ASSESSMENT OF COCONUT FLESH WASTE AND ITS SOLID BIOCHAR FOR BRIQUETTE PRODUCTION

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by

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LIST OF SYMBOLS

α	conversion degree
cm	centimeter
CO_2/kWh_e	carbon dioxide emission per net kWh energy produced
°C	degree Celsius
°C/min	degree Celsius per minute
g	gram
g/min	gram per minute
GWh	gigawatt-hour (1 GWh = 1000,000 kWh)
kg/cm^2	kilogram per square centimeter (1 kg/cm^2 = 1000 g/cm^2 =14.2233 psi = 0.9807 bar)
kg	kilogram
kg/m^3	kilogram per cubic meter
kJ/mol	kilojoules per mole
km^2	square kilometer
kWh	kilowatt-hour
m^3	cubic meter
mf wt. %	weight percent on moisture-free basis
mg	milligram
min	minute
MJ/kg	megajoules per kilogram
ml	milliliter
Mt	million tons (1 ton = 907.185 kg)
MWh	megawatt-hour (1 MWh = 1000 kWh)
Nm^3	normal cubic meter
wt. %	weight percent
yr^{-1}	per year
μm	micrometer
%	percent

LIST OF ABBREVIATIONS

AC	Ash content
APCC	Asian and Pacific Coconut Community
ASTM	American Society for Testing and Materials
BB	CFW biochar briquette
BB+R	CFW biochar briquette with additional reinforce material
BFD	Blast furnace dust
BPA	Biomass Power Association
C	Carbon
CB1	Commercial briquette 1: mangrove-wood charcoal briquette 1
CB2	Commercial briquette 2: mangrove-wood charcoal briquette 2
CB3	Commercial briquette 3: coconut shell charcoal briquette
CFW	Coconut flesh waste
CFWB	CFW biochar
CH	Coconut husk
CMW	Coconut meal waste
CO	Carbon monoxide
COVID-19	Coronavirus
CS	Coconut shell
CST	Corn starch
CO_2	Carbon dioxide gas
CP	Coconut peak
CH_4	Methane
$C_2H_4O_2$	Acetic acid
$C_6H_{12}O_6$	Glucose
DIN	Deutsche Industrie Norm
DOSM	Department of Statistics Malaysia
DTG	Derivative thermogravimetry
E_a	Activation energy

EC	Energy Commission
ECN	Energy Research Center of the Netherlands
EFB	Empty fruit bunch
EFWO	Activation energy from the FWO method
EKAS	Activation energy from the KAS method
EMC	Equilibrium moisture content
FAO	Food and Agriculture Organization of the United Nations
FiT	Feed-In Tariff
FWO	Flynn–Wall–Ozawa
GHG	Greenhouse gases
H	Hydrogen
HHV	Higher heating value
HRC	High-rank coal
HVC	High-volatile coal
H_2O	Water
IEA	International Energy Agency
IRENA	The International Renewable Energy Agency
K	Potassium
KAS	Kissinger–Akahira–Sunose
LHV	Lower heating value
LRC	Low-rank coal
MEA	Malaysian Economic Association
MESTECC	Ministry of Energy, Science, Technology, Environment and Climate Change
MCO	Movement Control Order
MF	Mesocarp fibre
MSW	Municipal solid waste
N	Nitrogen
Na	Sodium
NaOH	Sodium hydroxide

$NaClO_2$	Sodium chlorite
NO_x	Nitrogen oxides
NR	Not reported
N_2	Nitrogen gas
O	Oxygen
OECD	Organization for Economic Co-operation and Development
OPF	Oil palm frond
OPT	Oil palm trunk
P	Phosphorus
PKS	Palm kernel shell
POME	Palm oil mill effluent
PV	Photovoltaics
RB	Raw CFW briquette
RE	Renewable energy
S	Sulfur
SCW	Solid coconut waste
SEDA	Sustainable Energy Development Authority
SO_x	Sulfur oxides
SO_2	Sulfur dioxide gas
SS	Sodium silicate
TG	Thermogravimetry
UNFCCC	United Nations Framework Convention on Climate Change
USM	Universiti Sains Malaysia
VM	Volatile matter
W	Distilled water
WEC	World Energy Council

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PENILAIAN TERHADAP SISA HAMPAS KELAPA DAN PEPEJAL BIOARANGNYA UNTUK PENGHASILAN BRIKET

ABSTRAK

Malaysia dikurniakan sumber boleh diperbaharui yang banyak seperti biojisim. Beberapa dasar tenaga telah dimulakan untuk menggalakkan penggunaan biojisim bagi penjanaan tenaga boleh diperbaharui sekali gus mencapai pembangunan mampan. Satu kaedah yang patut diberi perhatian ialah penukaran biojisim melalui pirolisis untuk pengeluaran biofuel. Objektif utama kajian ini adalah untuk mengkaji potensi bioarang sisa isi kelapa (CFW) daripada pirolisis untuk pengeluaran biofuel pepejal (briket). Bioarang CFW dihasilkan melalui pirolisis sederhana dari 200°C hingga 300°C dan pirolisis perlahan dari 350°C hingga 600°C. Sebelum proses pirolisis, CFW mentah telah dicirikan untuk menilai kesesuaiannya sebagai sampel bahan mentah. Analisis proksimat menunjukkan bahawa CFW mentah mengandungi bahan meruap yang tinggi iaitu 91.03 mf wt. % dan kandungan abu yang sangat rendah iaitu 1.05 mf wt. %. Kandungan selulosanya yang tinggi sebanyak 73.17% menyumbang kepada nilai pemanasannya yang tinggi iaitu 28.85 MJ/kg, iaitu lebih tinggi daripada biojisim lain termasuk sisa-sisa kelapa dan kelapa sawit. Tenaga pengaktifan CFW mentah yang dikira menggunakan kaedah KAS dan FWO juga rendah, masing-masing pada 173.82 kJ/mol dan 174.93 kJ/mol. Kesemua kriteria ini menunjukkan bahawa CFW mentah adalah bahan suapan yang sesuai untuk proses penukaran termokimia seperti pirolisis. Selain itu, kandungan nitrogen dan sulfurnya sangat rendah, kurang daripada 2 mf wt. %, yang menunjukkan bahawa CFW mentah ialah bahan mentah yang mesra alam. Suhu pirolisis yang lebih rendah menghasilkan lebih banyak bioarang CFW dengan hasil tenaga yang lebih tinggi. Bioarang CFW yang dihasilkan pada 300°C mempunyai nilai pemanasan tertinggi, yang digunakan untuk proses briket. Tiga jenis pengikat yang berbeza termasuk pengikat organik, pengikat bukan organik dan pengikat kompaun telah digunakan dalam proses briket untuk mengkaji kesannya ke atas sifat briket. Kemudian, bahan diperkuatkan, sabut kelapa dimasukkan ke dalam campuran briket untuk menyiasat kesannya ke atas sifat briket. CFW mentah juga melalui proses briket untuk dibandingkan sifatnya dengan briket bioarang. Di antara ketiga-tiga bahan pengikat, briket yang dibuat dengan pengikat bukan organik mempunyai nilai pemanasan tertinggi, ketumpatan tertinggi dan kadar pembakaran paling rendah. Bahan diperkuatkan meningkatkan lagi sifat briket terutamanya pada ketumpatan dan kadar pembakarannya. Beberapa sifat briket CFW memenuhi keperluan kualiti standard antarabangsa untuk briket komersial dan setanding dengan briket-briket komersial tempatan, menunjukkan potensinya yang tinggi untuk aplikasi biofuel pepejal.

ASSESSMENT OF COCONUT FLESH WASTE AND ITS SOLID BIOCHAR FOR BRIQUETTE PRODUCTION

ABSTRACT

Malaysia is endowed with huge renewable resources such as biomass. Several energy policies have been initiated to encourage the use of biomass for renewable energy generation thus attaining sustainable development. One noteworthy method is the conversion of biomass via pyrolysis for biofuel production. The main objective of this study is to investigate the potential of coconut flesh waste (CFW) biochar from pyrolysis for solid biofuel (briquette) production. The CFW biochar was produced via mild pyrolysis from 200°C to 300°C and slow pyrolysis from 350°C to 600°C. Before the pyrolysis process, the raw CFW was characterized to evaluate its suitability as a sample of feedstock. The proximate analysis shows that raw CFW contains a high volatile matter of 91.03 mf wt. % and very low ash content of 1.05 mf wt. %. Its high cellulose content of 73.17% contributed to its high heating value of 28.85 MJ/kg, which is higher than the other biomass such as coconut husk, coconut shell and oil palm empty fruit bunches. The activation energies of raw CFW calculated using the KAS and FWO methods were also low at 173.82 kJ/mol and 174.93 kJ/mol, respectively. All of these criteria show that raw CFW is a suitable feedstock for the thermochemical conversion process such as pyrolysis. Additionally, its nitrogen and sulfur contents are very low, less than 2 mf wt. %, which indicates that raw CFW is an environmental friendly feedstock. Lower pyrolysis temperature produces more CFW biochar with higher energy yield. The CFW biochar produced at 300°C has the highest heating value, which was used in the briquetting process. Three different types of binders including organic, inorganic and compound binders were used in the briquetting process to study the effect on the properties of briquettes. Then, a reinforced material, coconut husk was introduced into the briquette mixture to investigate the effect on the briquette’s properties. The raw CFW also go through the briquetting process to compare the properties with its biochar briquettes. Briquettes made with inorganic binder have the highest heating value, highest density and lowest burning rate among the three binders. The reinforce material improved the briquette’s properties, especially on its density and burning rate. Some of the properties of CFW briquettes meet the international standard quality requirement for commercial briquettes and comparable to local commercial briquettes, which indicates its high potential for solid biofuel applications.

CHAPTER 1

INTRODUCTION

1.1 Energy Demand and Natural Fuel Resources

The world energy demand had constantly increased throughout the years. This scenario is mainly shaped by the increment of the human population and the constant evolution of technology since year 1970 (WEC, 2016). Electricity is the second-highest source of energy consumption in Malaysia after the oil product. According to International Energy Agency (IEA), the electric power consumption per capita in this country increased from 3.3 MWh to 5.1 MWh from the year 2008 to 2019 (IEA, 2022).

Electricity in Malaysia has been mainly generated by natural gas. Starting from year 2017, the statistics showed that coal had dominant the source of electricity generation and cover more than 42.59 % of electricity generation in Malaysia (EC, 2021). Coal is a cheap and widely available option for a source of electricity. However, it cost high emissions of nitrogen dioxides (NO_x), sulfur oxides (SO_x) and greenhouse gases (GHG) (Oliveira, 2018). Coal releases more than twice the amount of carbon dioxide (CO_2) released by natural gas, from the same power generated. The GHG emissions per kWh electricity generated from the combustion of coal and natural gas are 900 g CO_2/kWhe and 400 g CO_2/kWhe respectively (Babatunde et al., 2018).

Demand for energy generated by natural resources results in negative environmental impact and leads to its depletion. According to a statistic by Energy Commission (EC) Malaysia, the total reserves of natural resources in Malaysia are decreasing yearly. From year 2015 to 2018, the total reserves of crude oil and natural gas declined by 22.92% and 20.80% respectively (EC, 2021). Meanwhile, for the coal reserves, Worldometer estimated that Malaysia will only have about 6 years of coal left, which is calculated according to the current annual usage levels (Worldometer, 2022). In line with the environmental sustainability dimension in The Twelfth Malaysia Plan (MEA, 2019), Malaysia needs to further enhance the use of its sustainable energy sources to mitigate these problems. Among the best ways to achieve this goal is by maximizing the utilization of biomass which is one of the huge renewable energy sources in Malaysia.

1.2 Biomass as Sustainable Renewable Energy Source

Biomass is any renewable organic matter. Biomass grows by absorbing carbon from the atmosphere. If biomass is burned, its carbon content will be released back into the atmosphere. Hence, biomass-derived fuel or biofuel is considered a carbon-neutral fuel (Chen et al., 2019). Biomass is usually low in nitrogen, sulfur and ash content. Therefore, the gas emitted from the combustion of biofuel, for example, the NO_x and SO_x are less harmful compared to the natural fuel resources (Jahirul et al., 2012). Biomass is not only greener but its utilization also can avoid it from left to natural decay. As biomass decay, GHG such as CO_2 and methane would release into the atmosphere (Hunt et al., 2010).

Energy generated from the conversion of solid, liquid and gaseous products derived from biomass is known as bioenergy (OECD/IEA and FAO, 2017). Bioenergy receives great attention as an alternative source of energy due to its promising renewable resource and eco-friendly. There are four main renewable energy (RE) resources in Malaysia namely solar PV, biomass, biogas and small hydro. According to the Annual Report 2020 done by Sustainable Energy Development Authority (SEDA) Malaysia, biomass is the second-highest source of RE after the solar PV. Table 1.1 shows that from year 2012 to 2020, biomass contributed 27% of the total energy generated from RE projects in Malaysia. The total energy generated from RE projects is 6,892.79 GWh, where 1868.30 GWh was generated by biomass resources. The report also stated that using biomass as RE resources for 9 years from 2012 to 2020 had avoided more than 1 million tonnes of CO_2 released to the environment (SEDA, 2021).

Table 1.1 Annual energy generation (GWh) from renewable energy projects in Malaysia from year 2012 to 2020 (SEDA, 2021)

Year	**Resources**				
	Solar PV	**Biomass**	**Biogas**	**Small Hydro**	**Total (GWh)**
2012	6.93	104.54	7.56	28.68	147.71
2013	54.5	220.55	24.46	79.05	378.56
2014	194.25	200.16	50.27	69.58	514.26
2015	277.5	246.73	63.34	56.66	644.23
2016	359.54	248.48	107.11	50.28	765.41
2017	424.16	247.21	216.33	75.55	963.25
2018	467.89	226.09	251.78	89.67	1035.43
2019	471.9	225.22	314.29	220.6	1232.01
2020	420.43	149.32	384.91	257.27	1211.93
Total (GWh)	2677.10	1868.30	1420.05	927.34	6892.79
% of Total	39%	27%	21%	13%	100%

1.3 Problem Statement

The growing world population and technological advances increased the energy demand. As stated before in Section 1.1, this situation had created crises such as environmental degradation including global warming and the depletion of natural resources. The alternative RE is necessary to mitigate these global issues. The worldwide availability and potential for clean energy make biomass a growing RE resource. There are many biomass in Malaysia did not yet being explored its potential for solid biofuel feedstock. Knowledge about the thermal behavior of biomass will help to set up the proper way to specifically upgrade it for solid biofuel application. Additionally, exploring the characteristics of various biomass in Malaysia is beneficial in designing and optimizing its conversion process according to the demand application.

Coconut is the most consumed fruit in Malaysia. There is about 24.30 kg of coconut was consumed by a Malaysian in year 2020 (DOSM, 2021a). The highest demand from coconut is in the form of coconut oil and coconut milk product (APCC, 2017). This production will be accompanied by plenty of coconut residues including the coconut shell, coconut husk and coconut flesh waste (CFW) (Raghavarao et al., 2008). This makes coconut residue one of the potential biomass resources for RE in Malaysia. Raw CFW is the solid coconut residue produced after the extraction of coconut milk from grated coconut flesh. Raw CFW is usually left to rot as food waste. Meanwhile, some of them have been used as fertilizer or food for livestock and poultry animals (Sulaiman et al., 2014, Vetayasuporn, 2007). Some studies have been conducted using raw CFW as the feedstock, with the primary goal of producing liquid biofuel (Sulaiman et al., 2013, Sulaiman et al., 2014, Sulaiman and Ruslan, 2017, Talha and Sulaiman, 2018). To date, the fuel properties of raw CFW have not been fully elucidated and there is still a lack of evaluation for its potential in solid biofuel application.

Biomass usually have high moisture and ash content, low bulk density, low energy content and is difficult to store, handle and transport. Hence, biomass used for energy production is considered low due to this lack of fuel properties (Ani, 2016). The combination of pyrolysis and briquetting are two processes that can transform and upgrade the fuel properties of biomass for solid biofuel application (Shukla and Vyas, 2015). Mild pyrolysis also known as torrefaction transforms biomass into a biochar product with better fuel value compared to its raw material (Saadon et al., 2014). Meanwhile, briquetting is a process where the solid product from pyrolysis is mixed with binders in a certain ratio and pressed into a mold. Not all briquette was created equal. The physicochemical properties of the briquette depend on the type of feedstock and the operating parameters of pyrolysis and briquetting itself. For example, during pyrolysis, the main parameters such as the temperature range, heating rate and residence time should be concerned. Meanwhile, for the briquetting process, the important parameters include the different mix ratios (Shukla and Vyas, 2015) and the types of binder (Zhang et al., 2018). Understanding the physicochemical characterization of a briquette was beneficial for identifying its appropriate applications and for upgrading them.

It is important to get a comprehensive understanding on the fuel properties of a biomass prior to using it as a feedstock for briquette. Thus, the urge to the study of physicochemical properties of CFW as a potential feedstock for briquette has been raised in this study. A fundamental understanding of the optimal pyrolysis and briquetting parameters for CFW biochar is crucial to advance this knowledge for more sustainable applications or possibly for commercial purposes. The study will allow the design to produce high-quality CFW briquette and further boost the possibility of CFW utilization into green power, biofuels and bio-based products. Meanwhile, from the waste management viewpoint, the utilization of CFW for briquette solid fuel production is a cleaner alternative to dispose these wastes. The detailed knowledge about this particular biomass may provide information for its proper usage instead of leaving it as food waste.

1.4 Research Objectives

The objectives of the present study are:

i) To evaluate the physicochemical characteristics of CFW as a potential biomass feedstock for pyrolysis process and biochar production;

ii) To examine the effect of pyrolysis temperature on the yield and physicochemical properties of CFW biochar;

iii) To produce CFW biochar briquette using various types of binders from organic, inorganic and compound binders and study the effect on the briquette properties;

iv) To determine the effect of additional reinforce material in the CFW biochar briquette on the briquette properties;

v) To compare the properties of CFW briquettes with the standard values and commercial briquettes.

1.5 Scope of Study

The main work of this research will focus on the making of briquette from CFW biochar. This advancement is made to improve knowledge about the potential of raw CFW for solid fuel application rather than focusing solely on its liquid products, as reported by numerous existing published works. Correspondingly, the research begins with determining the properties of raw CFW to identify and evaluate its suitability for conversion to solid biochar via the pyrolysis process. Because the goal is to produce solid biochar, two types of pyrolysis, mild pyrolysis and slow pyrolysis were chosen, each with a different temperature range. The decision to use these two types of pyrolysis was made because they both operate at a low heating rate, which can produce more biochar product than fast pyrolysis, which primarily produces the liquid product. Neither the liquid nor the gas product was examined any further in this study. The pyrolysis process aims to identify the optimal temperature for producing a high yield of CFW biochar with good fuel properties (high heating value and energy content). The selected CFW biochar will then be subjected to the briquetting process to further improve its physicochemical and fuel properties.

The briquetting process will be done using various parameters including different types of binder and briquette mixture to study the effect on briquette properties. Meanwhile, other parameters such as compression pressure and relaxation time are fixed. The three types of binder are the organic binder (corn starch), inorganic binder (sodium silicate) and compound binder (the mixture of corn starch and sodium silicate). In terms of further enhancing the density of briquette, coconut husk will be introduced to the briquette mixture as a reinforce material. The effect of additional reinforce material will be investigated and compared to briquette without reinforce material. The raw CFW will also go through the briquetting process to compare its properties to the briquette made from CFW biochar. Only two main fuel properties of the briquettes will be focused in this research which is the density and the burning rate, considering it is as an assessment study for the potential of CFW for solid fuel resource. The properties of the briquettes were compared with the international standard quality requirement for commercial briquettes and local commercial briquettes, to evaluate its potential as a source of solid fuels.

1.6 Thesis Outline

The five chapters of this thesis are organised as follows:

Chapter 1 − Introduction

This chapter briefly introduces the research topic and basic idea of this thesis, including the problem statement, objectives and scope of this research.

Chapter 2 − Literature Review

The overview of biomass is thoroughly discussed in this chapter. More focus was given to the biomass and bioenergy in Malaysia and further down to the detailed information about the coconut wastes. Then, the next section of this chapter provides information about pyrolysis as one of the biomass conversion processes. The types of pyrolysis processes such as mild pyrolysis and slow pyrolysis were further elaborated. The effect of pyrolysis temperature on the solid product (biochar) yield and its fuel properties were also explained in this chapter. The biomass briquetting process will be discussed in the next section of this chapter. Starting from the overview of biomass briquette for biofuel application and then focusing on the effect of various briquetting parameters on the briquette qualities. The two main focuses of the briquetting parameters include the types of binder and the effect of additional reinforce material in the briquette mixture. Finally, the chapter concludes with a summary.

Chapter 3 − Methodology

Chapter 3 described the preparation of raw CFW as feedstock and the methods used to characterize the feedstock before the pyrolysis process. Then, this chapter elaborated on the experimental setup and the procedures of mild pyrolysis and slow pyrolysis experiment for CFW biochar production. The temperature parameter was varied for both pyrolysis processes, to study the effect on the CFW biochar product. Then, the analyses used to determine the chemical properties and the caloric value of the CFW biochar product were explained in detail. The selected CFW biochar from the previous pyrolysis process will undergo the briquetting process with various briquetting parameters. The following section of this chapter will explain the briquetting process, starting from the set-up to the varied parameters which include the type of binders and the additional reinforce material. The section followed by the elaboration on the analyses used to characterize the CFW briquettes, which comprises a few parts including the physical, chemical and fuel combustion properties.

Chapter 4 − Results and Discussion

Chapter 4 consists of a few main sections. The first section will cover the results on the characteristics of raw CFW as the feedstock for this study. Then, the two following sections will present and describe the data from mild pyrolysis and slow pyrolysis experiment. The main focus of the data is on the CFW biochar product. The effect of various temperatures on the percentage yield and compositions of CFW biochar will be further discussed. The following section will summarize and compare the results obtained from the previous mild pyrolysis and slow pyrolysis. Then, the fifth section will cover the results from the briquetting of CFW. This section will be divided into two parts. The first part is about the briquetting of CFW biochar with different types of binder. The second part focuses on the briquetting of raw CFW and CFW biochar with additional reinforce material. The discussion on both parts will be focusing on the briquette's properties. A summary of the research findings was presented at the end of the chapter.

Chapter 5 − Conclusion and Recommendations

This final chapter provided a conclusion remark based on the work presented in the previous chapter. This chapter also brings together some recommendations for future study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The previous chapter is an introduction to the world energy demand, how it brings negative impact on the environment and the depletion of natural resources. In this chapter, we are going to make an overview of biomass and how it can become one of the tools to mitigate those issues. This chapter also cover about the coconut waste as a potential biomass for biofuel resources. Then, this chapter will review about the biomass pyrolysis for solid biofuel production and the effect of pyrolysis temperature on the yield and fuel properties of the solid biochar product. Next, the overview about biomass briquetting was made as it is one of the pre-treatment to enhance the physical and fuel quality of biochar and raw biomass. The overview includes the utilization of biomass briquette for bio-fuel application and the effects of briquetting parameters such as the types of binder and the additional reinforcing material on the briquette properties.

2.2 Overview of Biomass

Biomass is defined as any renewable organism derived from plant or animal sources. Biomass conquers a wide spectrum ranging from tiny to massive plants, from small insects to livestock manures and any materials produced from these. Biomass comes from the alive or recently ‘dead’ organic material. It does not include fossil fuels produced from the transformation of organic materials from many millions of years ago. Biomass can be segregate into several components such as H_2O, CO_2 and other constituents by naturally biodegrade or by the thermochemical conversion process. The CO_2 released during the biomass conversion process is considered as ‘GHG neutral’ because biomass is formed by absorbing CO_2 from the atmosphere (Basu, 2018a). This feature together with being renewable makes biomass one of the most promising energy resources to substitute, reduce and support the fossil fuel demand.

2.2.1 Types of Biomass

Biomass types come under two broad groups and their sub-classification as listed in Table 2.1. The primary or virgin biomass is from the plant or animal itself, while the waste biomass is from the derived biomass products (Basu, 2018a).

Table 2.1 Two main groups of biomass and their sub-classifications (Basu, 2018a)

Biomass Group	Sub-classification	Examples
Primary/ Virgin biomass	Terrestrial biomass	Forest biomass, grasses, energy crops and cultivated crops
	Aquatic biomass	Algae and water plant
Wastes biomass	Municipal wastes	Municipal solid wastes (MSW), biosolids, sewage and landfill gas (mainly methane)
	Agricultural solid wastes	Livestock, manures and agricultural crop residue
	Forestry residues	Bark, leaves and floor residues
	Industrial wastes	Demolition wood, sawdust and waste oil or fat

Most of the biomass on Earth is in the form of lignocellulosic biomass (Isikgor and Becer, 2015). Dahmen et al. (2019) estimated the production of lignocellulosic biomass worldwide is around 181.5 billion tonnes per year. Lignocellulosic biomass is referring to the plant biomass that generally comprises three main constituents known as lignin, cellulose and hemicellulose (Den et al., 2018, Mamvura and Danha, 2020, Dahmen et al., 2019). Depending on its origin, lignocellulosic biomass may also comprise minor constituents of organic matter and inorganic matter. The organic matter includes extractives such as moisture, fat, protein, etc., while the inorganic matter includes ash or minerals such as potassium (K), sodium (Na), phosphorus (P), etc. (Dahmen et al., 2019, Mamvura and Danha, 2020).

2.2.1(a) Lignocellulosic Biomass

The general chemical composition in lignocellulosic or plant biomass was displayed in Figure 2.1. The figure shows that hemicellulose, cellulose and lignin are three macromolecular substances (polymers) in plant biomass. Cellulose covers the largest percentage of macromolecular substance in plant biomass which covers up to 44 wt. %.

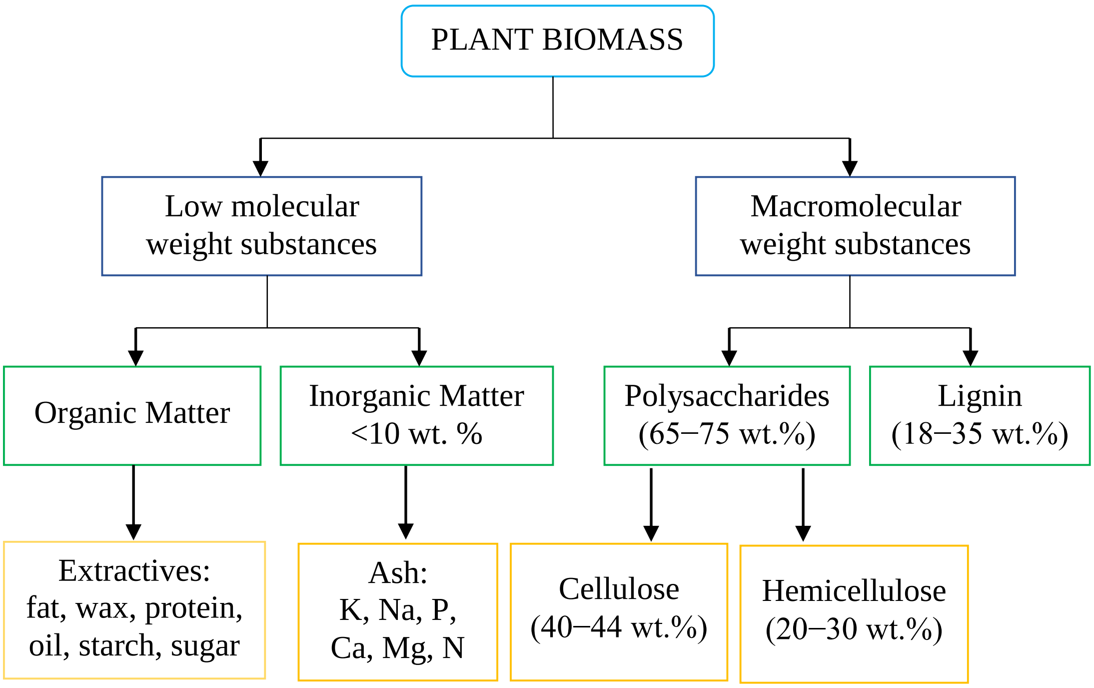


Figure 2.1 The overall chemical composition in plant biomass, adapted from Mamvura and Danha (2020)

Table 2.2 represents the actual percentage of cellulose, hemicellulose and lignin in some lignocellulosic biomass. The table shows that coconut flesh waste contains the highest cellulose content with 72.67 wt. %. Meanwhile, the highest hemicellulose content is from grasses with 50.00 wt. % and coconut husk contain the highest lignin content with 40.10 wt. %.

Table 2.2 Cellulose, hemicellulose and lignin content in some lignocellulosic biomass

Lignocellulosic biomass	Cellulose (%)	Hemicellulose (%)	Lignin (%)	References
Hardwood stems	40.4−54.1	18.4−35.9	15.5−24.1	Isikgor and Becer (2015)
Softwood stems	42.0−50.0	11.0−27.0	20.0−27.9	
Grasses	25.0−40.0	25.0−50.0	10.0−30.0	Fatma et al. (2018)
Semi-dried banana leaves	26.70	25.80	17.00	Fernandes et al. (2013)
Corn cob	45.88	39.40	11.32	Shariff et al. (2016)
Oil palm empty fruit bunch	23.73	21.55	29.15	Mohammed et al. (2011)
Oil palm kernel shell	20.93	18.59	39.38	Zubair Yahaya et al. (2020)
Rice husk	37.15	23.87	12.84	Xiujuan et al. (2011)
Rice straw	40.10	25.00	8.00	Budde et al. (2019)
Wheat straw	38.00	29.00	15.00	Díez et al. (2020)
Tapioca stem	47.67	27.79	32.26	Shariff et al. (2016)
Coconut flesh waste	72.67	1.13	1.88	Ng et al. (2010)
Coconut shell	23.01	35.20	24.25	Zubair Yahaya et al. (2020)
Coconut husk	24.70	12.26	40.10	Cabral et al. (2016)
Coconut frond	43.91	31.58	18.15	Aziz et al. (2018)

The different proportions of cellulose, hemicellulose and lignin in different biomass influence the product distributions from its conversion process. For example, the biomass conversion process via pyrolysis will result in a combination of products from individual pyrolysis of these 3 polymers, each with its kinetics profile or thermal decomposition characteristics (Mohan et al., 2006, Pasangulapati et al., 2012). Figure 2.2 shows the primary products from pyrolysis of cellulose, hemicellulose and lignin. As can be seen from the figure, cellulose, hemicellulose and lignin contribute to the formation of non-condensable gases and organic liquid during the pyrolysis process. Meanwhile, the solid biochar product is mainly derived from cellulose and lignin (Brown, 2009).

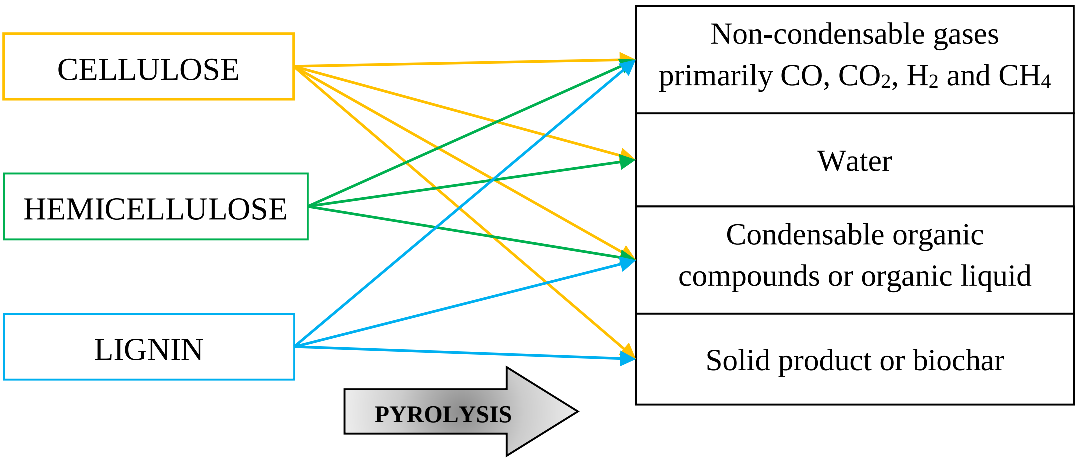
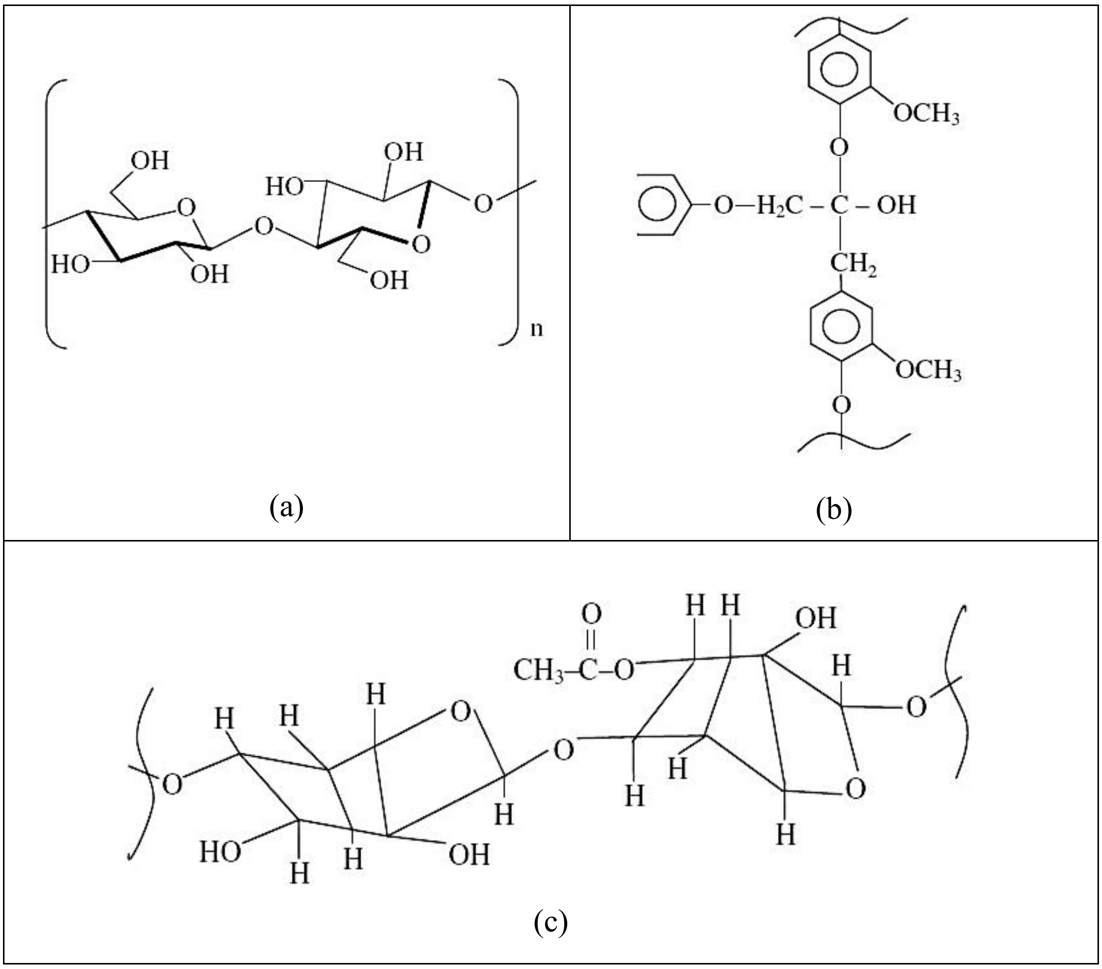


Figure 2.2 The product distribution of cellulose, hemicellulose and lignin via biomass pyrolysis process, adapted from Brown (2009)

Figure 2.3 (a), Figure 2.3 (b) and Figure 2.3 (c) had respectively shows the polymers or the chemical structures for cellulose, lignin and hemicellulose. Figure 2.3 (a) shows that different from the hemicellulose, cellulose consisted of a long polymer of glucose without branches. The structure of cellulose is in good order and very strong and its thermal stability is high (Yang et al., 2007). Meanwhile, Figure 2.3 (b) shows that lignin is full of aromatic rings with various branches that make it difficult to dehydrate during pyrolysis. This caused both cellulose and lignin to produce more solid biochar product (Brown, 2009, Yang et al., 2007, Raveendran et al., 1996).



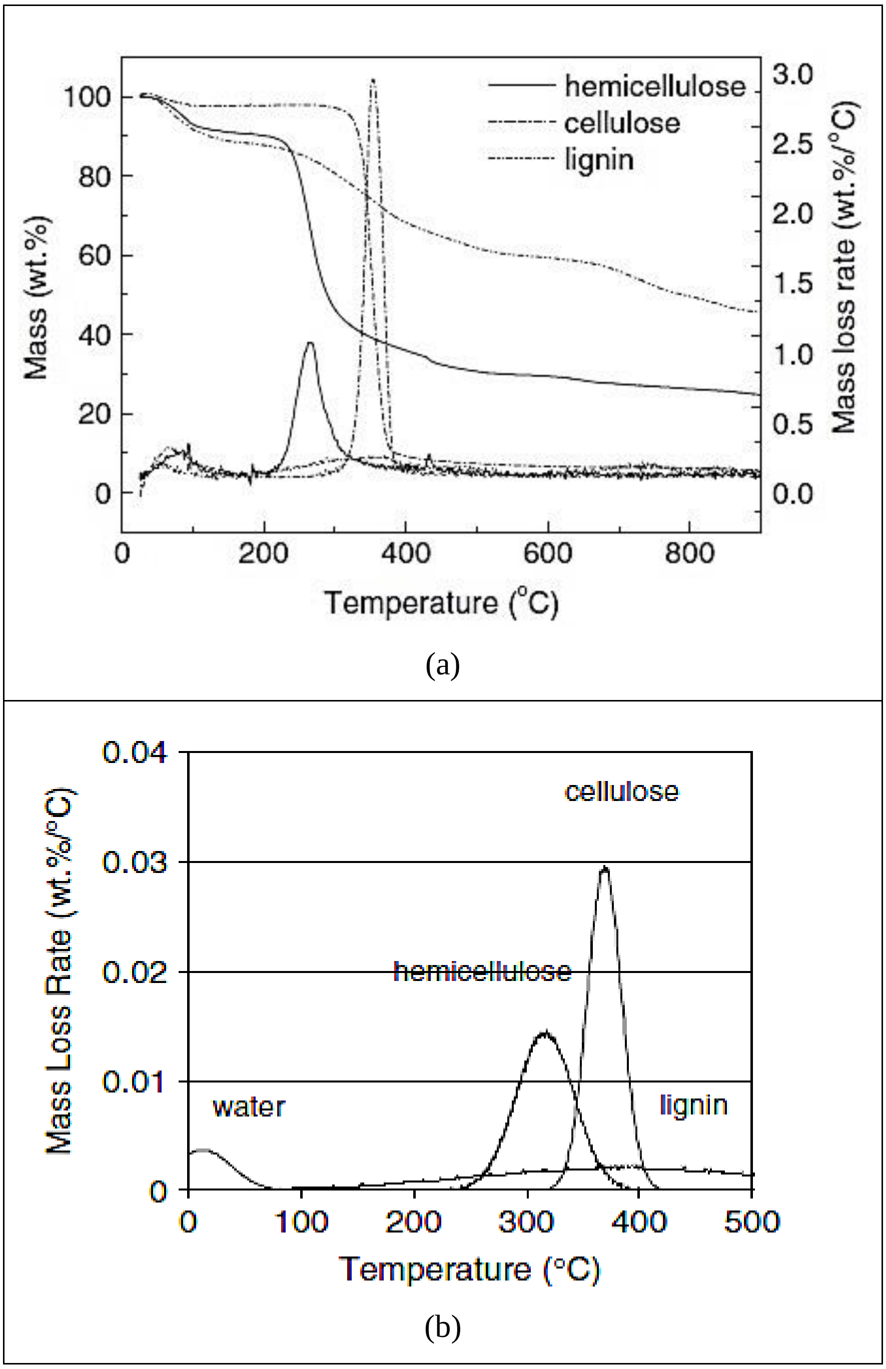
(a)

(b)

(c)

Figure 2.3 The chemical structures of (a) cellulose (b) lignin and (c) hemicellulose (Kabir et al., 2012)

Figure 2.4 (a) represents the decomposition rate of cellulose, hemicellulose and lignin at a temperature ranging from 0°C to 900°C (Yang et al., 2007). Meanwhile, Figure 2.4 (b) shows the decomposition rate of water and the three polymers from 0°C to 500°C (Jahirul et al., 2012).



(a)

(b)

Figure 2.4 Decomposition rate of water, cellulose, hemicellulose and lignin (a) from 0°C to 850°C (Yang et al., 2007) and (b) from 0°C to 500°C (Jahirul et al., 2012)

Both figures evidence that the pyrolysis behaviours of the three polymers show many differences in their kinetics profile. Figure 2.4 (b) shows the peak for water decomposition occurs at a temperature below 100°C. In both Figure 2.4 (a) and Figure 2.4 (b), the decomposition of hemicellulose and cellulose concentrated more or less in the same temperature range. The decomposition peak for hemicellulose in both figures showed to occur at the temperature ranged from 200°C to 400°C. Meanwhile, the decomposition peak for cellulose occurs later at the temperature ranging from 320°C to 420°C. For the thermal degradation analysis of lignin, Figure 2.4 (a) shows that the activity of the chemical bonds in lignin covered an extremely wide temperature range from the ambient to 900°C. Among the three polymers, lignin is the slowest one to decompose. Its decomposition process happens steadily at a very low mass rate and generates high yields of solid residues to more than 45% by weight of the original sample (Yang et al., 2007). Meanwhile, a study by Raveendran et al. (1996) showed that the solid biochar yield from lignin can be up to 50%.

The different pyrolysis behavior among cellulose, hemicellulose and lignin is possibly due to their different chemical structure and nature (Yang et al., 2007) as shown previously in Figure 2.3. Every lignocellulosic biomass has its proportions of these three main polymers. Knowledge about the chemical composition of biomass can help to predict part of its behavior during its conversion process and product distribution (Tripathi et al., 2016). It is therefore suggested to study the characteristics of each biomass to understand their behavior, to help in obtaining the desired product and to further find its potential for future application.

2.2.1(b) Lignocellulosic Biomass as a Bioenergy Source

Biomass stored the chemical energy produced from the photosynthesis process. The energy was stored in the glucose molecule within the plant (Basu, 2018a). Equation 2.1 shows the chemical reaction of photosynthesis. The plant absorbs the solar energy to metabolize the atmospheric CO_2 and H_2O, while the plant's chlorophyll act as the catalyst. This process would produce glucose ($C_6H_{12}O_6$), oxygen (O_2) and chemical energy (Hodge, 2010). The chemical energy produced is then transferred to the animals or humans that consumed the plant. Meanwhile, if the biomass is used as feedstock, it can be converted into renewable energy.

$$\text{Living plant} + 6CO_2 + 6H_2O + \text{Sunlight} \xrightarrow{\text{Chlorophyll}} C_6H_{12}O_6 + 6O_2 - 480\ \text{kJ/mol} \qquad (2.1)$$

Lignocellulosic biomass is by far the most abundant biomass in the world. These polymers usually are not for human consumption because it is a part of the plant fiber that did not contain starch (Mamvura and Danha, 2020, Cherubini and Strømman, 2011). It can be derived from biomass residues that do not compete with food crops. In this context, the usage of lignocellulosic biomass for renewable energy resources is particularly interesting because it does not affect the human food chain (Mamvura and Danha, 2020, Den et al., 2018, Basu, 2018a). Besides, the usage of biomass residue for bioenergy sources is considered more energy efficient because of its high energy density and lower cost (Papoutsidakis et al., 2018).

The wide usage of lignocellulosic biomass for the production of biofuel is also due to its environmental benefits. According to a prospective study done by Goh et al. (2010), the utilization of biomass waste for biofuel conversion could recycle and reproduce the organic waste into valuable products while reducing the cost of waste management. As biomass decay through natural degradation or is directly burned, GHG such as CO_2 will be released into the atmosphere. Besides, methane gas which is 21 times more potent GHG gas compared to CO_2 could be released if the biomass decomposed in the water (Basu, 2018a, Hunt et al., 2010). Biomass conversion for biofuel will produce ‘carbon neutral energy’ while avoiding the release of those GHG gases. For example, when biofuel was burned for energy, it will emit the CO_2 absorbed previously from the atmosphere by its lignocellulosic biomass feedstock (refer to Equation 2.1). So, the total additional CO_2 into the atmosphere is considered as zero

(Basu, 2018a). The carbon intensity of thermal power plants from renewable energy is also much lower than fossil fuels. According to a study done by Amin and Talebian-Kiakalaieh (2018), the percentage of CO_2 emitted from oil palm waste can be reduced by 57.0% to 89.2% compared to bituminous coal and diesel source of fuel. The study was done based on two power plants in Malaysia that use empty fruit bunch and palm oil mill effluent to power steam and gas turbines for electricity production.

According to an analysis done by Perea-Moreno et al. (2019), the trends of research and publications of biomass for renewable energy application had significant growth in the year 2008 onwards. The interest begins after the peaking of oil prices in June 2018 which encourage the energy policies in the industrialized countries to produce renewable energy from biomass. Asia-Arabian-Peninsula-UK is the number one cluster that makes the most collaboration about biomass research. Malaysia is among one of the countries in the cluster that make the most collaboration between countries in the topic of biomass for renewable energy. The collaboration work between countries occurs mainly due to the influence of the economy, type of biomass or geographical location among the countries in the cluster. The government in industrialized countries mostly promotes energy policies to encourage the reduction of GHG and global warming. Hence, it can be concluded that biomass utilization for renewable energy production is one of the major contributors to attaining sustainable development (Perea-Moreno et al., 2019).

2.2.2 Biomass Overview in Malaysia

Malaysia is a tropical Southeast Asia country with a total land area of 330,411.40 km^2 (DOSM, 2021b). The total forested area in Malaysia covers 67.6% of the land while the agricultural land reserved 26.3% of the land area (Knoema, 2021). The total population in Malaysia is 32,924,149 as of 7th November 2021, which is equivalent to 0.42% of the total world population (Worldometer, 2021). Agricultural activities, rapid urbanization and population growth had led to an abundance of biomass resources in Malaysia, up to 103 Mt. The biomass is mainly from agricultural waste, municipal solid waste (MSW) and forest residues (Salleh et al., 2020).

Agricultural waste covers 91% of the total biomass waste in Malaysia (Salleh et al., 2020). Malaysia is the second highest palm oil producer in the world which covers 31% of the global output (Nyakuma, 2018). Therefore, the main agricultural waste in Malaysia is produced from the oil palm industry, up to 51.19 million tonnes in the year 2017 (Hamzah et al., 2019). Palm oil only stands for 10% of the tree, while the rest is accounted as the oil palm biomass. 75% of oil palm biomass is generated at the plantation sites including oil palm trunks (OPT) and oil palm fronds (OPF). Meanwhile, the remaining is generated at the processing mills which include the empty fruit bunches (EFB), palm kernel shells (PKS), mesocarp fibers (MF) and oil palm effluent (POME) (Onoja et al., 2019).

According to a report done by MESTECC to UNFCCC, the wastewater from POME mill and landfill of solid waste are the top two major sources of methane emission in Malaysia after the oil and gas industries (MESTECC, 2018). POME is high organic content wastewater produced from the production of crude palm oil. Open ponding is the common treatment system used at the mills to discharge POME. Every cubic meter (m^3) of treated POME was estimated to release 34 Nm^3 of biogas that contained 54.4% of methane gas (Foong et al., 2020), which makes it the second major source of methane emissions in Malaysia (MESTECC, 2018).

45% to 50% of MSW composition in Malaysia is from the food waste (Sundaram and Gen, 2019, Yong et al., 2019). Food waste refers to the dumped spoiled food. Approximately 15,000 metric tonnes per day of food are wasted in Malaysia. 8,000 tonnes of them consist of food leftover while the others are from the farms and food processing (Sundaram and Gen, 2019). The landfill of solid waste disposal is the third-largest contributor to methane emissions in Malaysia, after the oil and gas industries and wastewater industry. The GHG emission from this main disposal approach for solid waste in Malaysia was increasing annually (MESTECC, 2018). 12% of the national GHG emission is from this solid waste disposal mainly caused by CO_2 and methane gases (Salleh et al., 2020). This is maybe due to the high organic content in the food waste as the main fraction of MSW in Malaysia (Heikal et al., 2020).

According to the decisions 1/CP.19 and 1/CP.20 of the UNFCCC, Malaysia's government had intended to contribute for the reduction of GHG emission at 45% by 2030 compared to year 2005 (UNFCCC, 2015). One of the planning processes includes the Renewable Energy Policy and Action Plan, which targeted to use the biomass and biogas, such as MSW, biogas from landfills and agricultural waste as the renewable source to generate bioenergy (Hamzah et al., 2019). The high production of biomass in Malaysia makes it a suitable source of bioenergy. It is a green source of energy that can be converted into various forms of liquid, solid or gas. However, there is still a lack of scientific research and development in a particular biomass conversion technology in Malaysia (Chala et al., 2019). Besides, the focus of biomass study in Malaysia was mostly only concentrated on the palm oil biomass, as it is the most abundant agricultural biomass. The exploration and more scientific research especially on the new biomass feedstock should be made to find their potential for greener product transformation and application. More utilization of biomass waste for bioenergy can help to maximize biomass usage in Malaysia while enhancing Malaysia's contribution to mitigate GHG.

2.2.3 Coconut Waste as a Potential Biomass

2.2.3(a) Overview of Coconut and Coconut Waste

The coconut palm tree (*Cocos nucifera*) may be the most useful tree on Earth known as the ‘tree of life’. Almost all parts of a coconut tree are useful for various product derivation. Coconut trees usually grow in the tropics and subtropics regions including Asia, Pacific Island and South America (Kek Hoe, 2018). The top three countries that produce coconut include Indonesia, Philippines and India. According to FAO (2021), Indonesia is the world’s leading coconut producer, accounting for around 17.13 million tonnes of coconuts. The annual global production of coconut had attained substantial growth over the past decade with the increment of more than 10 million tonnes of coconuts (FAO, 2021). The interest in coconut products had raised due to some of its important characteristics especially towards the health benefits (Srivastava et al., 2018, Savva and Kafatos, 2016). In addition, coconut oil also had gain attention as an export product for global lauric oil, due to its premium and higher market price as compared to palm oil (Kek Hoe, 2018).

According to The Department of Statistics Malaysia DOSM (2021a), coconut is recorded as the highest consumed fruit in Malaysia. The average coconut consumption per person in Malaysia is 18.5 kg/year in 2013 and the statistics keep on increasing up to 24.3 kg/year in 2020. Coconut is a versatile fruit not only for domestic use but also for commercial purposes. The domestic demand for coconut in Malaysia is in the form of fresh coconut, tender coconut, coconut oil and processed cream powders. Meanwhile, the exported coconut product from Malaysia includes desiccated coconut, coconut milk powder and activated carbon (Sivapragasam, 2008). The total area of coconut harvest in Malaysia is 76,776 hectares with the production of 536,606 tonnes of coconuts (FAO, 2021). The coconut supply in Malaysia is not sufficient to fulfil the local demands. The self-sufficiency ratio of coconut in Malaysia is recorded to be just 66.6% (DOSM, 2021a). As the result, Malaysia has to rely on and import more raw coconut products such as crude coconut oil and coconut meat mainly from Indonesia (Kek Hoe, 2018, DOSM, 2021a).

The high demand for coconut products coupled with the abundance of coconut wastes. Coconut trees generate wastes in the form of trunks and fronds (Griffin et al., 2014). Meanwhile, the waste from the fruit part alone includes the coconut shell, coconut husk, coconut coir fibre (Kek Hoe, 2018) and coconut flesh waste (CFW) (Raghavarao et al., 2008). By referring to Figure 2.5, coconut husk (mesocarp) and coconut shell (endocarp) are the two main parts that cover the coconut flesh or coconut meat (endosperm) (Heuzé et al., 2015).

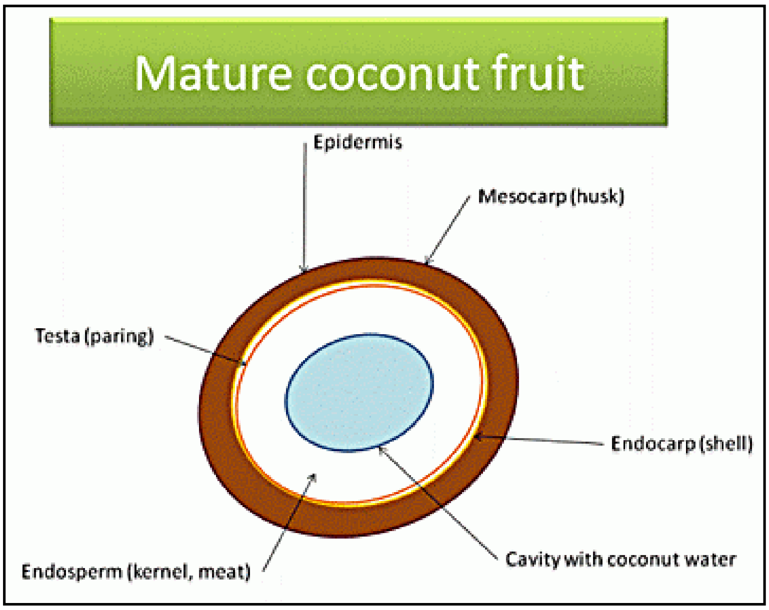


Figure 2.5 The scheme of a coconut fruit structure (Heuzé et al., 2015)

It has been reported that over 80% of the coconut fruit weight is not used and simply disposed of which contributes to the abundant biomass waste (Sangkharak et al., 2020). Coconut husk and coconut shell are the two parts of coconut wastes produced after the collection process of edible parts including coconut flesh and coconut water. Meanwhile, CFW is a coconut waste generated after the coconut milk was extracted from the grated coconut flesh by hand squeezed or expeller-pressed machine.

There are some studies done to explore and benefit coconut wastes usage. For example, the production of biochar from coconut shell (Sukartono et al., 2011, Wang et al., 2013, Rahman et al., 2015), the production of activated carbon using coconut husk (Foo and Hameed, 2012) and the utilization of CFW for biodiesel (Sulaiman et al., 2014, Sulaiman and Ruslan, 2017) and bioethanol production (Sangkharak et al., 2020). Most of the studies on coconut waste mainly concentrated on the coconut husk and the coconut shell. More research should be done on the other part of coconut waste such as CFW, as it is one of the promising biomass feedstock that is abundantly available especially in the Asia region. The research was done on coconut waste not only could help to reduce its quantity but also could find its potential to be used for more value-added applications.

2.2.3(b) Application of CFW and its Potential as a Biomass Feedstock

Coconut wastes such as CFW are considered as a food waste. CFW is generally thrown away and left to naturally rot producing no benefit. Only some of it was used as fertilizer and animal food (Vetayasuporn, 2007, Sulaiman et al., 2014). Food wastes may cause negative effects towards the environment depending on how it was managed. Food wastes that have been usually dumped in the landfill may lead to many health issues such as air pollution, bad odor and leaching. Besides, food waste which biodegrades relatively fast rate at 0.144 yr^{-1} can produce harmful methane gas, more than the other biodegrade material such as papers (Levis and Barlaz, 2011).