the residence time.

2.3.2 Ultimate analysis

A study done by Grevers et al. (2002) had focused on the ultimate analysis of torrefied pinewood which has been prepared at varying temperature and residence time of 230, 250, and 280^{o}C and 1, 2, and 3 hours respectively. Based on the study, the carbon content increase with the increase in the temperature and residence time, hydrogen and oxygen contents decrease with the increase in the temperature and residence time, while nitrogen content is approximately constant.

Another study done by Bridgeman et al. (2008) had focused on the ultimate analysis of torrefied reed canary grass, wheat straw, and willow which has been prepared under varying temperature of 230, 250, 270, and 290^{o}C and residence time of 30 minutes. Based on the study, increasing in the torrefaction temperature, increased the carbon content, decreased the hydrogen and oxygen content, and the nitrogen content were almost constant.

2.3.3 Calorific value

A study done by Pimchuai et al. (2010) had focused on the calorific value of torrefied rice husks, sawdust, peanut husks, bagasse, and water hyacinth which has been prepared under varying temperature and residence time of 250, 270, and 300^{o}C and 1, 1.5, and 2 hours respectively. Based on the study, calorific value of the torrefied product increase with the increase in the temperature and residence time. It is also noted in the study that temperature has more effect on the torrefaction process than the residence time.

Another study done by Uemura et al. (2010) had focused on the calorific value of torrefied empty fruit bunch, mesocarp fiber, and palm kernel shell which has been prepared under varying temperature of 220, 250, and 300^{o}C and residence time of 30 minutes. Based on the study, increasing in the torrefaction temperature resulted in a higher calorific value.

2.3.4 Proximate analysis

Different finding of the effect of torrefaction toward the proximate analysis can be found in a study done by Pimchuai et al. (2010) which had focused on the proximate analysis of torrefied rice husks, sawdust, peanut husks, bagasse, and water hyacinth under varying temperature and residence time of 250, 270, and 300^{o}C and 1, 1.5, and

2 hours respectively, and from a study done by Uemura et al. (2010) which had focused on the proximate analysis of torrefied empty fruit bunch, mesocarp fiber, and palm kernel shell which has been prepared under varying temperature of 220, 250, and 300°C and residence time of 30 minutes.

Based on the study done by Pimchuai et al. (2010), the moisture and volatile matter content decrease with the increase in the temperature and residence time, while the ash content and fixed carbon content increase with the increase in the temperature however majorly decrease in the residence time. But, according to the study done by Uemura et al. (2010), the moisture, volatile matter and ash content decrease with the increase in the temperature, while the fixed carbon content increase with the increase in the temperature.

2.4 PROPERTIES OF RAW PALM KERNEL SHELL

The properties of raw palm kernel shell (PKS) can be found in previous papers. The properties of raw PKS, regardless of its particle size obtained from the study done by Mahlia et al. (2001), Wahid et al. (2007) and Uemura et al. (2010) have been summarized in Table 2.1.

Table 2.1: Properties of raw PKS

	Literature Review		
Biomass properties	Mahlia et al.	Wahid et al.	Uemura et al.
Moisture (wt.%)	10.0	17.0	21.4
HHV (wet) MJ/kg	17.516	-	16.140
HHV (dry) MJ/kg	19.462	20.100	19.780
C (wt %)	52.4	-	46.68
H (wt.%)	6.3	-	5.86
N (wt.%)	0.6	-	1.10
S (wt.%)	0.2	-	0.06
O (wt.%)	37.3	-	42.01
Ash (wt.%)	3.2	3.0	4.38
Fixed carbon (wt.%)	-	13.5	-
Volatile Matter (wt.%)	-	83.5	-

CHAPTER 3

METHODOLOGY / PROJECT WORK

3.1 PROJECT FLOW DIAGRAM

1. Sample preparation

- Acquire the raw PKS (wet) from the local supply.
- Grind the raw PKS (wet) into a smaller particle size (i.e. 500 µm)
- Dry the raw PKS (wet) under the temperature of 105°C for 24 hours to remove its extrinsic moisture.
- Store the raw PKS (dry) in a low humidity cabinet for further process and analyses.

2. Torrefaction process

- Prepare a torrefied PKS with 9 set of different torrefaction condition (i.e. temperature & residence time)
- Will be done using tube furnace located at block P.
- Record the initial and final weight of the PKS.
- Store the torrefied PKS in a low humidity cabinet for analyses.

3. Ultimate analysis

- Determine the composition of C, H, N, S and O content in the PKS.
- Will be done towards the raw PKS (dry) and torrefied PKS.
- Will be done using CHNS analyzer located at block 4.

4. Calorific value analysis

- Determine the heating value of PKS.
- Will be done towards the raw PKS (wet and dry) and torrefied PKS.
- Will be done using bomb calorimeter located at block 4.

5. Proximate analysis

- Determine the intrinsic moisture content, volatile matter, ash content and fixed carbon content of PKS.
- Will be done towards the raw PKS (dry) and torrefied PKS.
- Will be done using thermogravimetric analyzer (TGA) located at block P.

3.2 GANTT CHART

Table 3.1: Gantt chart

		Week													
No.	Details	1	2	3	4	5	6	7		9	10	11	12	13	14
1	Sample preparation	▨	▨	▨	▨										
2	Torrefaction process					▨	▨	▨							
3	Ultimate analysis									▨	▨				
4	Calorific value analysis											▨	▨		
5	Proximate analysis													▨	▨

3.3 TOOLS AND EQUIPMENTS

Torrefaction process needs laboratory equipment named as tube furnace. However before this process can be conducted, the raw palm kernel shell need to be prepare first. For this purpose, tools like grinder and drying oven are needed. After torrefaction process had been done, the analyses towards the products of the torrefaction process will be done. Equipment such as carbon, hydrogen, nitrogen, and sulphur (CHNS) analyzer, thermogravimetric analyzer (TGA), and bomb calorimeter need to be used for the analyses. The summary of major tools and equipment used in this project are listed in Table 3.2.

Table 3.2: Tools and equipment

EXPERIMENT PART	ANALYZING PART
Tube Furnace	Thermogravimetric Analyzer (TGA)
Grinder	CHNS Analyzer
Drying Oven	Bomb Calorimeter

3.4 EXPERIMENTAL

3.4.1 Sample preparation

In this process, the raw PKS (wet) obtained from the local supply will be ground into a smaller particle size before drying. Drying towards the raw PKS (wet) was done in order to remove extrinsic moisture of the raw PKS. The required apparatus for this process are the grinder, weighing scale, heat resistant glove and the drying oven.

Sample preparation methodology

1. The raw PKS (wet) obtained from the local supply is cleaned to remove physical impurities.
2. The raw PKS (wet) which has been cleaned is crashed into smaller particle size of 500 µm using grinder.
3. The raw PKS (wet) with the particle size of 500 µm is weighed and recorded as initial weight.
4. The raw PKS (wet) is dried in the drying oven at a temperature of 105°C, with constant heating rate of 10°C/min for 24 hours.
5. The drying oven is turned off after 24 hours and the sample (raw PKS) is left to cool down to the ambient temperature (or at least until 50°C)
6. The raw PKS (dry) is removed from the drying oven.
7. The raw PKS (dry) is weighed and recorded as a final weight.
8. The amount of weight loss is calculated by subtracting the initial weight and the final weight of the raw PKS, to obtain the result of extrinsic moisture content of the raw PKS.
9. The raw PKS (dry) is stored inside a low humidity cabinet.

After completing the sample preparation process, the raw PKS (dry) will be used to undergo:

- Analyses (i.e. ultimate, calorific value, and proximate)
- Torrefaction process.

3.4.2 Torrefaction process

In this process, the raw PKS (dry) will be torrefied at varying temperature and residence time of 240, 260 and 280^{o}C and 30, 60, and 90 minutes respectively. The torrefaction conditions are varied in order to prepare a various type of torrefied products, and the changes towards the properties of every torrefied PKS from the raw PKS (dry) will be determined after the PKS undergo several analyses (ultimate, calorific value, and proximate). The required apparatus for this process are the tube furnace, weighing scale, and ceramic crucible.

Torrefaction methodology

1. The raw PKS (dry) is weighed and recorded as an initial weight.
2. The weighed raw PKS (dry) is placed in a ceramic crucible and put inside the tube furnace combustion chamber and the combustion chamber is closed tightly.
3. The tube furnace power supply is switched on.
4. Nitrogen gas cylinder is connected to the nitrogen gas inlet of the tube furnace combustion chamber.
5. The nitrogen gas valve is opened and the flow of the nitrogen inside the tube furnace combustion chamber is controlled by 50 ml/min.
6. The amount of the oxygen inside the tube furnace combustion chamber is observed at the panel next to the tube furnace.
7. The temperature of the tube furnace is set to 240^{o}C after the nitrogen gas flowrate is stable and the amount of oxygen inside the tube furnace combustion chamber is below 1.0%.
8. The cut off temperature of the tube furnace is set to 255^{o}C (15^{o}C higher than set point temperature).
9. The residence time of the tube furnace is set to 30 minutes.
10. The supply of nitrogen gas into the tube furnace combustion chamber is ensured to be sufficient throughout the torrefaction process, or otherwise change the nitrogen gas cylinder and step 4-9 is repeated.

11. The heater is switched on and the tube furnace combustion chamber will be heated up to the set temperature (step 7) with constant heating rate of 20°C/min.
12. The heater of the tube furnace is switched off after the residence time ended and the sample (torrefied PKS) will be cool down to the ambient temperature (or at least until 50°C).
13. The flow of the nitrogen inside the tube furnace combustion chamber is left until the sample is cooled down.
14. The sample (torrefied PKS) is removed from the tube furnace combustion chamber.
15. The sample (torrefied PKS) is weighed and recorded as a final weight.
16. Step 1 to 15 is repeated for every set of torrefaction conditions (240, 260,280°C and 30, 60, 90 minutes).
17. The result of the initial and final weight is used to calculate the mass yield (%) according to the equation (2) in section 2.2.3

3.5 ANALYSES

3.5.1 Ultimate analysis

The ultimate analysis is done towards the raw PKS (dry) and torrefied PKS to determine the elemental composition. The changes of the elemental composition between raw PKS (dry) and every torrefied PKS is determined from the result of this analysis. The required apparatus for this process are the CHNS analyzer, weighing scale, and tin capsule.

Samples preparation for CHNS

1. The tin capsule is weighed.
2. Approximately 2 mg of sample (standard material) is put into the tin capsule.
3. The tin capsule together with the sample is folded properly and the weight is recorded.
4. Step 1-3 is repeated for other samples (raw PKS and torrefied PKS).
5. The sample which has been folded is placed into the slot inside the CHNS analyzer.
6. The weight of the samples (not include tin capsule weight) is keyed-in the analyzer database.

7. The CHNS analyzer is started and each sample is analysed only in 3 minutes.
8. The result of C, H, N, S contents are obtained while the O content is determined according to the equation (1) in section 2.1.5.

Standard operating procedure (SOP)

1. Helium, Oxygen and compressed air are made sure being set to 40 psi.
2. The ambient monitor is checked for proper values.
3. The CO_2, H_2 and Sulphur IR Cells are monitored to be between '7.5-9.2' volts.
4. The Oxidation Furnace Temperature is set to 1000^oC
5. The Reduction Furnace Temperature is set to 650^oC
6. The leak check is done if necessary.
7. 'Auto/Manual' switch is set to Auto when using carousel/to manual when loading samples individually.
8. The gas switch is set to analyse position.
9. Furnace temperature is waited until stable.
10. Blank analysis and standard samples are done.
11. The experiment samples are started.

3.5.2 Calorific value analysis

The calorific value analysis is done towards raw PKS (dry) and torrefied PKS to determine the higher heating value (HHV). The changes of the heating value between raw PKS (dry) and every torrefied PKS is determined from the result of this analysis. The required apparatus for this process are the bomb calorimeter, weighing scale, and glass crucible.

Bomb calorimeter methodology

1. The oxygen gas regulator is switched on (pressure: 20-30 kg/cm^2).
2. The bomb calorimeter unit and refrigerator batch is switched on and waited for 20 minutes to allow it to stabilize.
3. The sample of approximately 0.5 g is prepared.
4. The sample is placed into the glass crucible and a cotton thread with a loop is immersed in it through the middle of the ignition wire.
5. The glass crucible is place into the decomposition vessel.

6. The decomposition vessel is suspended into the filling head of the measurement cell cover.
7. The sample dialog window is opened and the weight of the sample is keyed-in the database.
8. The bomb calorimeter is started the decomposition vessel is closed by the measurement cell cover and filled with oxygen.
9. The inner vessel is filled with water.
10. A graph of temperature vs. residence time of the inner vessel is displayed as soon as the system begins with the experiment.
11. The result of the sample HHV is displayed after the experiment is completed.
12. The decomposition vessel is removed from the filling head and cleaned up.
13. Step 3-12 is repeated for the next sample.
14. The HHV of raw PKS (dry) and every torrefied PKS is used to determine the energy yield (%) according to the equation (3) in section 2.2.3.

3.5.3 Proximate analysis

The proximate analysis is done towards raw PKS (dry) and torrefied PKS to determine the intrinsic moisture, volatile matter, ash, and fixed carbon content. The changes of the proximate analysis between raw PKS (dry) and every torrefied PKS is determined from the result of this analysis. The required apparatus for this process are the thermogravimetric analyzer (TGA), weighing scale, and ceramic crucible.

TGA methodology

1. Sample weight about 4.5 – 5.0 mg is placed in a ceramic crucible
2. The ceramic crucible is loaded into the heated zone of the TGA
3. The TGA furnace is closed and the TGA is waited to stabilize before the initial weight is captured.
4. The sample is heated from 50–110^{o}C at a heating rate of 60^{o}C/min and with a nitrogen gas flowrate of 30 ml/min.
5. After the temperature reached 110^{o}C, the sample is held isothermally for 5 minutes.
6. The furnace is heated up to 950^{o}C at a heating rate of 100^{o}C/min with the same nitrogen flowrate.

7. The sample is held isothermally for another 3 minutes after the temperature reached 950°C.
8. The purge gas is switched to oxygen gas with flowrate of 30 ml/min and the sample is held isothermally for another 15 minutes.
9. The process is ended and the results for moisture, volatile matter, and ash content are evaluated from the graph plotted by built-in software in a computer attached to the TGA.
10. The results of moisture, volatile matter, and ash content are used to calculate the fixed carbon content by difference.
11. The TGA furnace is let to cool down to 50°C.
12. The sample is removed from the TGA furnace after the temperature reached 50°C
13. Step 1 – 12 is repeated for the next sample.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 THE PROPERTIES OF RAW PALM KERNEL SHELL

As been mentioned in the section 3.4.1, the raw palm kernel shell (PKS) that has completed the sample preparation process will undergo several analyses in order to determine its properties. The data obtained from the experiment and analyses is discussed below.

4.1.1 Extrinsic moisture content of raw PKS

Results and discussion

The moisture content of the raw PKS is obtained by determining the mass loss of the raw PKS (wet) after undergoes the drying process in the oven at the temperature of 105^{o}C. The result is shown in Table 4.1.

Table 4.1: Mass loss of raw PKS

BEFORE DRYING	AFTER DRYING
1.390 kg	1.350 kg
% Mass Loss = 2.88%	

Temperature of 105^{o}C during the drying process of raw PKS (wet) is the temperature where the moisture content of the PKS will evaporate. As been mention in section 2.1.1, there were two forms of moisture content that are of interest in biomass, which is intrinsic and extrinsic moisture. The moisture that has been removed after the raw PKS (wet) undergoes this process is the ‘extrinsic moisture’ content of PKS and it is assume that the raw PKS has been completely dried after this process. Extrinsic moisture content is highly influenced by prevailing weather conditions during harvesting or storage condition (Uemura et al., 2010).

From the result, the extrinsic moisture content of the raw PKS is relatively low, which is 2.88%, compare to the study that had been done by Mahlia et al. (2001), Wahid et al. (2007), and Uemura et al. (2010), which are 10, 17, and 21.4% respectively. In this project, the PKS obtained from the local supply were kept in the low humidity cabinet under the temperature below 5^{o}C for so long, which is more than 5 months and hence the extrinsic moisture content of the PKS obtained is low.

4.1.2 Calorific value of raw PKS

Results and discussion

Calorific value of raw PKS (wet) and raw PKS (dry) is expressed as higher heating value (HHV) of wet-basis and dry-basis respectively. The result of the calorific value of PKS together with its moisture content is shown in the Table 4.2.

Table 4.2: HHV of raw PKS

Biomass	Moisture (%)	HHV (wet) (MJ/kg)	HHV (dry) (MJ/kg)
PKS	2.88	18.491	18.814

From the results, the HHV of the raw PKS (dry) is 18.491 MJ/kg, which rise about 1.75% from the raw PKS (wet). Also based on the data from Table 4.2, it is clearly shown that the decrease in moisture content gives larger HHV rise. The HHV rise is relatively low compared to the HHV rise from the study done by Mahlia et al. (2001) and Uemura et al. (2010) which is 11.11 and 22.55% respectively. In this project, since the moisture content of the raw PKS (wet) is low, the HHV rise of the raw PKS (dry) is insignificant.

The HHV obtained for the raw PKS (dry) in this project is also compared with the HHV obtained from the study done by Mahlia et al. (2001), Wahid et al. (2007), and Uemura et al. (2010) where the differences are calculated to be 3.33, 6.39, and 4.88% respectively. The HHV difference occurs between the same biomass materials is because of physical environmental conditions and harvesting season of the PKS. The difference in the HHV is also expected because of the size of the PKS that have been done in this project is differ from the others.

4.1.3 Ultimate analysis of raw PKS

Results and discussion

The carbon (C), hydrogen (H), nitrogen (N), and sulphur (S) contents were obtained from the CHNS analyzer, while the oxygen content is determined using equation (1) in section 2.1.5. There were no specific elemental composition data for raw PKS (wet) with its constituent extrinsic moisture content. Thus, only the elemental composition of raw PKS (dry) will be present and the result is shown in Figure 4.1.

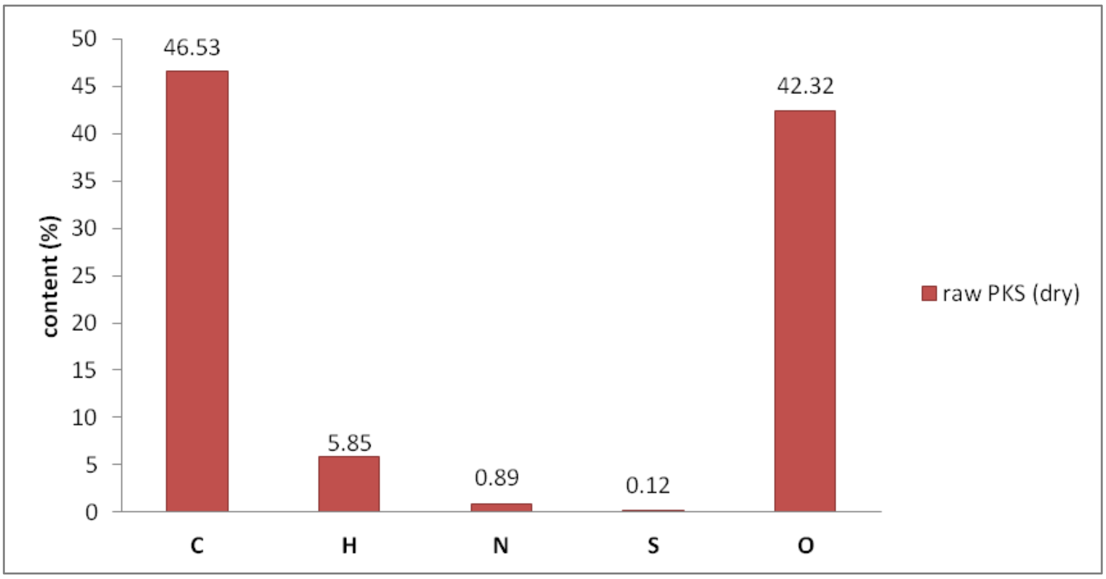

Figure 4.1: C,H,N,S,O contents for raw PKS

From the results, the C, H, N, S and O of the raw PKS (dry) are 46.53, 5.85, 0.89, 0.12 and 42.32% respectively. The elemental composition obtained for the raw PKS (dry) in this project is also compared with the elemental composition obtained from the study done by Mahlia et al. (2001) and Uemura et al. (2010) where the differences for C content are calculated to be 11.2 and 0.32% respectively, H content are 7.14 and 1.0% respectively, N content are 48.33 and 19.09% respectively, S content are 40 and 100% respectively, while O content are 13.46 and 0.74%. The large differences for N and S contents compared to the previous studies, are actually acceptable since the amount of these element (N and S) contents are still below 1%, which doesn't gives impacts towards the fuel properties as the content of C, H, and O, which are of interest in the study to determine the potential of PKS as a fuel.

4.1.4 Proximate analysis of raw PKS

Results and discussion

The moisture, volatile matter (VM), and ash contents were obtained from the thermogravimetric analyzer (TGA), while the fixed carbon content is determined by difference, as per mentioned in section 2.1.3. It should be noted that the moisture content obtained from the proximate analysis process is the 'intrinsic moisture' content of the raw PKS (dry). There were no specific proximate analysis data for raw PKS (wet) with its constituent extrinsic moisture content. Thus, only the proximate analysis of raw PKS (dry) will be present and the result is shown in Figure 4.2.

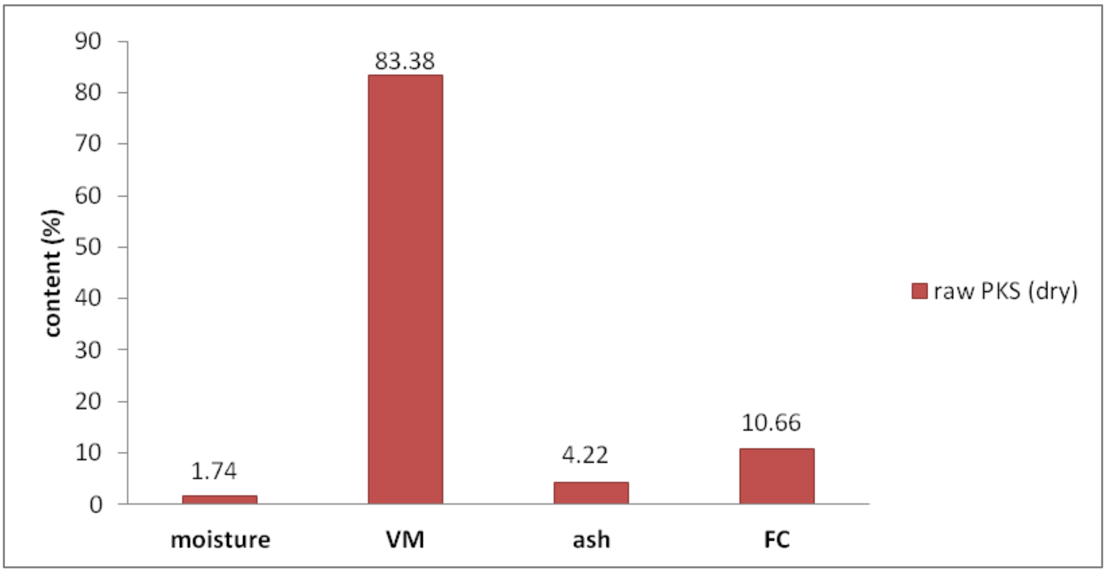

Figure 4.2: Moisture, volatile matter, ash, and fixed carbon content for raw PKS

From the results, the percentage of moisture, volatile matter, ash and fixed carbon content for raw PKS (dry) are 1.74, 83.38, 4.22, and 10.66% respectively. The proximate analysis obtained for the raw PKS (dry) in this project is also compared with the proximate analysis obtained from the study done by Wahid et al. (2007) where the difference for moisture, VM, ash, and FC content are calculated to be 89.76, 1.75, 40.67, and 21.04% respectively. The difference in the proximate analysis is expected because of the size of the PKS and the methodology that has been done in this project is not similar from the others.

4.2 THE PROPERTIES OF TORREFIED PALM KERNEL SHELL

As been mentioned in the section 3.4.2, every torrefied PKS will undergo several analyses to determine the properties changes occurs towards the raw PKS (dry) after completed the torrefaction process under varying temperature and residence time. The data obtained from the experiment and analyses is discussed below. The results for the properties of the raw PKS (dry) obtained from the previous section will also be used in this section for comparison purposes.

4.2.1 Mass yield of torrefied PKS

Results and discussion

The percentage of mass yield of torrefied PKS is obtained from the final weight data of the torrefied and raw PKS which is then calculated using equation (2) in section 2.2.3 *(refer Appendix A)*. The results are shown in Figure 4.3 and 4.4 for the influence of temperature and residence time respectively.

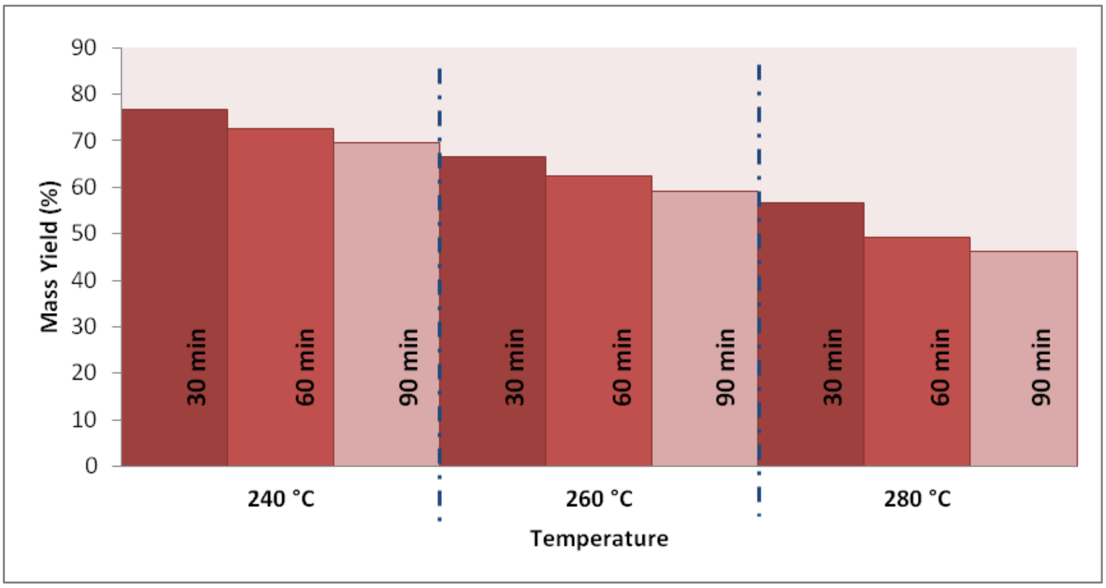

Figure 4.3: Influence of temperature towards mass yield of torrefied PKS

From the above figure, the percentage of mass yield decrease with the increase in the torrefaction temperature. The similar results were also reported from a study done by Pimchuai et al. (2010) for the torrefaction of rice husks, sawdust, peanut husks, bagasse, and water hyacinth under varying temperature and residence time of 250, 270, and 300^{o}C and 1, 1.5, and 2 hours respectively.

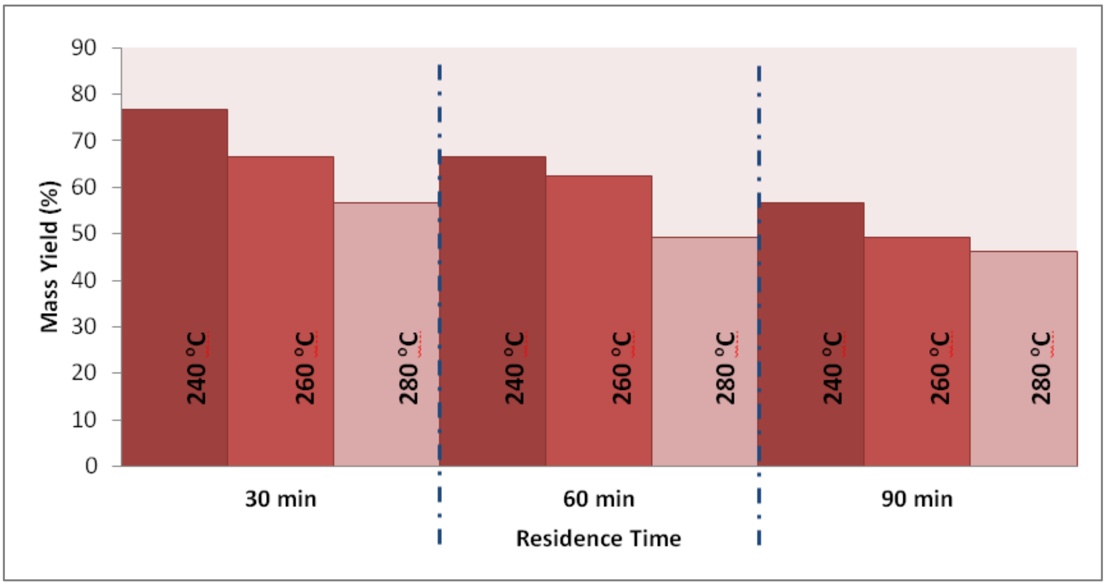

Figure 4.4: Influence of residence time towards mass yield of torrefied PKS

From the above figure, the percentage of mass yields continually decreases with the increase in the residence time. And the result were also similar from a study done by Pimchuai et al. (2010) for the torrefaction of rice husks, sawdust, peanut husks, bagasse, and water hyacinth under varying temperature and residence time of 250, 270, and 300^{o}C and 1, 1.5, and 2 hours respectively.

From both figure, it is also being noticed that the temperature gives more effect on torrefaction than the residence time. This can be explained by more decrease in the moisture and volatile matter content of the PKS at higher torrefaction temperature. Decomposition of some reactive components of the hemicellulose also becomes more vigorous in the higher torrefaction temperature (Bergman et al., 2005). The influence of residence time is only significance to the mass loss which is attributed to the decomposition of the less reactive components of the hemicelluloses (Pimchuai et al., 2010). The similar results were also reported in various studies done by Nimlos et al. (2003), Prins et al. (2006), and Pimchuai et al. (2010).

4.2.2 Energy yield of torrefied PKS

Results and discussion

The percentage of energy yield of torrefied PKS is obtained from the HHV data of the torrefied and raw PKS which is then calculated using equation (3) in section 2.2.3 *(refer Appendix A)*. The results are shown in the Figure 4.5 and 4.6 for the influence of temperature and residence time respectively.

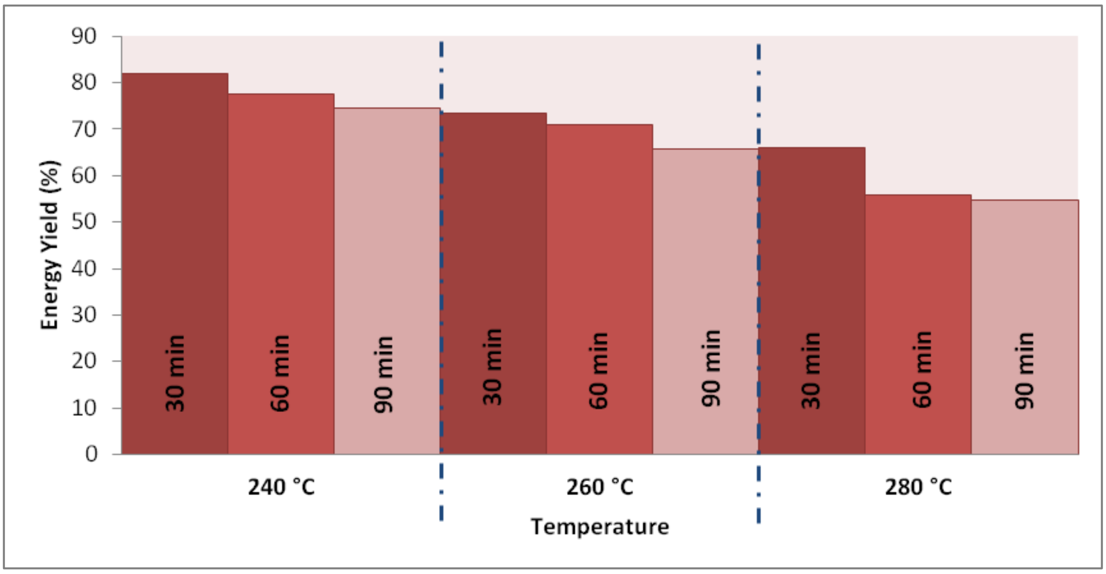

Figure 4.5: Influence of temperature towards energy yield of torrefied PKS

From the above figure, the percentage of energy yield decrease with the increase in the torrefaction temperature. The similar results were also reported from a study done by Pimchuai et al. (2010) for the torrefaction of rice husks, sawdust, peanut husks, bagasse, and water hyacinth under varying temperature and residence time of 250, 270, and 300°C and 1, 1.5, and 2 hours respectively.

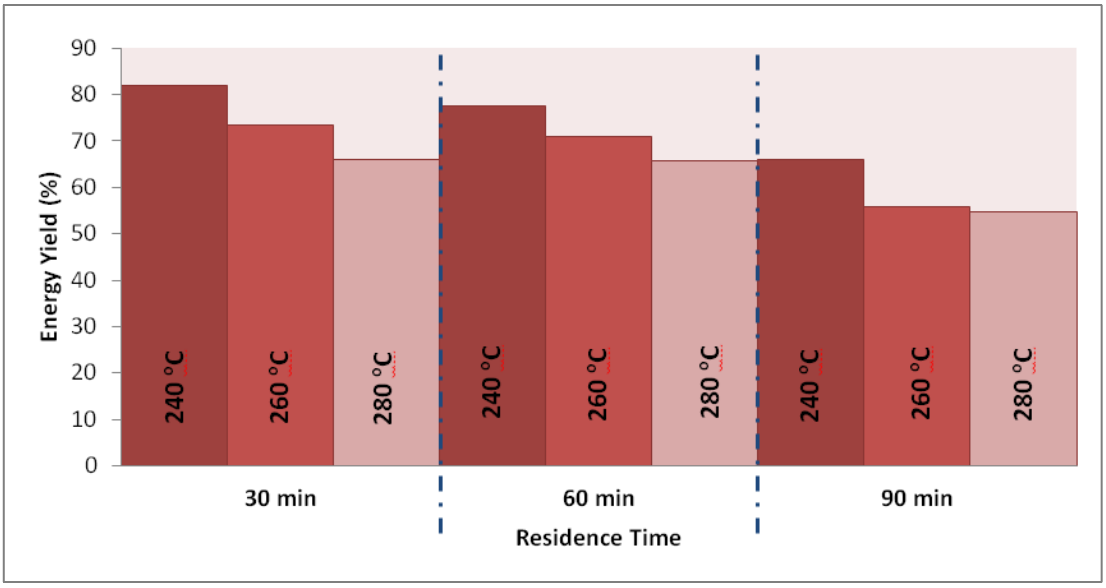

Figure 4.6: Influence of residence time towards energy yield of torrefied PKS

From the above figure, the percentage of energy yield decrease with the increase in the residence time. And the similar results were also reported from a study done by Pimchuai et al. (2010) for the torrefaction of rice husks, sawdust, peanut husks, bagasse, and water hyacinth under varying temperature and residence time of 250, 270, and 300^{o}C and 1, 1.5, and 2 hours respectively.

From both figure, it is also being noticed that the temperature gives more effect on torrefaction than the residence time. Energy yield of the torrefaction product is greater than the mass yield, which follows and agree with the explanation in section 2.2, and the energy densification of the torrefied PKS were achieved *(refer Appendix A)*. The similar results were also reported in various studies done by Nimlos et al. (2003), Prins et al. (2006), and Pimchuai et al. (2010).

4.2.3 Elemental composition of torrefied PKS

Results and discussion

The percentage of C, H, N, and S contents of torrefied PKS is obtained from CHNS analyzer, while the O contents of torrefied PKS is obtained from the C,H,N,S and ash contents data of the torrefied PKS which is then calculated using equation (1) in section 2.1.5 *(refer Appendix B)*. The results of every elemental composition of torrefied and raw PKS are shown in the figure below for the influence of temperature and residence time respectively.

- C content

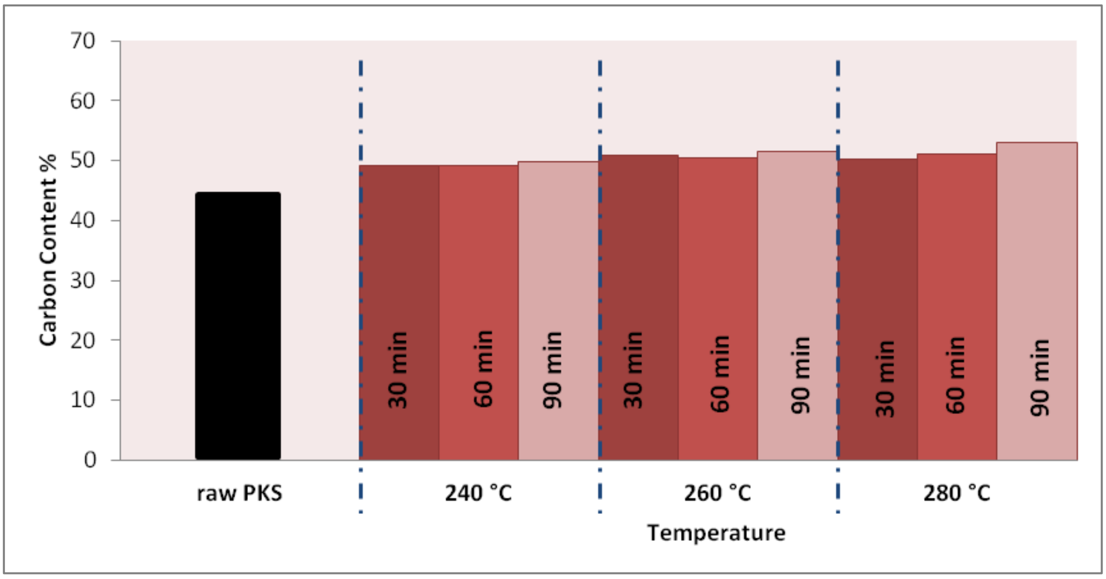

Figure 4.7: Influence of temperature towards C content of torrefied PKS

From the above figure, the percentage of carbon content increase with the increase in the torrefaction temperature. And the similar results were also reported from a study done by Grevers et al. (2002) for the torrefaction of pinewood at varying temperature and residence time of 230, 250, and 280°C and 1, 2, and 3 hours respectively.

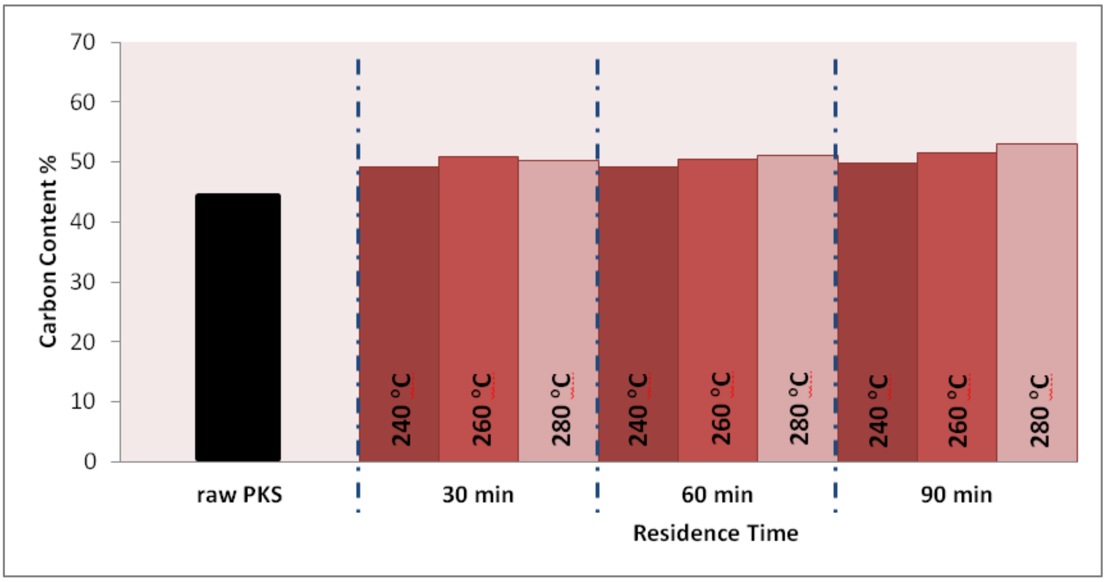

Figure 4.8: Influence of residence time towards C content of torrefied PKS

From the above figure, the percentage of carbon content increase with the increase in the residence time. The similar results were also reported from a study done by Grevers et al. (2002) for the torrefaction of pinewood at varying temperature and residence time of 230, 250, and 280°C and 1, 2, and 3 hours respectively.

From both figure, it is also being noticed that the temperature gives more effect on torrefaction than the residence time. The similar results were also reported in a study done by Grevers et al. (2002). Overall, the carbon content of torrefied PKS increase about 10-20%

- H content

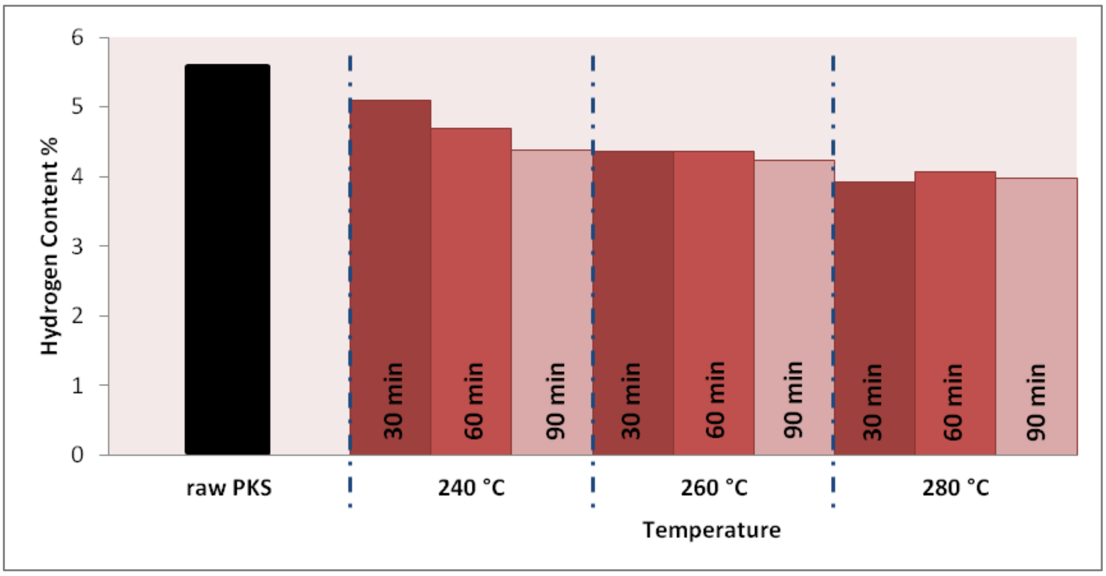

Figure 4.9: Influence of temperature towards H content of torrefied PKS

From the above figure, the percentage of hydrogen content decrease with the increase of the torrefaction temperature. And the similar results were also reported from a various study done by Grevers et al. (2002) for the torrefaction of pinewood at varying temperature and residence time of 230, 250, and 280°C and 1, 2, and 3 hours respectively, and a study done by Bridgeman et al. (2008) for the torrefaction of reed canary grass, wheat straw, and willow at varying temperature of 230, 250, 270, and 290°C and residence time of 30 minutes.

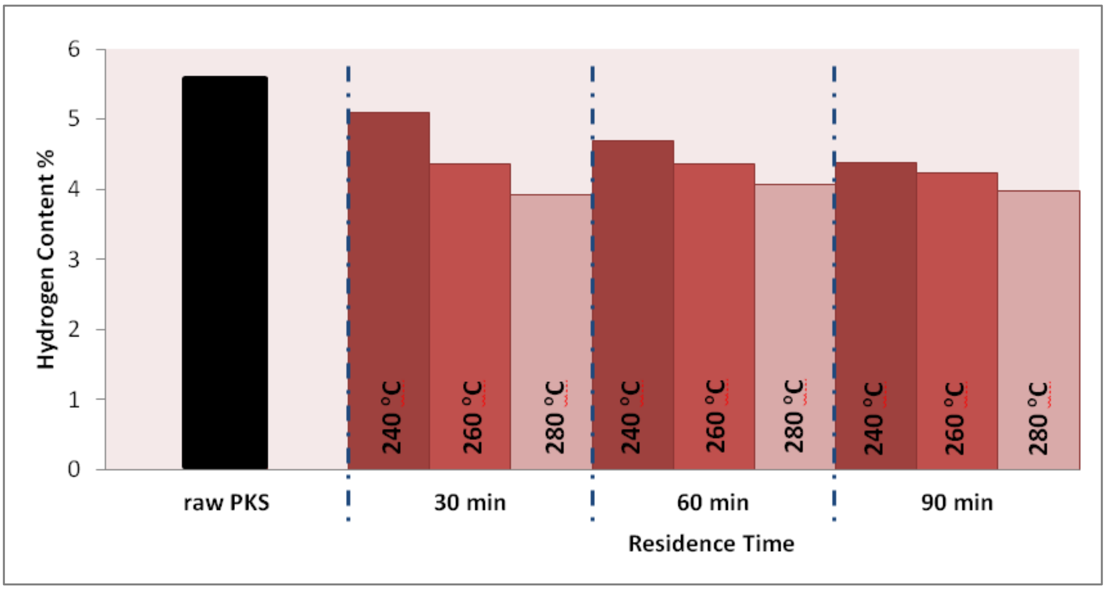

Figure 4.10: Influence of residence time towards H content of torrefied PKS

From the above figure, the percentage of hydrogen contents decreases with the increase of the residence time. The similar results were also reported from a study done by Grevers et al. (2002) for the torrefaction of pinewood at varying temperature and residence time of 230, 250, and 280°C and 1, 2, and 3 hours respectively.

From both figure, it is also being noticed that the temperature gives more effect on torrefaction than the residence time. The similar results were also reported in a study done by Grevers et al. (2002). Overall, the hydrogen content of torrefied PKS decrease about 9-29%.

- N content

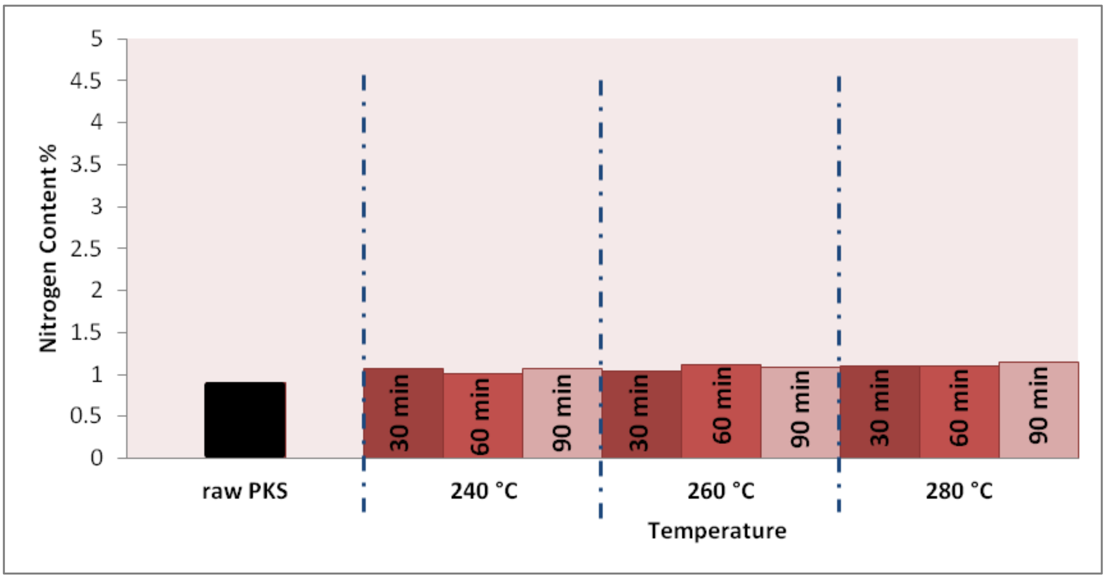

Figure 4.11: Influence of temperature towards N content of torrefied PKS

From the above figure, the percentage nitrogen contents are fluctuating with just a slight difference around 0.13%, and being assumed that the nitrogen content are approximately constant with the increase of the torrefaction temperature. And the similar results were also reported from a various study done by Grevers et al. (2002) for the torrefaction of pinewood at varying temperature and residence time of 230, 250, and 280°C and 1, 2, and 3 hours respectively, and a study done by Bridgeman et al. (2008) for the torrefaction of reed canary grass, wheat straw, and willow at varying temperature of 230, 250, 270, and 290°C and residence time of 30 minutes.

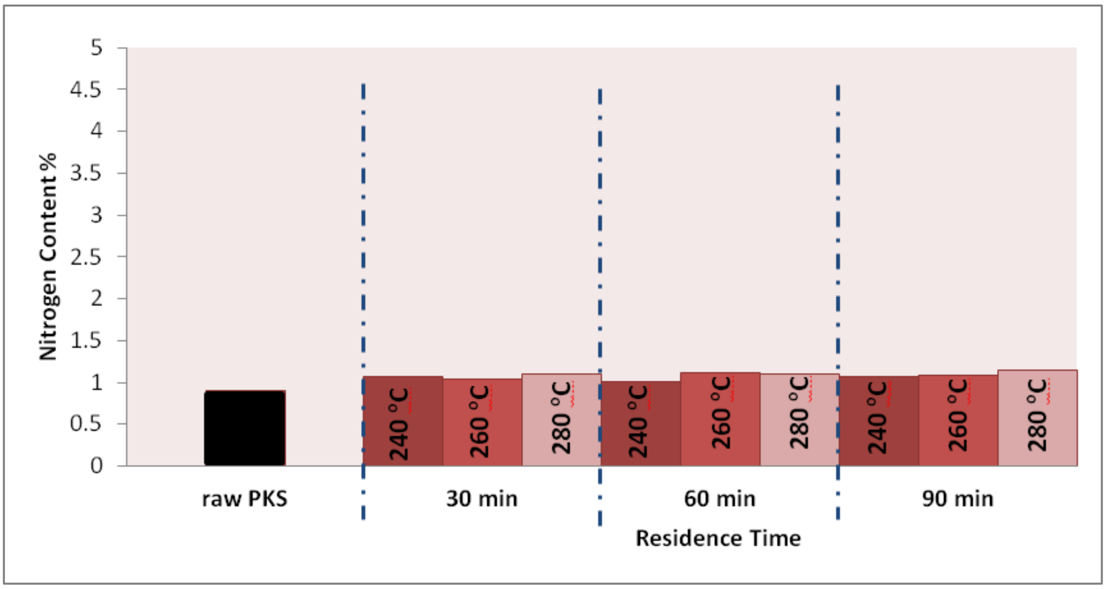

Figure 4.12: Influence of residence time towards N content of torrefied PKS

From the above figure, the percentage of nitrogen contents are fluctuating with just a slight difference around 0.13%, and being assumed that the nitrogen contents are approximately constant with the increase of the residence time. The similar results were also reported from a study done by Grevers et al. (2002) for the torrefaction of pinewood at varying temperature and residence time of 230, 250, and 280^{o}C and 1, 2, and 3 hours respectively.

- S content

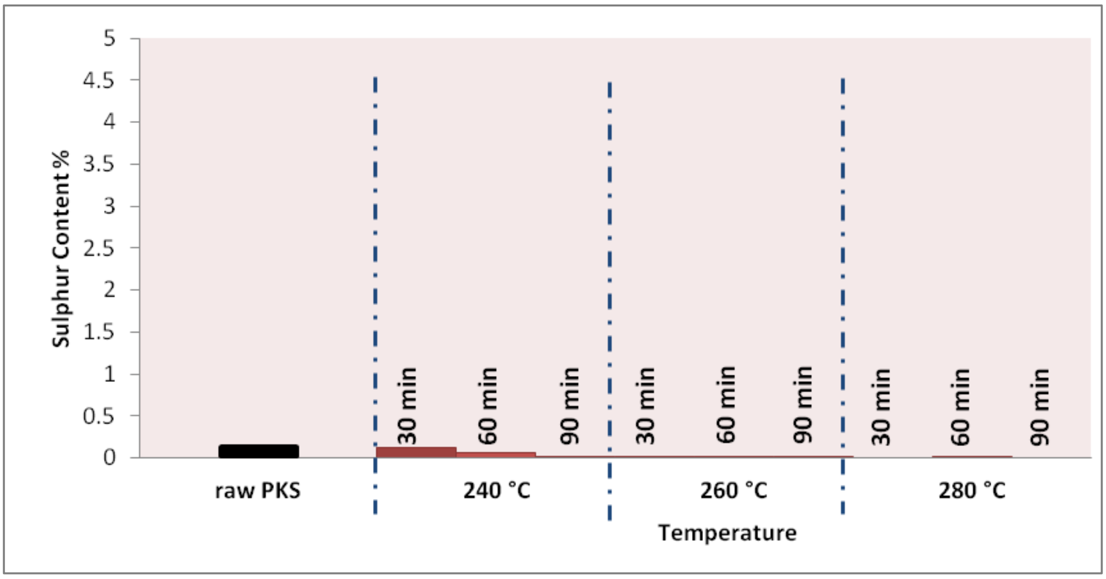

Figure 4.13: Influence of temperature towards S content of torrefied PKS

From the above figure, the percentage of sulphur content is maintain low with the increase of the torrefaction temperature.

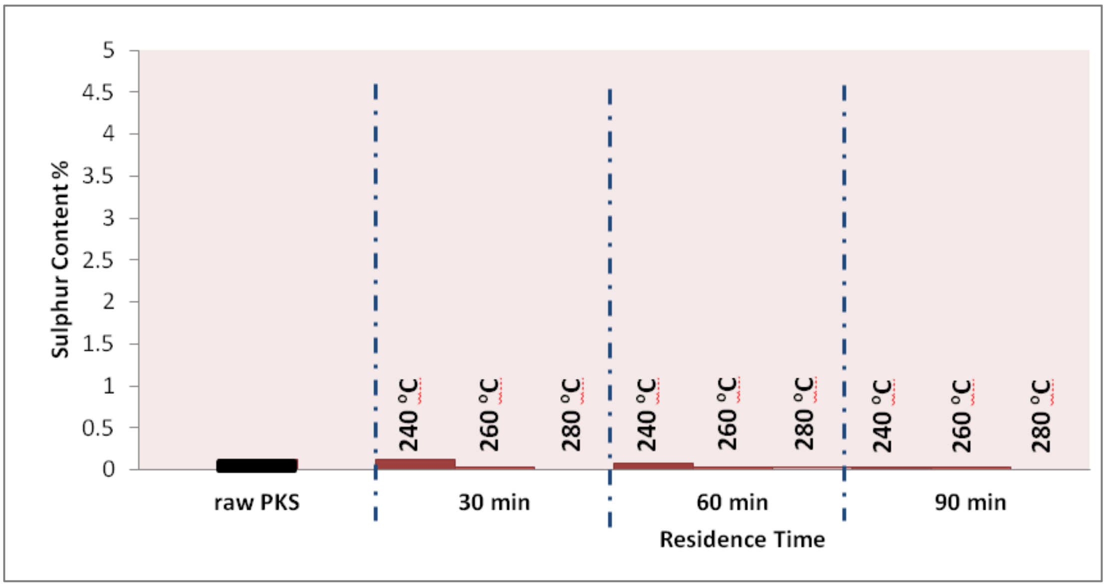

Figure 4.14: Influence of residence time towards S content of torrefied PKS

From the above figure, the percentage of sulphur content is maintain low with the increase of the residence time.

There was not much study that reported about sulphur content of the torrefied biomass since the content of sulphur in the raw biomass has been relatively very low. Similar from what has been obtained from this project, which the sulphur content in PKS before and after torrefaction is relatively low which is typically below 1%. Low sulphur content in the fuel would sufficiently reduce the pollutants and thus the PKS is an environmental friendly fuel.

- O content

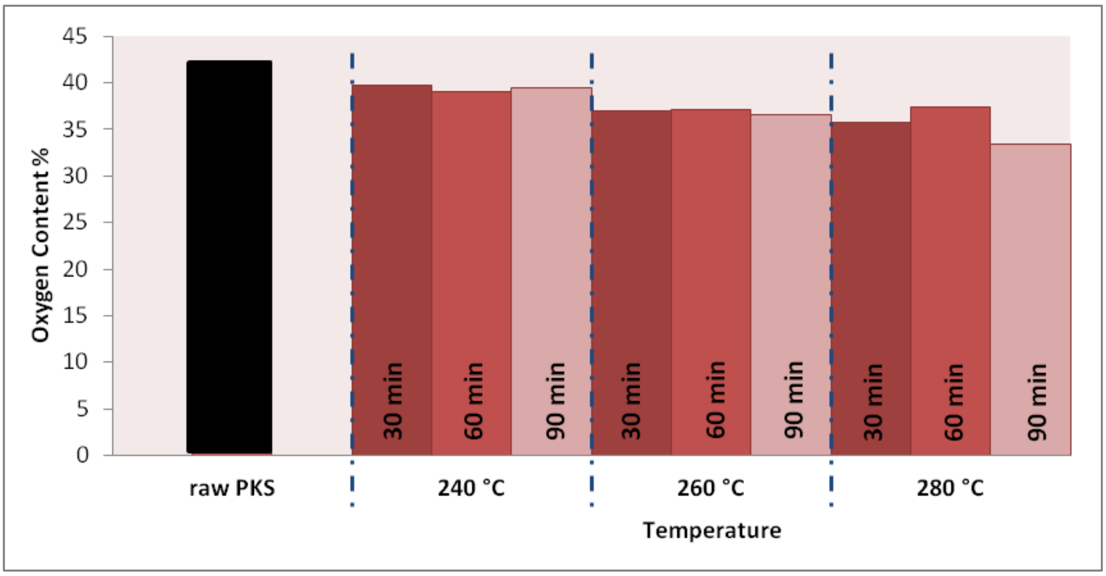

Figure 4.15: Influence of temperature towards O content of torrefied PKS

From the above figure, the percentage of oxygen content decrease with the increase of the torrefaction temperature. And the similar results were also reported from a various study done by Grevers et al. (2002) for the torrefaction of pinewood at varying temperature and residence time of 230, 250, and 280°C and 1, 2, and 3 hours respectively, and a study done by Bridgeman et al. (2008) for the torrefaction of reed canary grass, wheat straw, and willow at varying temperature of 230, 250, 270, and 290°C and residence time of 30 minutes.

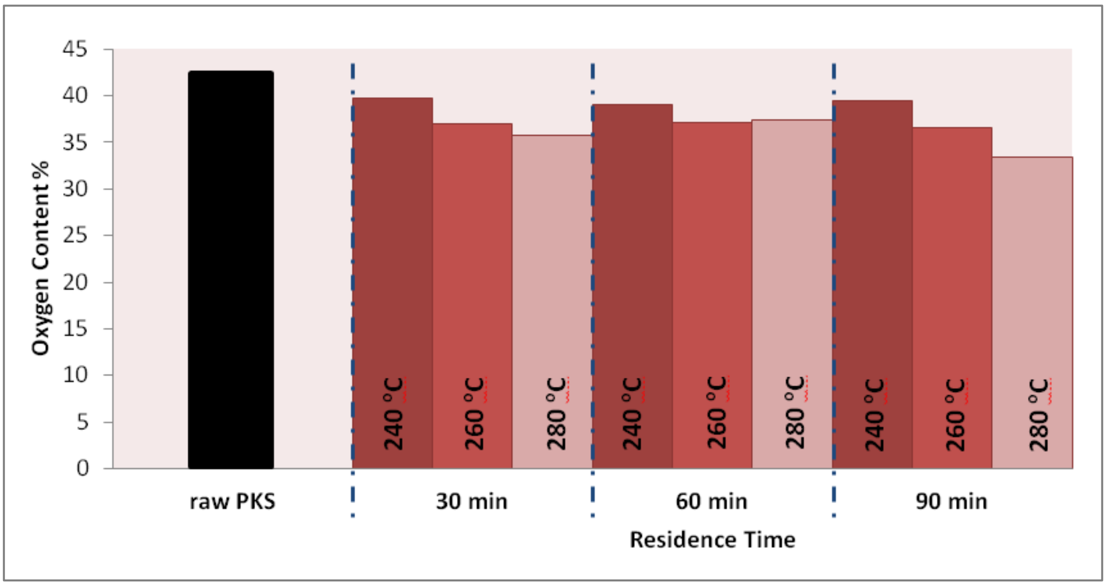

Figure 4.16: Influence of residence time towards O content of torrefied PKS

From the above figure, the percentage of oxygen content decrease with the increase of the residence time. The similar results were also reported from a study done by Grevers et al. (2002) for the torrefaction of pinewood at varying temperature and residence time of 230, 250, and 280°C and 1, 2, and 3 hours respectively.

From both figure, it is also being noticed that the temperature gives more effect on torrefaction than the residence time. The similar results were also reported in a study done by Grevers et al. (2002). Overall, the oxygen content of torrefied PKS decrease about 6-21%.

4.2.3 Calorific value of torrefied PKS

Results and discussion

Calorific value of every torrefied PKS is expressed as higher heating value (HHV). The results of the HHV for every torrefied and raw PKS *(refer appendix J)* are shown in Figure 4.17 and 4.18 for the influence of temperature and residence time respectively.

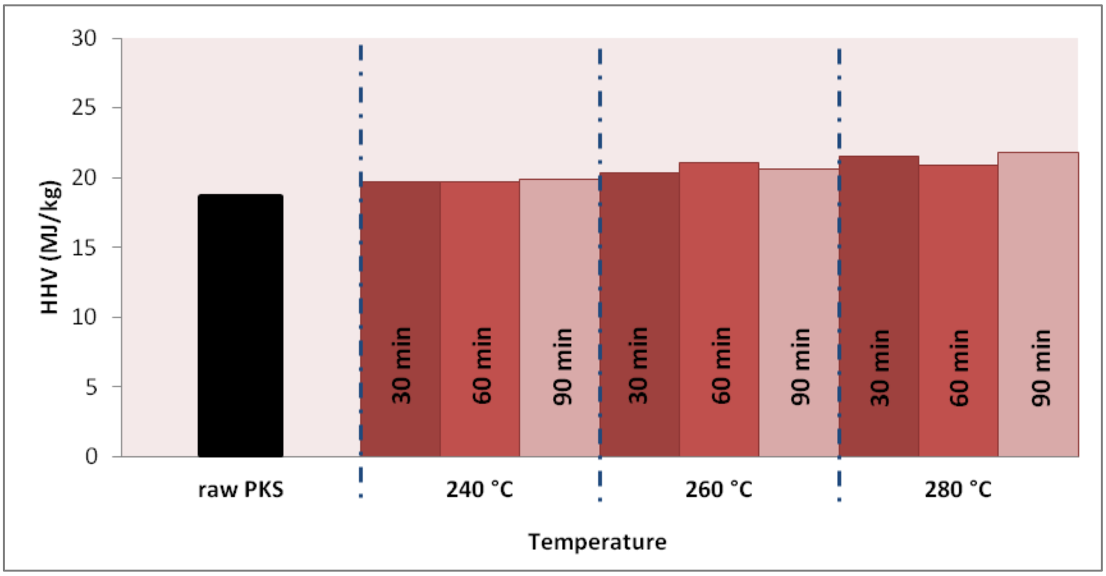

Figure 4.17: Influence of temperature towards HHV of torrefied PKS

From the above figure, the HHV increase with the increase of the torrefaction temperature. And the result were also similar from a various study done by Y. Uemura et al. (2010) for the torrefaction towards empty fruit bunch, mesocarp fiber, and kernel shell which has been done under varying temperature of 220, 250, and 300°C and residence time of 30 minutes, and a study done by Pimchuai et al. (2010)

for the torrefaction of rice husks, sawdust, peanut husks, bagasse, and water hyacinth which has been done under varying temperature and residence time of 250, 270, and 300°C and 1, 1.5, and 2 hours respectively 30 minutes.

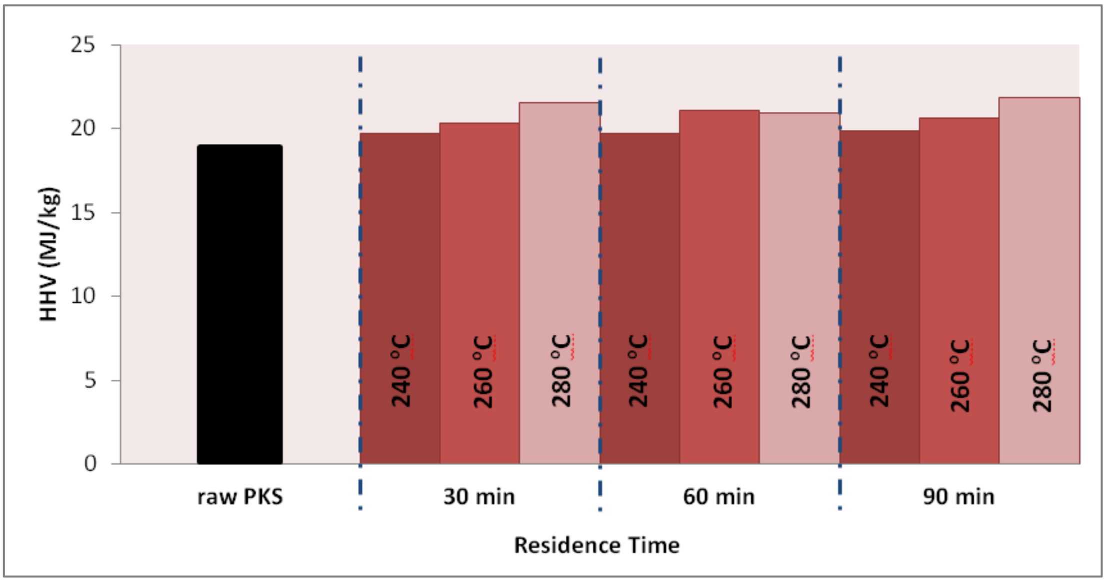

Figure 4.18: Influence of residence time towards HHV of torrefied PKS

From the above figure, the HHV increase with the increase of the residence time. The similar results were also reported from a study done by Pimchuai et al. (2010) for the torrefaction of rice husks, sawdust, peanut husks, bagasse, and water hyacinth which has been done under varying temperature and residence time of 250, 270, and 300°C and 1, 1.5, and 2 hours respectively 30 minutes.

From both figure, it is also being noticed that the temperature gives more effect on torrefaction than the residence time. This can be explained by the results of carbon content obtained from the previous section 4.2.2, where the increase in the carbon concentration is significant with the effects of temperature. An increase in the carbon concentration leads to an increase in the HHV. Also the intrinsic moisture content reduction of the torrefied biomass is among the main factor contributing to the increase in the heating value. The similar results were also reported in a study done by Pimchuai et al. (2010). Overall, the rise of the HHV of the torrefied PKS increase about 4.72-16.17% *(refer Appendix C).*

4.2.5 Proximate analysis of torrefied PKS

Results and discussion

The percentage of moisture, VM, and ash contents of torrefied PKS are obtained from the TGA, while the percentage of FC content of torrefied PKS are obtained from the moisture, VM, and ash contents data of the torrefied and raw PKS which is then used to determine the FC content by difference, as per stated in section 2.1.3 (*refer Appendix D*). The results of the proximate analysis of raw and torrefied PKS are shown in the figure below for the influence of temperature and residence time respectively.

- Moisture content

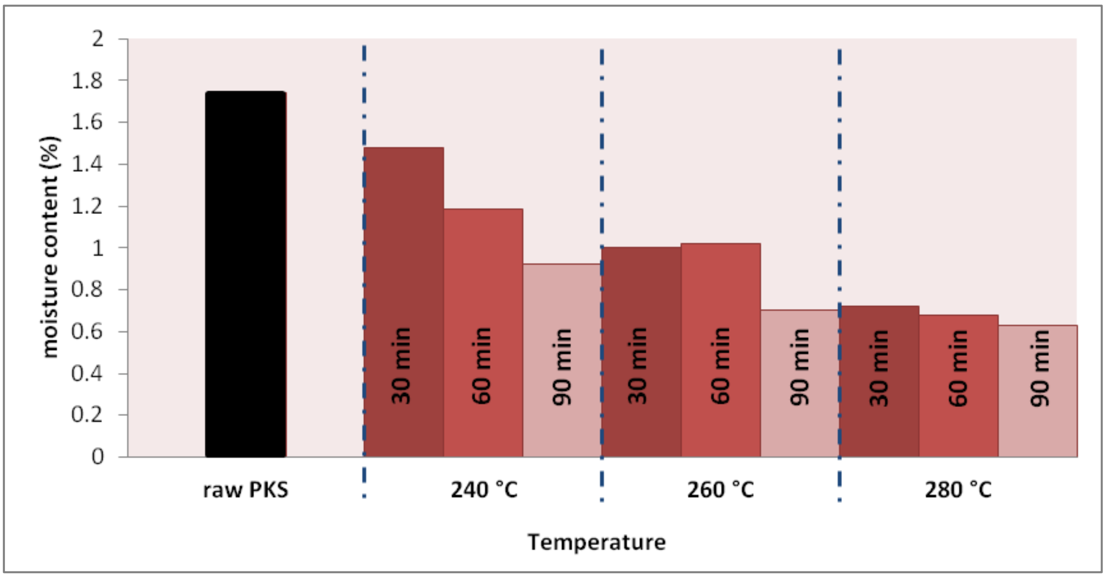

Figure 4.19: Influence of temperature towards moisture content of torrefied PKS

From the above figure, the percentage of moisture content decrease with the increase in the torrefaction temperature. And the similar results were also reported from a study done by Pimchuai et al. (2010) for the torrefaction of rice husks, sawdust, peanut husks, bagasse, and water hyacinth under varying temperature and residence time of 250, 270, and 300°C and 1, 1.5, and 2 hours respectively.

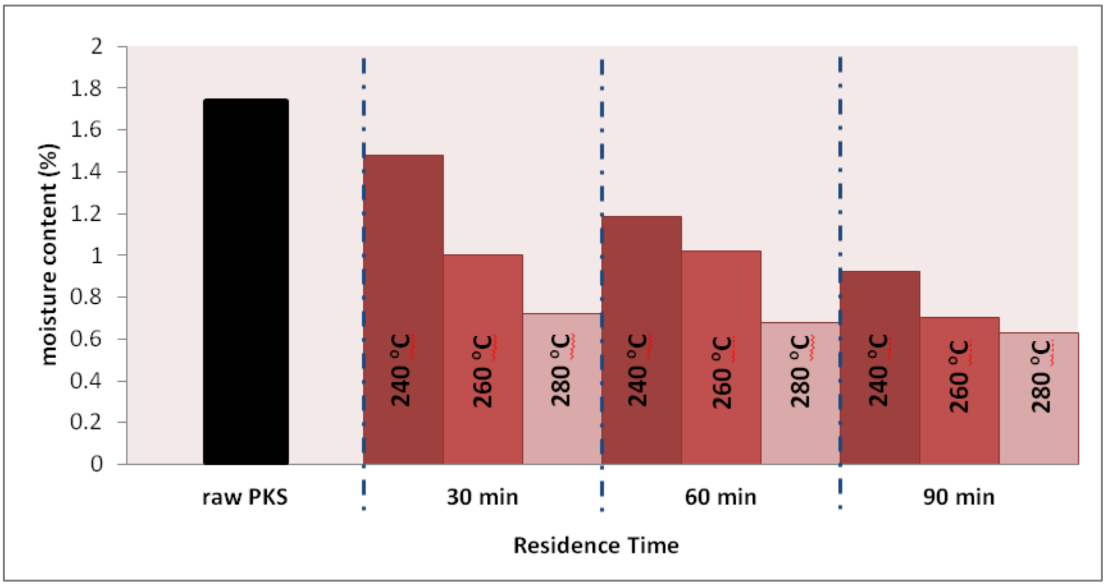

Figure 4.20: Influence of residence time towards moisture content of torrefied PKS

From the above figure, the percentage of moisture content decrease with the increase in the residence time. And the similar results were also reported from a study done by Pimchuai et al. (2010) for the torrefaction of rice husks, sawdust, peanut husks, bagasse, and water hyacinth under varying temperature and residence time of 250, 270, and 300°C and 1, 1.5, and 2 hours respectively.

From both figure, it is also being noticed that the temperature gives more effect on torrefaction than the residence time. The similar results were also reported in a study done by Pimchuai et al. (2010). Overall, the moisture content of torrefied PKS decrease about 15-64%.

- VM content

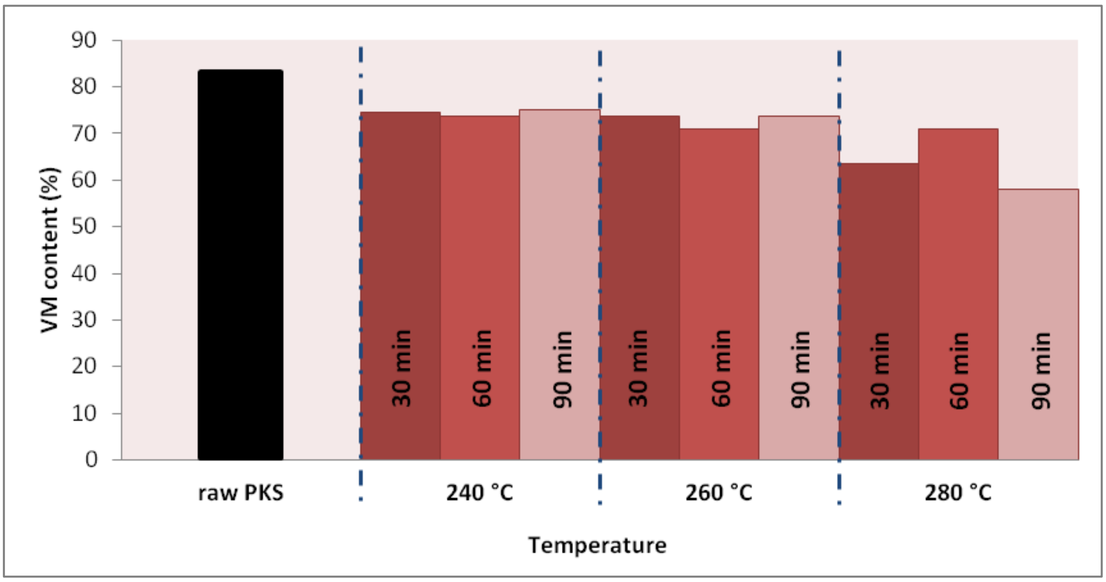

Figure 4.21: Influence of temperature towards VM content of torrefied PKS

From the above figure, the percentage of VM content decrease with the increase in the torrefaction temperature. And the similar results were also reported from a study done by Pimchuai et al. (2010) for the torrefaction of rice husks, sawdust, peanut husks, bagasse, and water hyacinth under varying temperature and residence time of 250, 270, and 300^{o}C and 1, 1.5, and 2 hours respectively.

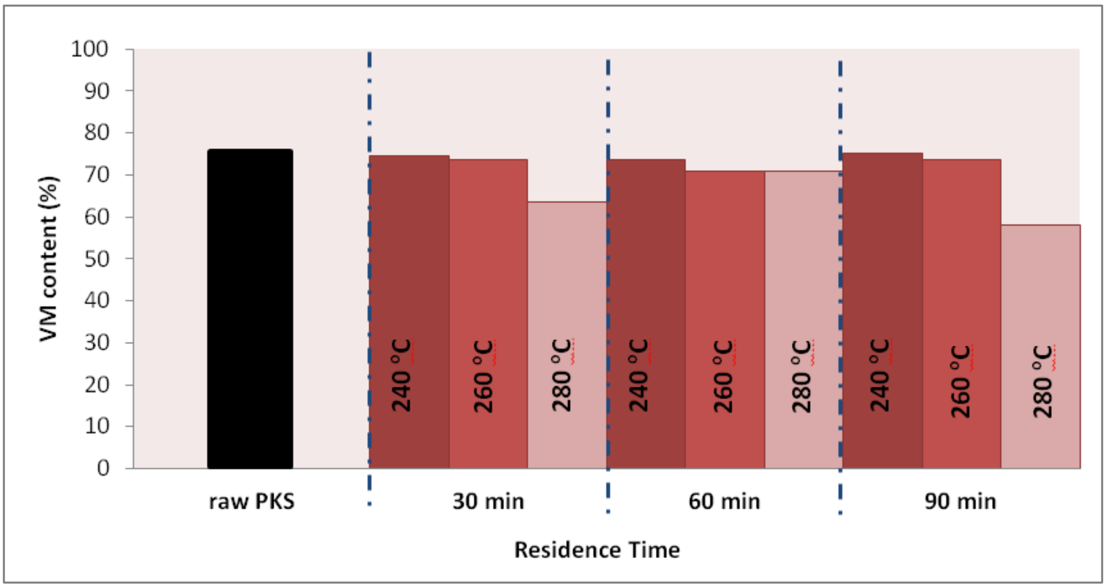

Figure 4.22: Influence of residence time towards VM content of torrefied PKS

From the above figure, the percentage of VM content decrease with the increase in the residence time. And the similar results were also reported from a study done by Pimchuai et al. (2010) for the torrefaction of rice husks, sawdust, peanut husks, bagasse, and water hyacinth under varying temperature and residence time of 250, 270, and 300°C and 1, 1.5, and 2 hours respectively.

From both figure, it is also being noticed that the temperature gives more effect on torrefaction than the residence time. The similar results were also reported in a study done by Pimchuai et al. (2010). Overall, the VM content of torrefied PKS decrease about 10-30%.

- Ash content

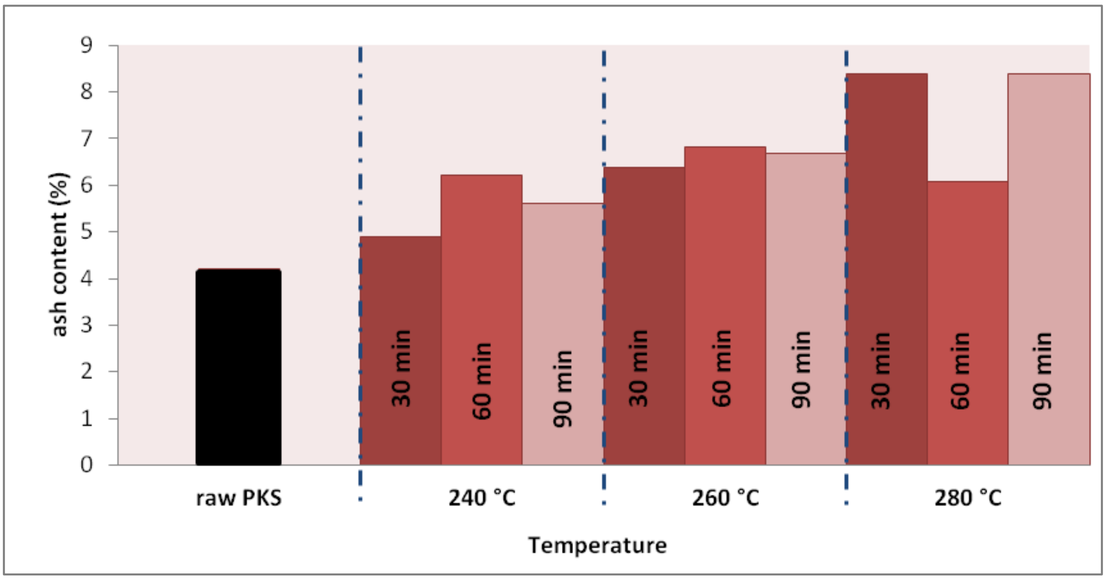

Figure 4.23: Influence of temperature towards ash content of torrefied PKS

From the above figure, the percentage of ash content increase with the increase in the torrefaction temperature. And the similar results were also reported from a study done by Pimchuai et al. (2010) for the torrefaction of rice husks, sawdust, peanut husks, bagasse, and water hyacinth under varying temperature and residence time of 250, 270, and 300°C and 1, 1.5, and 2 hours respectively. However, the results is differ from a study done by Uemura et al. (2010) which reported that the ash content of PKS is decrease with the increase in the torrefaction temperature.

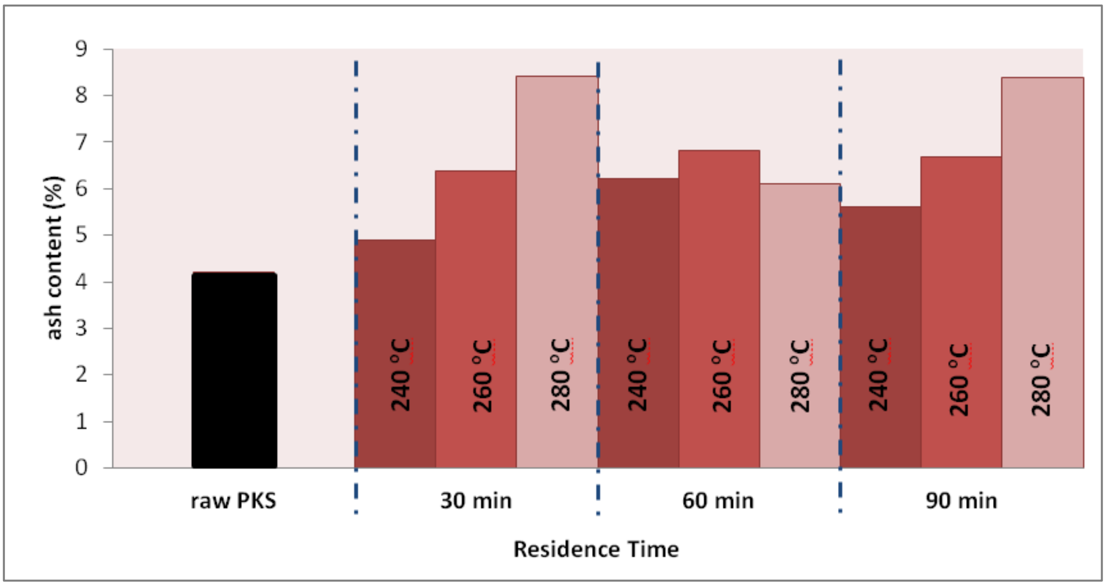

Figure 4.24: Influence of residence time towards ash content of torrefied PKS

From the above figure, the percentage of ash content decrease with the increase in the residence time. And the similar results were also reported from a study done by Pimchuai et al. (2010) for the torrefaction of rice husks, sawdust, peanut husks, bagasse, and water hyacinth under varying temperature and residence time of 250, 270, and 300°C and 1, 1.5, and 2 hours respectively.

From both figure, it is also being noticed that the temperature gives more effect on torrefaction than the residence time. The similar results were also reported in a study done by Pimchuai et al. (2010). Overall, the ash content of torrefied PKS increase about 16-99%.

- FC content

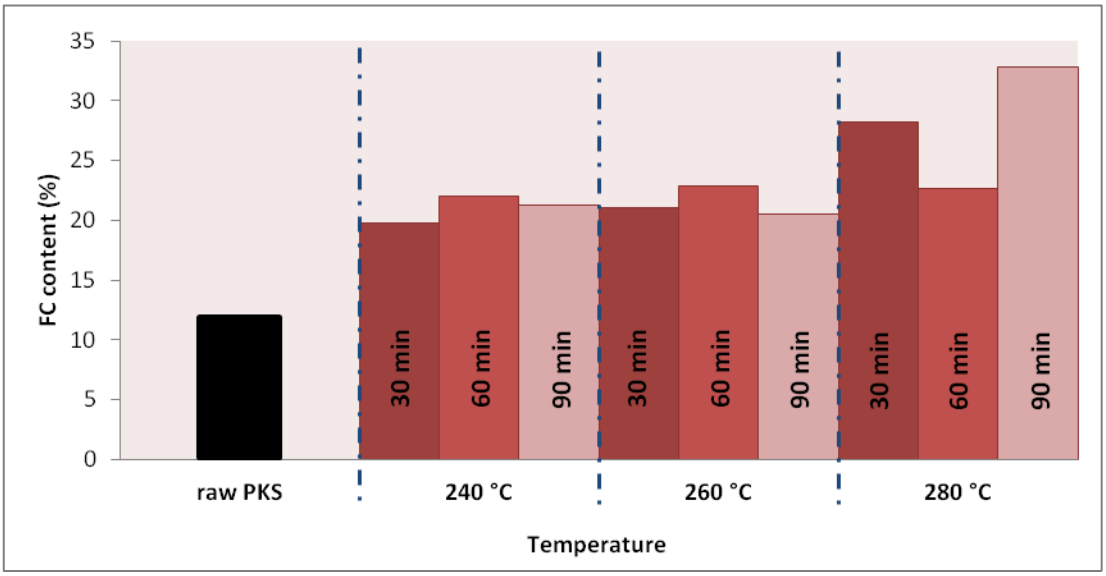

Figure 4.25: Influence of temperature towards FC content of torrefied PKS

From the above figure, the percentage of FC content increase with the increase in the torrefaction temperature. And the similar results were also reported from a study done by Pimchuai et al. (2010) for the torrefaction of rice husks, sawdust, peanut husks, bagasse, and water hyacinth under varying temperature and residence time of 250, 270, and 300^{o}C and 1, 1.5, and 2 hours respectively.

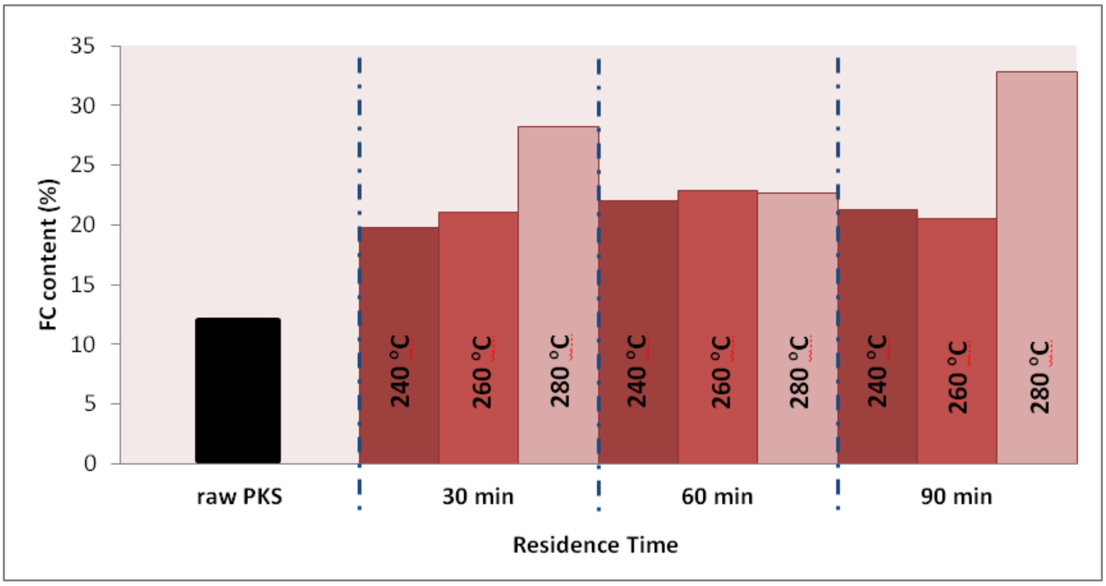

Figure 4.26: Influence of residence time towards FC content of torrefied PKS

From the above figure, the percentage of FC content decrease with the increase in the residence time. And the similar results were also reported from a study done by

Pimchuai et al. (2010) for the torrefaction of rice husks, sawdust, peanut husks, bagasse, and water hyacinth under varying temperature and residence time of 250, 270, and 300^{o}C and 1, 1.5, and 2 hours respectively.

From both figure, it is also being noticed that the temperature gives more effect on torrefaction than the residence time. The similar results were also reported in a study done by Pimchuai et al. (2010). Overall, the FC content of torrefied PKS increase about 85-208%.

CHAPTER 5
CONCLUSION & RECOMMENDATION

5.1 CONCLUSION

Palm kernel shell (PKS) characteristic and properties shows a good potential as a renewable energy sources. Throughout this project, torrefied PKS had been prepared using different temperature and residence time. Torrefaction greatly improved the properties of PKS. The experimental and analyses results shows that the mass and energy yields of torrefied PKS decrease with the increase of the torrefaction temperature and residence time. The C:C bond increase as the C content increase, while C:H bond decrease as the H content decrease with the increase of torrefaction temperature and residence time. The N contents are approximately constant after torrefaction and the low sulphur contents before and after torrefaction indicates that the PKS is an environmental friendly fuel. The HHV of torrefied PKS increase within the range of 7-19% with the increase of the torrefaction temperature and residence time. The fixed carbon content of torrefied PKS increased, while the moisture and volatile matter decrease. Overall, the temperature had stronger effects towards torrefaction process.

5.2 RECOMMENDATION

More time and facilities is needed to analyse the PKS since some results obtained do not meet the results which has been reported by some researchers on previous papers. It is also recommended that more analyses to be done in order to determine the upgrade properties of the PKS such as hydrophobic test of torrefied PKS, combustibility test, tenacious test of torrefied PKS, and etc. More understanding towards the properties of torrefied PKS can also be done by analysing the chemical composition of torrefied PKS in more detail, to determine its main components and degree of polymerization. Knowledge of the hemicellulose content could enable more accurate determination of the required residence time at different temperatures.

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APPENDICES

Appendix A

<u>Mass and energy yield (%) of torrefied PKS.</u>

	torrefaction temperature °C								
	240			260			280		
	torrefaction time (min)								
	30	60	90	30	60	90	30	60	90
mass yield (%)	76.8	72.7	69.5	66.6	62.3	59	56.6	49.3	46.2
energy yield (%)	81.8	77.5	74.6	73.3	71	65.7	66	55.7	54.6
energy density	1.07	1.07	1.07	1.1	1.14	1.11	1.16	1.13	1.18

- The mass yield (%) is calculated using equation:

$$Mass\ Yield\ (\%) = \frac{torrefied\ product\ \ weight}{raw\ material\ (dry)\ weight} \times 100\%$$

- The energy yield (%) is calculated using equation:

$$Energy\ yield\ (\%) = \frac{torrefied\ product\ weight}{raw\ material\ (dry)\ weight} \times \frac{HHV_{product}}{HHV_{raw(dry)}} \times 100\%$$

- The HHV of product and raw material is obtained from calorific value analysis result.

- The energy density is calculated using equation:

$$Energy\ density = \frac{energy\ yield\ (\%)}{mass\ yield\ (\%)}$$

Appendix B

<u>Elementary and ash analyses (wt.%) of raw and torrefied PKS.</u>

		torrefaction temperature °C								
		240			260			280		
		torrefaction time (min)								
elements	raw material	30	60	90	30	60	90	30	60	90
C	46.53	49.08	49.26	49.90	50.84	50.50	51.49	50.26	51.16	53.07
H	5.85	5.10	4.37	3.92	4.68	4.36	4.06	4.38	4.23	3.97
N	0.89	1.07	1.02	1.07	1.03	1.12	1.08	1.10	1.10	1.14
S	0.12	0.12	0.07	0.00	0.03	0.02	0.01	0.00	0.02	0.00
O	42.32	39.67	39.00	39.45	36.99	37.11	36.61	35.80	37.36	33.37
ash (dry)	4.29	4.96	6.28	5.67	6.43	6.89	6.73	8.46	6.13	8.44

- The data for the elementary (CHNS) content is obtained from ultimate analysis result.

- The O content is calculated using equation:

$$O(\%) = 100 - C(\%) - H(\%) - N(\%) - S(\%) - ash\ (dry)(\%)$$

- The ash content on 'dry basis' is obtained from proximate analysis result.

Appendix C

HHV of raw and torrefied PKS.

Temperature (^{o}C)	residence time (min)	HHV (MJ/kg)	HHV rise (%)
240	30	19.702	4.72
	60	19.715	4.79
	90	19.856	5.54
260	30	20.351	8.17
	60	21.085	12.07
	90	20.587	9.42
280	30	21.542	14.50
	60	20.913	11.16
	90	21.856	16.17
raw PKS		18.814	

- The data for HHV of raw and torrefied PKS obtained from calorific value analysis result.

- The data for HHV rise (%) is calculated using:

$$HHV\ rise\ (\%) = \frac{HHV_{product} - HHV_{raw}}{HHV_{raw}} \times 100\%$$

Appendix D

HHV rise of torrefied PKS.

Temperature (°C)	residence time (min)	HHV rise (%)
240	30	4.72
	60	4.79
	90	5.54
260	30	8.17
	60	12.07
	90	9.42
280	30	14.50
	60	11.16
	90	16.17

- The data for HHV rise (%) is calculated using:

$$HHV\ rise\ (\%) = \frac{HHV_{product} - HHV_{raw}}{HHV_{raw}} \times 100\%$$

Appendix E

Proximate analysis result (wt. %) for raw and torrefied PKS

		torrefaction temperature (°C)								
		240			260			280		
		torrefaction time (min)								
proximate	raw material	30	60	90	30	60	90	30	60	90
moisture	1.74	1.48	1.19	0.92	1.00	1.02	0.70	0.72	0.68	0.63
VM	83.38	74.56	73.77	75.15	73.66	70.84	73.63	63.56	70.84	58.07
VM (dry)	84.86	75.68	74.66	75.85	74.40	71.57	74.15	64.02	71.33	58.44
ash	4.22	4.89	6.21	5.62	6.37	6.82	6.69	8.40	6.09	8.39
ash (dry)	4.29	4.96	6.28	5.67	6.43	6.89	6.73	8.46	6.13	8.44
FC	10.66	19.77	22.04	21.25	21.06	22.83	20.51	28.25	22.72	32.86
FC (dry)	10.85	20.07	22.31	21.45	21.27	23.07	20.65	28.45	22.88	33.07

- The data for the moisture, volatile matter (VM), and ash content is obtained from proximate analysis result.

- The fixed carbon (FC) content on 'wet basis' is calculated using equation:

$$FC\ (\%) = 100 - moisture(\%) - VM(\%) - ash(\%)$$

- The volatile matter (VM) content on 'dry basis' is calculated using equation:

$$VM\ (dry)\ (\%) = \frac{VM\ (\%)}{100 - moisture(\%)}$$

- The ash content on 'dry basis' is calculated using equation:

$$ash\ (dry)\ (\%) = \frac{ash\ (\%)}{100 - moisture(\%)}$$

- The fixed carbon (FC) content on 'dry basis' is calculated using equation:

$$FC\ (dry)\ (\%) = \frac{FC\ (\%)}{100 - moisture(\%)}$$