COMPARISONS OF LIFE CYCLE ASSESSMENT OF BIOETHANOL PRODUCTION FROM OIL PALM EMPTY FRUIT BUNCH AND MICROALGAE IN MALAYSIA

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A project report submitted in partial fulfilment of the
requirements for the award of Bachelor of Engineering
(Hons.) Chemical Engineering

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

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I, Teow Jia Wei, the sole writer of this report, would like to dedicate this to my beloved family and friends for their constant support throughout the period of my research. In addition to that, I am also grateful for a good supervisor, Dr Steven Lim who has been guiding me throughout the entire period of my research study.

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ABSTRACT

Malaysia is currently at its developing stage of biofuel industry based on the fact that bioethanol is seen as a promising alternative fuel energy. Furthermore, Malaysia has million tonnes of solid palm residues which has the potential as the feedstock that used in production of bioethanol to create better sustainability environmental fuel energy. There are many Life Cycle Assessment (LCA) studies conducted in worldwide for the different types of bioethanol feedstock. However, so far very few LCA studies of bioethanol production from different feedstock such as lignocellulosic biomass and microalgae have been carried out to address the environmental issues in Malaysia. This research will mainly base on the comparison between LCA of two different types of feedstock; **oil palm empty fruit bunch and microalgae**. The assessments include the evaluation of life cycle between each type of feedstock's energy input and output and greenhouse gas (GHG) emissions. This report will continue to cover the simulation of bioethanol production from different feedstock. The simulation will focus the bioethanol production, i.e. from the pre-treatment process of feedstock until a pure ethanol are produced. The Life Cycle Inventory (LCI) will be analysed starting from the cultivation and plantation of the feedstock activity to the harvesting and processing and the final stage of bioethanol production. In addition, this report will also compare the Net Energy Ratio (NER) and GHG emissions results by using sensitivity analysis on the environmental impact between different methods used in microalgae harvesting stage. In this LCA study, the life cycle of bioethanol production from using palm EFB as feedstock gives a NER of 1.08 which it implies that the life cycle energy output is higher than the energy input. In contrast, bioethanol production from using microalgae as feedstock produces a NER of 0.084 which indicates that the life cycle energy output is significantly less than the energy input. The estimated total life cycle GHG emissions produced from 1 ton of EFB based and microalgae based bioethanol are 9,947.246 kg of CO_2 and 81,821.742 kg of CO_2 respectively per year. Moreover, alternative of dewatering methods which can replace thermal dewatering have been studied and conventional solar drying is able to improve the energy efficiency of the system. The NER has net positive life cycle energy and GHG emissions were greatly reduced. However, solar drying method is a slow process as compared to other alternatives and it is weather dependent. Therefore, the results of this LCA research has shown that EFB bioethanol has the potential to become a major renewable fuel energy source in the near future of Malaysia.

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LIST OF SYMBOLS / ABBREVIATIONS

$GHG_{production}$	total life cycle GHG emissions of the bioethanol production, kg CO_2eq/tonne
$GHG_{cultivation}$	total GHG emissions from feedstock cultivation stage, kg CO_2eq/tonne
$GHG_{transportation}$	total GHG emissions from transportation, kg CO_2eq/tonne
$GHG_{combustion}$	total GHG emissions from the combustion involved in plant processing units, kg CO_2eq/tonne
GHG_{other_waste}	total GHG emissions from the waste produced and waste treatment, kg CO_2eq/tonne

CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide equivalent
CPO	Crude Palm Oil
EFB	Empty fruit bunch
FFB	Fresh fruit bunch
FGB	First-generation biofuels
GHG	Greenhouse gas
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
K	Potassium
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LUC	Land used change
P	Phosphorus
PBR	Photobioreactor

PKC	Palm kernel cake
PKO	Palm kernel oil
POME	Palm oil mill effluents
N	Nitrogen
NER	Net Energy Ratio
NH_3	Ammonia
SGB	Second-generation Biofuels

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CHAPTER 1

INTRODUCTION

1.1 Background

The growing of energy demand, environmental concerns and natural resources availability have led to the exploration of more renewable energy resources. In the past, majority of the countries were depended on non-renewable energy such as oil, gas and coal. However, the consumption of fossil fuels over the years has brought some negative impacts to the environment such as global warming, rise of the sea level and etc. (Gupta and Verma, 2014) . These situations are contributed by the emission of GHG through combustion of fossil fuels for electricity generation and transportation. Hence, the development of renewable energy has been facilitated in order to mitigate the high level of GHG such as carbon dioxide in the atmosphere.

According to the World Bank (2015), the carbon dioxide emission in Malaysia was 7.9 metric tonnes per capita in year 2010. The carbon emission in Malaysia had increased tremendously from 5.41 to 7.9 metric tonnes per capita since year 2000. This is considered as a huge increment and this increasing trend has dragged the public concerns when comparing with neighbouring countries such as Indonesia and Thailand. The CO_2 emission by Malaysia is at least 80% higher than Indonesia and Thailand. Besides, several developed countries have shown their efforts in reducing CO_2 emission as shown in Figure 1.1. In year 2001, New Zealand has almost 8.89 metric tonnes per capita CO_2 emission. It was gradually decreasing and eventually became lower than Malaysia in year 2009. Hence, this implies that Malaysian government have to start taking actions in order to mitigate the increasing of CO_2 emission. One of the actions could be looking for alternative fuels that are sustainable in terms of environment and availability eventually as the substitution of conventional fossil fuels.

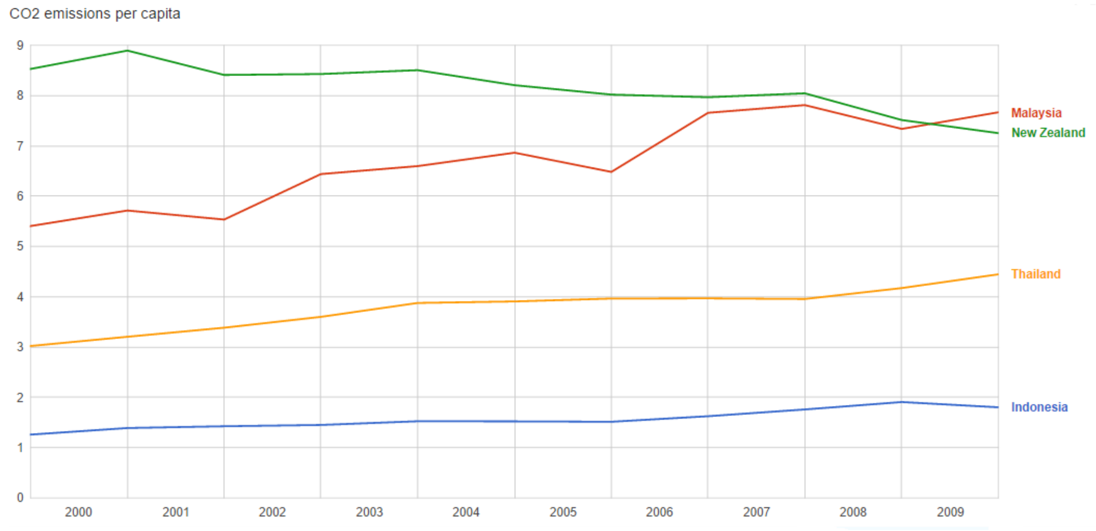


Figure 1.1: The Carbon Dioxide Emissions between Malaysia, Indonesia, Thailand and developed country such as New Zealand from the year 2000 to 2010. (Adapted from World Bank)

1.1.1 Introduction of Biofuels

Among the renewable energy resources, biofuel is one of the options that has the potential to replace fossil fuels in transportation sector. Despite the research of Gupta and Verma (2014) have shown the benefits of using biofuel over fossil fuels, the utilization of biofuel in Malaysia is still not put into practice. This is due to the abundance of domestic energy resources, particularly the oil and gas availability in the country. Biofuels consists of biodiesel, bioethanol and biogas and they can be classified as first-generation, second-generation and third-generation biofuels. These categorizations are based on the types of feedstock used in producing biofuels. Basically, first-generation biofuels (FGB) are processed and directly converted from edible agriculture such as rapeseed oil, palm oil, sugarcane, wheat, barley, and corn. Meanwhile, second-generation biofuels (SGB) feedstock are obtained from non-food based products such as lignocellulosic biomass. Feedstock derivation from the agricultural waste made them more sustainable than first generation feedstock. Third generation biofuel feedstock are generally derived from microalgae or cyanobacteria (Scaife, et al., 2014).

In the last decade, there was tremendous development in the research and commercialization of biofuel due its potential as the substitution of conventional fossil fuels. These has led to the usage of blended biodiesel from extracted plant oil or bioethanol from energy crops with car gasoline and petroleum in developed and developing countries (Raman and Gnansounou, 2014). One of the alternatives to replace a portion of the conventional gasoline fuels for vehicles is bioethanol. It can be blended with the gasoline with up to 10% of proportion without any modification of the car engines. In developed countries, the mixture of gasoline with proportion up to 85% bioethanol can be used in the so called flexi-fuel vehicles. Besides, 100% bioethanol is possible to be used in particularly designed engine (Morales, et al., 2014).

In Malaysia, the production of biodiesel has increased significantly and is widely distributed in Indonesia and Thailand in the last few years. Although the FGB can substitute fossil fuels as a source of energy supply, but the usage of food sources as feedstock has triggered strong controversy over the food versus fuel issue. These advancements are one of the reasons of causing the increase of food price (Raman and Gnansounou, 2014). In order to overcome this situation, the derivation of second-generation bio-ethanol from non-food based resources and agricultural waste like lignocellulosic biomass and microalgae has become the subject of interest worldwide.

According to Scaife, et al. (2014), the principles of governing the biofuel production must be a positive energy balance when all the energy that used in production is included. Besides, he stated that a sustainable production process should not only consider carbon production, the other usage of finite resources such as nitrogen and phosphorus were important as well. The process would be deemed as sustainable process when all these criterion were fulfilled because it had the capacity to continue indefinitely at a given rate. All in all, global climate change has made the carbon neutrality which falls into the definition of sustainability important in social and political aspects. Carbon neutrality describes net production of carbon by considering all the aspects of process. Hence, a feasible biofuel production process must be sustainable and low in terms of cost.

1.1.2 Bioethanol as an Alternative Fuel

Bioethanol production from agricultural biomass could be promising alternative fuel which involves four main processes of acid pre-treatment, enzymatic hydrolysis, fermentation and distillation. The pre-treatment is the initial step in separating the cellulose from lignocellulosic biomass. While the second process is the hydrolysis of cellulose to glucose with the present of microbes that able to secrete cellulose enzyme. Several microbial species of *Colostridium, Cellulomonas, Thermonospora*, *Bacillus* and also some fungi such as *Trichoderma, Penicillium, Fusarium* are capable to produce cellulose enzyme. The third process is fermentation process which involves the conversion of glucose to ethanol. This can be done by microbes such as *Saccharomyces cerevisae, Escherichia coli, Zymomonas mobilis* and etc. (Gupta and Verma, 2014). Among all the microbes, *Saccharomyces cerevisae* is the best known safe microorganism and commonly used in bioethanol fermentation due to its several beneficial characteristics such as highly resistant to ethanol and toxic materials (Ishizaki and Hasumi, 2014).

Generally, bioethanol is a promising alternative energy fuel in terms of carbon emission reduction, energy efficiency and competition with food source. Among all the available lignocellulosic feedstock in Malaysia, palm empty fruit bunch (EFB) has the highest potential as the feedstock that used in production of bioethanol. In year 2011, 44 million tonnes of solid palm residues which consisting of 54% (23.8 million tonnes) of EFB, 30% (13.2 million tonnes) of shells and 16% (7.9 million tonnes) of fibre are generated as shown in Figure 1.2 (Chiew and Shimada, 2012). All palm oil mills were relied on the shells and fibre as fuels to produce heat and surplus electricity power. On the other hand, EFB contains cellulose and hemicellulose that can be converted to simple sugar, glucose. The left over lignin also can be used as fuel in generating electricity in the bioethanol production. This shows the sustainability of bioethanol fuel by utilizing the waste from palm oil production.

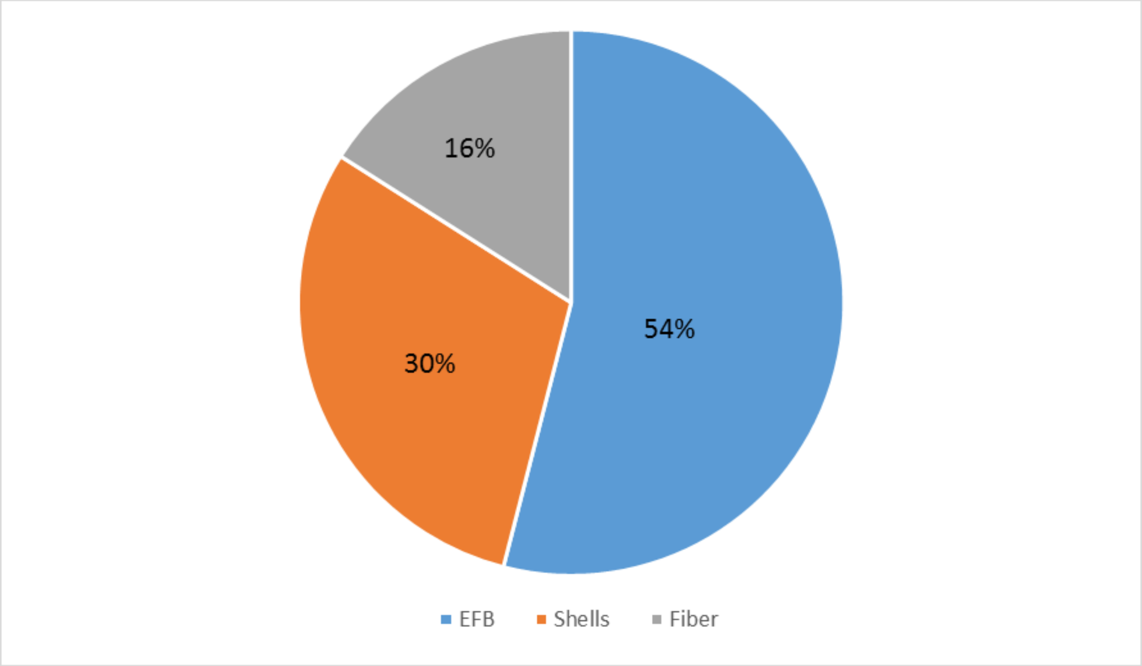


Figure 1.2: Composition of the Solid Palm Residues Produced in Malaysia in year 2011 (Chiew and Shimada, 2012).

LCA of SGB particularly bio-ethanol production from different types of feedstock based on Malaysia local context was performed in order to evaluate the feasibility and potential environmental impacts. Basically, LCA is the study of the input, output and potential environmental impacts of interested product or process beginning from raw material extraction, production processes, product transportation or distribution and use, to an end of life stages. The assessment was conducted based on the International Organization for Standardization (ISO) 14044:2006 standard (ISO 2006) conditions and the results with realistic data based criteria are used to improved process, support policy and decisions making before mass production of a product. A LCA analysis consists of four steps, they are goal and scope definition, inventory analysis, impact assessment and interpretation (Kurma et al., 2012).

Life cycle assessment studies of biofuel system always gives different results with respect to net energy ratio and greenhouse gases reduction due to different assumptions on important variables that have deciding impact on the energy and

GHG emission. They are the biomass yields and conversion technologies, fertilizer application rates, evaluation, number of energy inputs included in the calculation and approach used for inputs-outputs attribution between product and co-product (Kumar, et al. 2012)

So far, very few LCA studies of bioethanol production from different feedstock such as lignocellulosic biomass and microalgae have been carried out to address the environmental issues. LCA analysis can help in analysing the possible environmental impacts from the cultivation and plantation, segregation of biomass to the process and production of bioethanol. Moreover, LCA method is useful in the planning and actions to further reduce the environmental issues and lower the energy and chemical usage in the later stages.

1.2 Problem Statement

Among all the biofuels, preliminary studies showed that SGB and TGB especially bioethanol were more promising than FGB. They are able to reduce the competition of food source and also not contribute to the rising of food price. Bioethanol can integrate with the existing transport fuel system with 5% or 10% of proportion in conventional fuel without any modification. However, when comparing different feedstock used in bioethanol production, the GHG emission differences can be observed at the same mixture proportion

The problems statements of this research are:

- The GHG emissions particularly the net balance of CO_2 in life cycle of bioethanol production from feedstock such as palm EFB and microalgae.
- The formula used and calculation of net energy ratio (NER) of bioethanol production from different types of feedstock.
- The types of bioethanol feedstock which possess the greatest potential in minimizing energy consumption and the environmental impacts, i.e. GHG emission.

- The percentage reduction in terms of net balance of CO_2 and NER by comparing each of the bioethanol from different feedstock.
- The effects of the plantation of crops and utilization of the waste on the biodiversity and habitat.
- The direct and indirect land used change (LUC) according to the plantation and cultivation of bioethanol feedstock.
- To deal with how the sensitivity analysis affects the results obtained.

The problem statements that listed as above will be studied carefully. All results obtained will be calculated and tabulated after getting enough supporting information. Therefore the information will evaluate the proposed LCA for the type of bioethanol feedstock with high possibility to reduce the environmental impacts.

1.3 Aims and Objectives

The main objective of this research is to conduct the LCA analysis to evaluate and compare the potential environmental impacts of the bioethanol production from different feedstock in Malaysia. The available feedstock in Malaysia are palm EFB and microalgae. In this research, the potential environmental impact in terms of net energy ratio, net balance of CO_2 and also land used change in life cycle of the bioethanol production from the feedstock mentioned as above will be assessed. All the respective process stages will be analysed beginning from the plantation and cultivation of the feedstock activity including land use change, collection of agriculture biomass, acid pre-treatment, enzymatic hydrolysis, fermentation, distillation and until the usage of bioethanol in vehicles.

The LCA features and approaches such as functional units, assumptions and interpretation of data in determining the inadequacy of current research and also for future research needs are important. Life cycle assessment studies of biofuel system always give different results due to different assumptions on variables that have deciding impact on the energy and GHG emission. The emission factors for Global

Warming Potential (GWP) which follows the guidelines of Intergovernmental Panel on Climate Change (IPCC) will be used in calculating the GHG emission. Morales, et al. (2014) stated that the stages in life cycle of bioethanol production such as plantation stage, transport of supply, bioethanol process and the distribution and use stages are contributed to GHG emission. The GHG gases that are of concerned are CO_2 and nitrous oxide. The net balance of CO_2 is useful in determining carbon emission and defined as the CO_2 released from the production and subtract the CO_2 transferred from the atmosphere to biomass. Apart from that, some cases are in zero CO_2 emission as the researchers assuming that amount of CO_2 from the atmosphere absorbed by the plants via photosynthesis is exactly the same as the amount released from bioethanol production (Gupta and Verma, 2014). In other words, the cycle is an almost closed CO_2 cycle.

In this research, the life cycle approach flow for each type of bioethanol feedstock supply chain will be studied through sensitivity analysis method. This is intended to compile the inventory of bioethanol production inputs and outputs from its feedstock and evaluate their associated environmental implication from the database for the life cycle assessment. The LCA of bioethanol production mainly the energy input and output in this research will be calculated through the net energy ratio (NER). NER aims to appraise the capacity of bioethanol to substitute fossil fuels (Morales, et al., 2014). The function of NER is to calculate if the bioethanol produced contains more useful energy than its production required. NER is always defined as the ratio of the heat content of the main product i.e. bioethanol to the non-renewable fossil energy used to produce the main product (Lim and Lee, 2011) (Morales, et al., 2014).

This research is mainly based on the comparison between LCA of different types of bioethanol feedstock: Palm EFB and microalgae. The information that are related to the bioethanol production from local production plant will be obtained and analyse. In addition, the results will be obtained through simulation tool such as Aspen Hysys based on the data and optimized operating conditions for each stage of bioethanol production process from academic journals or patents. Besides, any relevant data and findings within Malaysia or neighbour countries such as Indonesia and Thailand that have the almost same conditions and climate as Malaysia, based on the bioethanol production from interested feedstock will also be collected.

The aims and objectives of this research can be summarized as following:

- To compile and simulate the inventory of bioethanol production inputs and outputs from its feedstock and evaluate their associated environmental implication from the database for the life cycle assessment.
- To assess and compare the potential environmental impacts of the bioethanol production from different type of feedstock in Malaysia, i.e.: palm EFB and microalgae through life cycle assessment analysis.
- To study the life cycle approach flow through sensitivity analysis for the feedstock.

The problem statements and objectives that mentioned in this chapter will be further discussed in detail based on the LCA analysis and results from each bioethanol feedstock. Every stage of the life cycle and the emission factor will be provided along with data source. Lastly, the compiled data and results will be analysed and compared between each feedstock so that the sustainability of the bioethanol production from different feedstock can be evaluated.

CHAPTER 2

LITERATURE REVIEW

2.1 Basic Concept of Life Cycle Assessment

LCA is a methodology framework that used to estimate and assess the environmental impact of a product throughout its life cycle from cradle to grave. Most of the LCA consists of three stages with the interpretation occurring throughout, i.e.: firstly, goal and scope definition, then life cycle inventory and life cycle impact assessment. In the first phase, the main purpose of the study, system boundaries and selection of suitable functional units will be determined by defining the goals and scopes. While for the second phase, all the relevant inputs and outputs of product life cycle data will be collected. In Life cycle impact assessment (LCIA), the data from Life Cycle Inventory (LCI) will be used to assess and evaluate the potential environmental impacts and estimate the resources used in the methodology. Finally, the interpretation of the collected data is required in order to identify the significant issues, assess results to reach conclusions, explain the limitations and provide any recommendations (Tokunaga et al., 2012).

The academia, LCA practitioner, industry product manufacturers, consumers and governmental or private sector regulators are common users of LCA methodology. It provides clear and understandable descriptions and motivations of the chosen functional units, system boundaries, assumptions and explain the limitations that have faced. Therefore, the LCA study must be transparent where all the sources of the results, assumptions and limitations of data during the process must be clearly stated.

The application of LCA for bioethanol feedstock in Malaysia is still in a developing stage while in other countries such as Brazil has shown significant progression particularly in SGB such as sugarcane based bioethanol over the years. It is important to achieve consensus of the goals, challenges, structure and procedural issues in LCA analysis. Majority of the LCA research begins with the cultivation and plantation of feedstock stage until the end usage of biofuels.

2.2 Goal and Scope Definition

Goal and scope definition defines the purpose of study, the expected products in the system, system boundaries, functional unit and assumptions. Usually, the system boundary is illustrated by an overall input and output flow diagram. All the factors and operations that will contribute to the product life cycle and process are fall within the system boundary.

2.2.1 Benefits of using bioethanol

According to the LCA research that had been reviewed, many goals and purposes were studied. However, most of the researchers were focusing on the environmental impacts such as GHG emission and also the primary energy usage in the LCA study of biofuels (Lim and Lee, 2011) (Sander and Murthy, 2012). Besides, the studies showed that there were many environmental benefits of using bioethanol as compared to fossil fuel, the primary energy usage in production and the global warming potential (GWP) of using bioethanol had significantly reduced.

Furthermore, exhaust gases of bioethanol are cleaner than conventional gasoline as it burns faster i.e. higher complete combustion of bioethanol without the aid of catalytic converter and hence producing less carbon (soot) and carbon monoxide. Usage of ethanol-blended fuel such as E10 is able to reduce the GHG emission as well as the amount of octane additives in fuel. Due to many benefits offered in this industry, more and more researchers worldwide have decided to further assess the life cycle of different feedstock to produce bioethanol from cradle to grave.

2.2.2 Main Purpose of Reviewed LCA Studies

Most of the LCA analysis were performed based on single type of bioethanol feedstock. The main objective stated by most analysis was to investigate the environmental impacts throughout life cycle production of bioethanol which include all the stages involved. Moreover, the other objectives of LCA stated by Morales, et al. (2015) is to synthesis and evaluate the available and updated information which related to LCA of lignocellulosic bioethanol and to compare its environmental impacts with first generation bioethanol. Other than that, the LCA studies can propose any improvements and suggestions to the current environment conditions and to reach the targets of usage of bioethanol in transportation sectors.

According to Lim and Lee (2011), the LCA study had been carried out to determine the environmental consequences by maximizing the output from palm oil plantations through inclusion of bioethanol processing into current palm oil biodiesel productions. The result produced by using a consequential system expansion approach had proven that the implementation of bioethanol processing into palm oil biodiesel production did not give a significant reduction of energy consumption and GHG emission. In this research, it stated that current technology for bioethanol was energy intensive and provided low conversion yield. Besides, the lignin-rich palm oil shell and fibre were also examined and had proven that palm oil fronds and empty fruit bunch were more suitable to be used as feedstock in bioethanol processing.

In the LCA study of Sander and Murthy (2012), the main purpose of the analysis was to provide the baseline information for the algae biodiesel process which include the coproduct expansion, i.e. production of the bioethanol. A well-to-pump approach was conducted to investigate the overall sustainability of the microalgae biofuels process. Furthermore, the environmental aspects such as NER and GHG emissions were assessed in the study. In this research, they had identified the largest energy input in the life cycle of biodiesel production was drying of the algae cake. They also mentioned that new technologies were needed in order to make algae biofuels a sustainable and commercial reality.

Moreover, the main purpose of the report of MacLean, et al. (2008) was to provide assessment of LCA of bioethanol and gasoline in terms of environmental footprint in Canada. They did an overview of energy, emissions and economic modelling activities in order to improve the environmental policy development in Canada. In their report, the crude oil production, refinery and gasoline combustion were compared with the production of bioethanol from the energy-crops such as corn and wheat. The results showed that GHG emissions in life cycle of gasoline production was almost 200% higher than corn ethanol production, i.e. 86719 g CO_2 eq/ GJ for gasoline and 39454 g CO_2 eq/ GJ for corn ethanol (MacLean, et al., 2008). The bioethanol production in Canada was well developed and there was no commercial production of synthetic ethanol from ethylene anymore.

From all the LCA studies that have been discussed as above, the energy balance and GHG emission throughout the life cycle stages were often assessed in LCA although the types of feedstock for bioethanol production were different. Hence, it is essential to identify the functional units, allocation methods for co-product and avoided emissions to the result of analysis.

2.2.3 Functional Unit

In order to achieve the goal that has been set in the LCA study, the functional unit must be determined. According to Pereira, et al. (2014), the functional units used in their study were kg of butanol produced, US$ earned and km run by a vehicle. These functional units were used in their LCA study because the main goal was to do the comparison of different technological configuration for the butanol production in sugarcane refineries from the environmental angle. They wanted to investigate butanol as potential environmentally friendly drop-in fuel. Besides, the impacts in terms of revenue using different technological scenarios to produce bio-butanol were compared. The unit of km was used with the purpose of comparing the usage of butanol and gasoline as fuel and run by a vehicle in the end stage. The economic allocation based on the selling price of butanol fuel was applied in this study. Concisely, this study was mainly to investigate the possible revenue to be earned and selection of suitable production technology in which possess the least environmental impacts.

In the research done by Kumar, et al. (2012), the functional unit used was 1 ton of biodiesel produced from Jatropha. The primary energy requirement and GHG emissions were estimated based on the functional unit, i.e.: 1 ton of biodiesel production. However, this functional unit is not suitable for the estimation of GHG emissions reduction with respect to gasoline. They estimated the GHG emission reduction by using the GHG generated during the LCA of biodiesel and gasoline to produce 1 GJ of energy through their combustion in car engine. The importance of having this energy basis of 1 GJ is to cancel the effect of the difference in energy contents of biodiesel and gasoline on emissions reduction percentage.

Whereas in some research, the functional units are straight forward and can be simplified as one, for example in terms of area and time period. According to Lim and Lee (2011), 1 hectare of land for palm oil plantation in time interval of 100 years was chosen. It was selected as the main interest of the research was to maximize the output from a limited land area without neglecting the maintenance of balancing the energy and GHG emissions effects. The whole process that was of interest in the LCA was the palm oil based bio-refinery and also the product expansion. No comparison was made except for the sensitivity analysis of LUC in this study.

2.2.4 System Boundaries

It is important to have a clear and well defined system boundaries in order to get comparable and consistent data. All processes that were relevant to the bioethanol production were included within the boundary of fuel systems. For example, the system was separated into four main subsystems, i.e.: feedstock cultivation, bioethanol refinery, ethanol blends production and final use (González-García, Moreira and Feijoo, 2010). However, not every LCA study carried out based on the boundary system mentioned above.

According to Tokunaga, et al. (2012), the data such as GHG emissions can be collected following the standard convention of dividing the biofuel life cycle into five stages: feedstock production, feedstock logistics, conversion, distribution, and end-use. Figure 2.1 shows the five steps of value chain of biofuel as well as the fossil fuel (gasoline for vehicles)

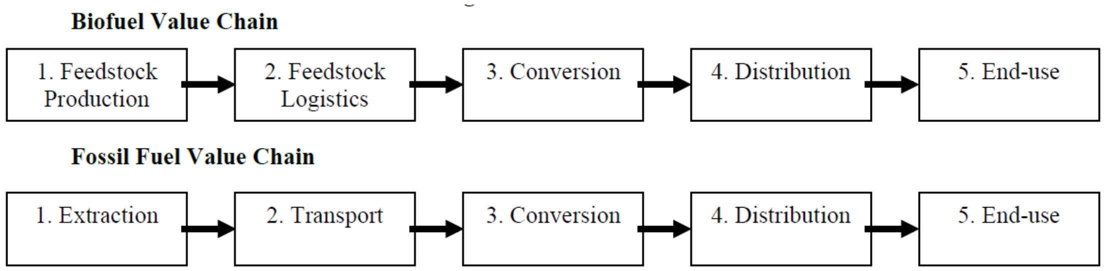


Figure 2.1: Biofuel and Fossil Fuel Value Chain (Adapted from Tokunaga et al., 2012).

In fact, selection of the elements in system boundary is crucial as different methodologies will have different system boundaries.

2.3 Life Cycle Impact Assessment

In this stage, all the relevant inputs and outputs of bioethanol production life cycle data will be collected. These data will be used to assess and evaluate the potential environmental impacts and estimate the resources used in the methodology. The data was extracted or calculated from manufacturing companies, plant reports, simulation reports and literature reviews. In fact, most of the LCA research determined the energy balance and the GHG emissions from the cultivation of bioethanol production feedstock until the final usage in transportation sector, industrial machinery and electricity power generation. (González-García, Moreira and Feijoo, 2010), (Do, et al., 2015).

Besides, LUC was also considered in most of the research. However, several reports had neglected the direct LUC because it had not much impacts in the LCA of bioethanol feedstock production (Scaife, et al., 2014). This can be seen from the bioethanol feedstock such as cultivation of microalgae. Nevertheless, most of the LCA studies on palm oil EFB do include the assessment of LUC.

Usually, LUC was considered in the first stage of LCA of bioethanol production, i.e. cultivation of feedstock. Most researchers had discovered that there was a significant change in the GHG emissions reduction and this had driven further evaluation on LUC impacts (Tokunaga, et al. 2012). This implied that there was a change of carbon stocks due to the LUC factor which resulted the GHG saving to be reduced or increased. The GHG emissions with respect to LUC may differ between biotic community and specific locations.

2.3.1 Environmental Impacts of Life Cycle of Palm Empty Fruit Bunch Based Bioethanol Production

The local research on the LCA method with the purpose of evaluating the environmental impacts of the palm EFB based bioethanol had increased over the years due to the development of the palm oil industry in Malaysia. Several well-known companies such as Sime Darby and researchers had put in effort to further study the palm empty fruit bunch based bioethanol (IL Bioeconomista, 2014). This was due to the abundance of palm biomass produced and using EFB can help to solve the current environmental impacts such as GWP.

2.3.1.1 Source of Oil Palm Empty Fruit Bunch

Bioethanol production is a big industry in Brazil and the industry will continue to expand as huge tracts of land is devoted to sugarcane. For Malaysia, the potential feedstock would be palm oil milling waste, which generates at a rate of 40 million tonnes in a year (The Star, 2014). Approximately 4 kg of dry biomass are produced with every kg of palm oil production. Then, one third of the dry biomass is EFB and the remaining are oil palm trunks and fronds (Geng A., 2013). The oil palm and EFB are shown in Figure 2.2.

Figure 2.2: Oil Palm (left) and Oil Palm Empty Fruit Bunch (right) (Adapted from Geng A., 2013)

In the past, EFB was used for power generation and steam utilization in the palm oil mills by burning it. However, environmental pollutions due to the incomplete combustion and the release of soot and ash can be caused by direct burning of EFB. Therefore, utilizing the conversion of EFB into bioethanol is a better alternative and have less environmental impacts.

2.3.1.2 Energy Balance of Palm Empty Fruit Bunch Based Bioethanol Production

Basically, all studies reported that bioethanol production from EFB would produce positive energy balance and this indicates that EFB is a feasible feedstock (Lim and

Lee, 2011) (Do, et al., 2015) (Tan, Lee and Mohamed, 2010). The NER data of bioethanol production from different reviewed studies is shown in Table 2.1. However, the results are based on their own normalization in different system boundaries of their report.

Energy balance targets to determine the energy of bioethanol to non-renewable energy resources which used for production of bioethanol. The NER can be defined as the ratio of the total energy output from the bioethanol (MJ/kg) to the non-renewable primary energy consumed to generate 1 kg of bioethanol.

Table 2.1: NER of the Reviewed Reports.

No.	Reference	NER
1	Chiew and Shimada 2013	2.10
2	Do, et al. 2015	1.11 - 5.95
3	Lim and Lee 2011	4.48
4	Tan, Lee and Mohamed 2010	2.26

According to Tan, Lee and Mohamed (2010), the NER reported was 2.26 and very closed to the value reported by Chiew and Shimada (2013), while the others have higher NER. In fact, the values of NER as shown in the Table 2.1 were depended on several technical factors for instance the type of chemical pre-treatment they used, temperature for the fermentation process and moisture content of EFB. Besides, different results and different methodologies were used in every report.

NER results can be improved by considering other steps such as waste and co-products into palm oil processing expansion system. The trunks and fronds from oil palm can also be used as the feedstock of bioethanol production. However, the NER could be improved slightly only as the cellulose content of trunks and fronds are lesser compared to EFB. In the LCA research done by Lim and Lee (2011), the NER value reported by them is higher than the others because the palm oil fronds were included in the conversion to bioethanol.

Do, et al. (2015) claimed that with the heat integration system in bioethanol processing plant, the NER could be as high as 5.95 compared to 1.11 without the heat integration system. From all the research that had been reviewed, the NER was calculated based on the heat and electricity consumed in the production of bioethanol only except Lim and Lee (2011). Hence, it could be very difficult to compare as the system boundaries were not consistent.

2.3.1.3 GHG emission of Palm Empty Fruit Bunch Based Bioethanol Production

25% of the global GHG emissions are from the worldwide transportation sector, and the emissions from that particular sector is rising over time (Morales, et al., 2014). Basically, the GHG emissions sources are the cultivation stage, supplies transportation, bioethanol production stage and end use stage. Several studies from Brazil had shown that sugarcane-based ethanol can reduce GHG emissions up to 85% with the case of no significant land use change (Department of Transport, 2008).

Currently, sugarcane-based bioethanol which under commercial production in Brazil is considered as the most efficient biofuel in terms of the GHG emissions reduction. According to Morales, et al. (2014), the LCA report showed that the bioethanol production from sugarcane released 50.6-59.3 g CO_2 equivalent /MJ (with cogeneration) and 112.1-123.4 g CO_2 equivalent/ MJ (without cogeneration). From the result, the GHG emissions can be reduced up to 51.9% with the energy cogeneration from lignin.

In Malaysia, there are a lot of agricultural crop biomass such as EFB which suitable as the feedstock for bioethanol production. These wastes are available in very low cost and generate in large amount every year. Delivand and Gnansounou (2013) claimed that the GHG emissions from the bioethanol production in palm-based refinery was around 150 kg CO_2 eq/ ton FFB. The functional unit for the study was 1 ton FFB and the bioethanol production was the co-production by stripping the materials from FFB.

2.3.1.4 Other Environmental Impacts

From the reviewed studies, most of them include wide range of environmental impacts indicator for all feedstock of bioethanol. More than half of the cases considered the global warming or energy balance. However, other environmental impacts such as acidification, eutrophication, ozone layer depletion and biodiversity loss were used in Morales, et al. (2014). The impact of acidification and eutrophication for lignocellulosic bioethanol increased due to the emission of nitrogen compounds (NOx), sulfur compound (SOx), usage of fertilizer and the enzyme or microbe production that utilized nitrogen as source (Morales ,et al., 2014). Nevertheless, the impacts were highly influenced by the raw materials and hence they needed to be analysed accordingly. Therefore, the impacts could be lower when the bioethanol production feedstock was obtained from biomass wastes or organic residues instead of directly from the cultivated crops.

The eutrophication and acidification impacts were reported in less uniform manner (Morales, et al., 2014). Hence, it is difficult to compare the result and normalized it. In the case of palm oil based biofuel, these impacts were usually caused by the agricultural and EFB extraction stage. Ammonia emission and Nitrogen leaching were associated with these stages.

While in the ozone layer depletion case, the environmental impacts reported was lower when comparing the use of partial bioethanol fuel or completely bioethanol fuel to the gasoline used in vehicle. Moreover, due to the complication in determining the impacts on biodiversity loss, there was no unified calculation on these indicators (Menichetti E., Otto M., 2008)

2.3.2 Environmental Impacts of Life Cycle of Microalgae Based Bioethanol Production

Nowadays, bioethanol production feedstock is majorly obtained from starch crops and also lignocellulosic biomass such as palm EFB and rice straw. However, due to the high demand of using agricultural crops and waste as the feedstock for bioethanol production, problems such as limited arable lands and limited water supply have being created. Besides, it required a very high cost to produce SGB from lignocellulosic materials as the lignocellulosic biomass contains high lignin composition, which requires extra energy to be used before further process in saccharification process.

Microalgae is being recognized as a third-generation feedstock for bioethanol production and it has potential to replace the first and second-generation feedstock. Due to several microalgae species which contains high carbohydrate composition, in the form of starch and cellulose (without the presence of lignin), they were considered as the feedstock for bioethanol production. Hence, it is easier to convert to simple sugar compared with lignocellulosic materials.

Microalgae are easy to be cultivated and it is less costly compared to other feedstock. Hence, microalgae has a great potential in producing renewable biofuel in Malaysia. Countries such as USA and Brazil had started to invest tremendously and build the facilities and pilot plants for research (Scaife, et al., 2014). While in Malaysia, this field is still in development stage and lab-scale.

2.3.2.1 Advantages and Disadvantages of Microalgae as Feedstock for Bioethanol Production.

Microalgae such as *Chlorella, Dunaliella, Chlamydomonas, Scenedesmus, Spirulina* have high content of starch and glycogen, i.e. more than 50% of the dry weight. Therefore it is useful to provide abundance of raw materials for bioethanol production. Besides, the algae have lower land requirement, fast growth rates, and can grow to high densities by using light, carbon dioxide and other nutrients efficiently.

Basically, the cultivation of microalgae is divided into two main methods: photosynthetic and heterotrophic. Photosynthetic cultivation refers to the microalgae harvesting the light energy from sun and use CO_2 as carbon source to produce their own food for growing. Whereas, heterotrophic is refer to microalgae which cannot make their own food and grows using organic compounds synthesized by other organisms (Perez-Garcia, et al., 2010).

The advantages and disadvantages for photosynthetic and heterotrophic cultivation method are shown in Table 2.2.

Table 2.2: Advantages and Disadvantages of Microalgae Photosynthetic and Heterotrophic (Scaife, et al., 2014).

	Advantages	**Disadvantages**
Photosynthetic	- Avoid the production of CO_2 from typical farming processes.	- Limited by the light availability and dependant on climate.
	- No arable land is required	- Scalable by area instead of volume.
	- Reduce the demand on irrigation source as non-potable water is used.	- Exposed to the risk of contamination and invasion which affect the production.
	- Biomass is free of lignin.	- Intense energy is required in downstream process.
	- Input flexibility in cultivation- it can be low to high input.	
Heterotrophic	- Production is not affected by climate and geography.	- Energy input is high in growth phase.
	- The productivity is 2 times higher than photosynthetic processes.	- High cost for running the process and infrastructure.
	- Scale by volume instead of area, hence the land usage reduced.	
	- Final product is zero	

	chlorophyll.	
	- A closed system which has high reproducibility and reliability of culture.	

2.3.2.2 Energy Balance of Microalgae Based Bioethanol Production

According to the Sander and Murthy (2010), the energy input for the growth of microalgae per unit process (1000 MJ functional unit) was 15.43 MJ. However, during the harvesting stage in the LCA of microalgae, the energy input was 2915.27 MJ which is almost 80% of the energy input into the cradle to gate. However, the total energy consumption for coproduct expansion which is the bioethanol production was not stated in this research.

Due to the absence of lignin in the microalgae, the production steps for microalgae as the feedstock of bioethanol conversion are reduced as compared to lignocellulosic biomass as feedstock. Hence, it does not require to undergo the pre-treatment process that aims to separate cellulose from the lignin. Eventually, the energy consumption in the bioethanol processing may be lesser than EFB as the feedstock.

2.3.2.3 GHG emissions of Microalgae Based Bioethanol Production

Over the years, a lot of research has been conducted on algae biofuels production and CO_2 bioremediation (John, et al., 2010). In fact, the usage of microalgae as feedstock for bioethanol production plays an important role in the future as it consumes carbon source such as CO_2 to grow and resulted in “carbon neutral” after it has been converted to biofuels.

After reviewed several studies, most of the LCA research focused on biodiesel production instead of bioethanol production (Sander and Murthy, 2010) (Souza, et al., 2010). However, some of them had considered the coproduct expansion by converting the microalgae meal which assumed to contain 30% of cellulose from carbohydrates into ethanol (Sander and Murthy, 2010). The GHG emission reduction has increased due to larger output produced when including the bioethanol production.

As mentioned above, one of the benefits of microalgae towards the environment impacts is to capture CO_2 and eventually reducing the GHG emissions up to 45% (Sander and Murthy, 2010). The GHG emissions that produced from the downstream process of bioethanol production can be credited when this factor has taken into considerations. On top of that, microalgae cultivation has less impact on the LUC as algae can be cultivated in off-shore waters. Besides, the bioreactors require an area of land to operate but it is considered smaller than other agricultural crop cultivations.

2.3.3 Sensitivity Analysis in Other Research

Sensitivity analysis is used to examine changes in the outputs of a model which response to changes in the input parameters values and to make sure of the model is responding properly (McGrath D., 2006). The outputs (dependent variables) is influenced by the inputs (independent variables) and both may be either continuous or discrete (Budavari, et al., 2011).

Besides, sensitivity analysis can be used to evaluate and analyse the parameters when there are uncertainty of inputs or outputs or some data that might not be available due to lack of information (Budavari, et al., 2011). In the research of Raman and Gnansounou (2014), the solid loading in pre-treatment process and enzyme loading in saccharification were examined with sensitivity analysis method. The solid loading was increased from 10% to 20% where the conditions were maintained at optimized condition. The results showed that the composition of glucose and xylose in liquid effluent were almost doubled. However, the mass recovery showed no significant difference in the result. On the other hand, the enzyme (Cellulase) dosage was reduced from 20 FPU/g glucan to 10 FPU/g glucan and the yield of glucose was reduced by 15%. Hence, these implied that the effectiveness of the processes was the same even though the parameters have been changed.

Moreover, the sensitivity analysis method was used in the research of Souza, et al., (2010), the variations of NER and GHG emissions due to the changes in the selected input parameters such as bunches yield per hectare, nitrogen, phosphorus, potassium, and magnesium utilization rate per hectare. In overall, the results showed that the NER was slightly reduced and GHG emissions was increased when each of the inputs was increasing. In the case of increasing the usage of fertilizers, the NER were slightly reduced because the use of coproduct to power generation would improve the energy balance. This is mainly due to the energy produced from the combustion of coproduct was larger than the energy required to produce fertilizers. However, the GHG emissions would increase which resulted from the direct combustion of coproduct and usage of fertilizers.

2.4 Overview of the Bioethanol Production Processes

2.4.1 Pre-treatment Process

Pre-treatment process is an important step to unwind the cellulose which embedded in hemicellulose and lignin. After that, the cellulose will be more susceptible for enzymatic hydrolysis. Usually, the pre-treatment steps refer to the solubilization and separation of components of agricultural residues or biomass which give only cellulose at the end of process (Sudiyani, et al., 2013).

Chemical pre-treatment is the most common used technology in pre-treatment process, i.e. alkali chemical pre-treatment and acid chemical pre-treatment. Gupta A. and Verma J.P. (2014) reported that chemicals generally employed are sodium hydroxide, perchloric acid, peracetic acid, acid hydrolysis using sulfuric acid and formic acid. However, dilute sulfuric acid pre-treatment is the most famous among all the chemicals due its availability and cheaper cost. Furthermore, the pre-treatment consists of physical pre-treatment and biological pre-treatment. These pre-treatments were seldom practiced as they possess some challenges, e.g.: physical pre-treatment requires more energy inputs and inhibitory compounds were released during the pre-treatment and eventually affect the subsequent stage. Whereas the hydrolysis rate of biological pre-treatment was low but relatively safe and energy saving because less mechanical support. The schematic diagram of pre-treatment process is shown in Figure 2.3.

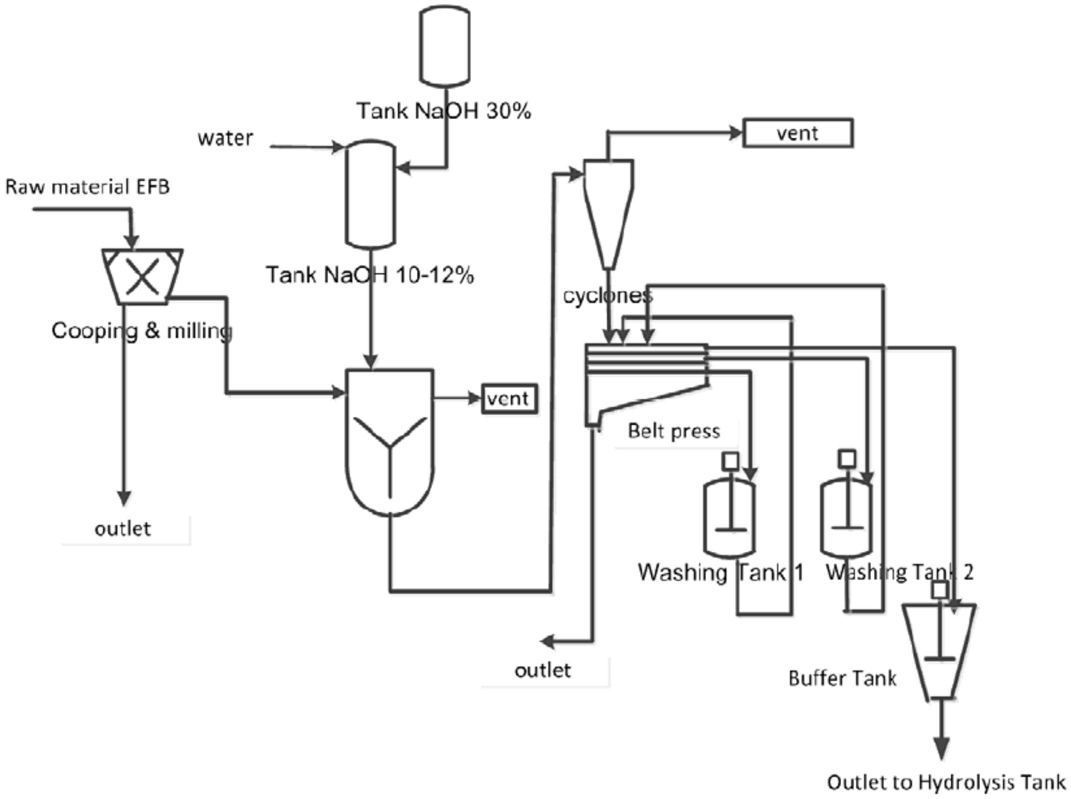


Figure 2.3: Schematic Diagram of Pre-treatment Process (adapted from Sudiyani, et al., 2013).

2.4.2 Enzymatic and Chemical Hydrolysis

Generally, enzymatic and chemical (acid and alkaline) hydrolysis are commonly used in commercial industry. Enzymatic hydrolysis is the stage where the complex carbohydrates are broken down to simple monomers. Cellulase is the most important enzyme in this process which can be naturally obtained from cellulolytic microbes such as *Cellulomonas, Bacillus, Bacteriodes* and other fungi for instance *Penicilium.* These enzymes are used to convert the cellulose to glucose and galactose. This method is preferred due to its low toxicity, utility cost and low corrosion compared to acid and alkaline hydrolysis. Besides, there is no secretion of inhibitory by-product as the cellulose enzyme is highly substrate specific (Gupta A. and Verma J.P., 2014).

On the other hand, acid hydrolysis is a faster, easier and relatively low cost than other types of hydrolysis. However, the acidic conditions may cause the simple sugar broken down into unwanted compounds that will inhibit the fermentation process (Gupta A. and Verma J.P., 2014).

2.4.3 Fermentation and Distillation

In this stage, microorganisms are used for the fermentation of sugars. Ideally, a commercially feasible fermentation process should have an effective microbe with characteristics such as high ethanol yield and productivity at wide range of temperature and broad substrate usage. According to the reviewed studies, the common used microbe is *Saccharomyces* yeast due its robustness and high yield of ethanol from glucose. Nowadays, simultaneous saccharification and fermentation (SSF) is generally used in ethanol production as it can remove the end product inhibition and avoid the usage of separate reactors (Sudiyani, et al., 2013). The schematic flowsheet of saccharification and fermentation process is shown in Figure 2.4.

It is important to understand the bioethanol production processes as the usage of chemicals and enzymes are the factors that cause the environmental impacts such as acidification and eutrophication. Besides, the processes are needed to be evaluated in order to obtain GHG emissions and energy balance data. The operating conditions such as temperature and the type of microbes used may be assess in the sensitivity analysis.

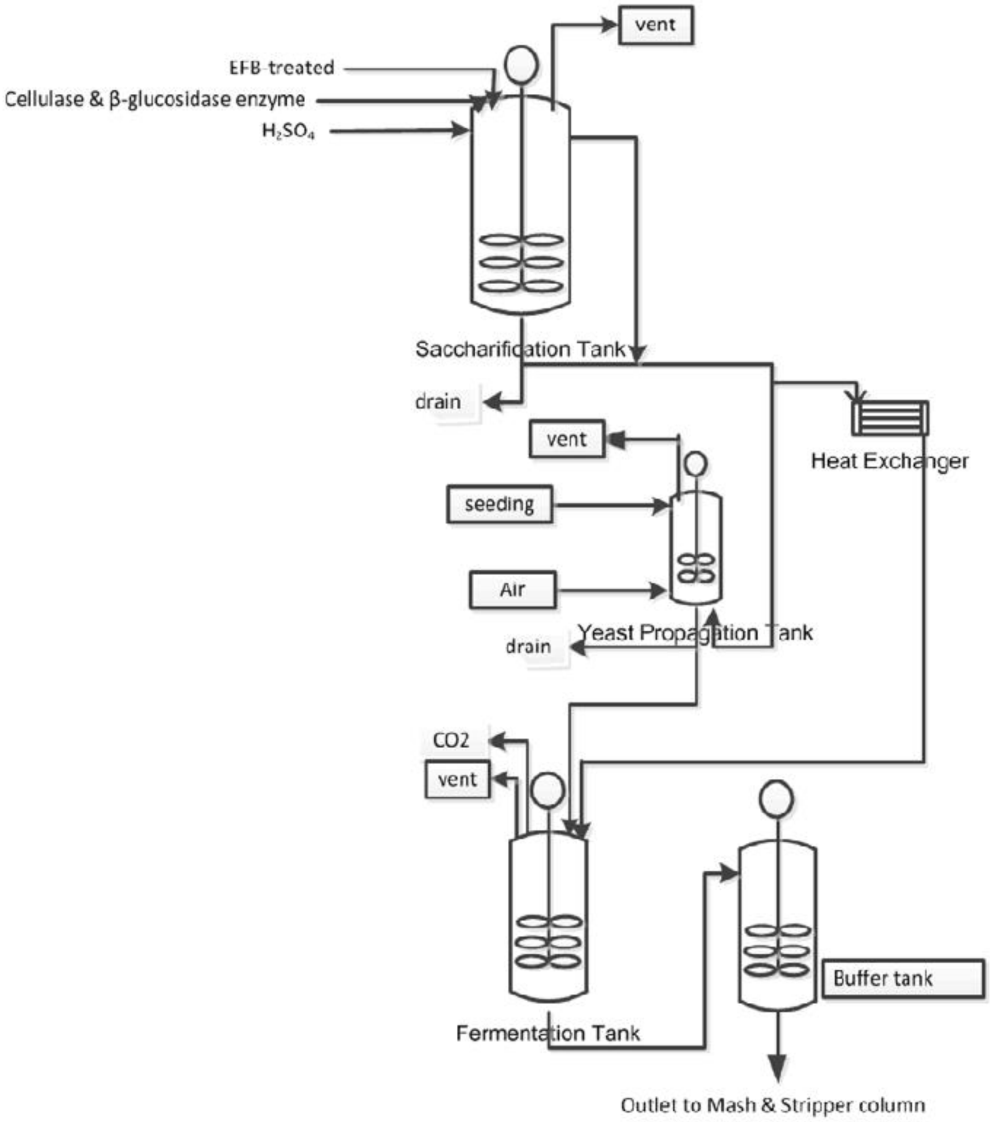


Figure 2.4: Schematic Flowsheet of Saccharification and Fermentation Process (adapted from Sudiyani, et al., 2013).

2.5 Simulation of Bioethanol Production Processes

Commercial ethanol production can be divided into two type, i.e. synthetic ethanol and fermentation ethanol. Basically the synthetic ethanol is produced from hydrolysis of hydrocarbon such as ethylene to react with water in the presence of strong acid that served as catalyst. While the fermentation ethanol is produced from materials which containing high composition of complex and simple sugars.

By using a simulation software such as ASPEN Plus, the yield of ethanol and energy used can be simulated by inserting the parameters. These parameters and conditions will be obtained from journals. The simulation of bioethanol production includes 3 major steps, they are hydrolysis of complex sugar to glucose, fermentation of glucose to ethanol and separation of ethanol from fermentation broth (Zhang, et al., 2009).

Acids hydrolysis or enzymes hydrolysis can be used in the first step of bioethanol production. In the research of Lassmann, et al. (2014), a enzymatic hydrolysis together with a steam explosion step was chosen. The steam explosion was an extra pre-treatment step to ensure the lignocellulosic structure are broken down and accessible for enzymatic attack. The yield of monosaccharides can be up to 95% (Lassmann, et al., 2014). In another case, Zhang, et al., 2009 were using dilute hydrochloric acid in hydrolysis. A two staged hydrolysis is used to increase the monosaccharides concentration and reduce degradation. The conditions of process simulation in two staged hydrolysis are shown in Table 2.3.

Table 2.3: Conditions of two staged hydrolysis (Zhang, et al., 2009)

Parameter	Value
Acid Concentration (%)	1
First and Second Stage Temperature (^oC)	165, 120
Residence Time in First and Second Stage (min)	25, 15
Conversion rate of glucose from Hemicellulose and Cellulose.	80, 70

Next, the fermentation process is to convert glucose to ethanol at 95% conversion rate (Zhang, et al., 2009) (ProSim, 2009). According to Nanda S., (2014), the optimum conditions for production of ethanol with recombinant bacterium Zymomonas mobilis is 33 ^{o}C and cultured for 30 hours. Whereas Zhang, et al., (2009) suggested optimum fermentation temperature at 38 ^{o}C. Then, the broth which containing 4 wt% of ethanol and more than 80wt% of water entered into separation zone with two distillation columns (Lassman, et al., 2009). The ethanol separated from the first column can be concentrated up to 55% and followed by 99.4% at the end of process. The specification of the two column are listed in Table 2.4.

Table 2.4: Conditions of the two distillation columns used in Lassman, et al., 2009.

Parameter	First Column	Second Column
Operational Pressure	2.03 bar	2.03 bar
Number of stages (actual)	32	60
Column efficiency	48%	57%
Reflux ratio	3	3.2

CHAPTER 3

METHODOLOGY

3.1 Scope of the LCA Research

This life cycle assessment (LCA) study will be carried out according to established guidelines under ISO 14000 series, Environmental Management Standards (EMS) in ISO 14044:2006. LCA is a technique to evaluate the environmental aspects and potential impacts throughout the interested product's life cycle from cradle-to-grave, i.e. from raw material acquisition until the end of life. Besides, the functional unit that will be used as a reference unit for comparison and system boundaries of each type of feedstock will also be included. All the relevant inputs and outputs of entire bioethanol production life cycle data will be collected and evaluated. These inputs and outputs are include the resources consumption, energy consumption and greenhouse gas (GHG) emissions throughout each stage of their life cycle.

This LCA study will compare the environmental impact in terms of energy balance (energy input and output) and GHG emissions of bioethanol production from different types of feedstock which are EFB and microalgae.

Basically, all the inputs and outputs that involved in every stage of the entire process system will be traced back to the primary energy such as electrical energy from national grid and fossil fuels. Moreover, the fertilisers that were used in feedstock cultivation are source of nitrogen and phosphorus for growth. The input and output in terms of energy consumption and emissions of each processing unit involved in the palm oil mill, bioethanol processing plant and etc. Transportation and machinery that involved in the life cycle of bioethanol production will be considered as well from each functional unit. The life cycle of the bioethanol production boundary systems from different feedstock will be modelled by using ASPEN PLUS simulation software in order to gather and compare the inventory analysis data.

Two parameters that will be used in this LCA study are the energy balance and GHG emissions. A lot of coproducts can be produced from the feedstock in this LCA, but the allocation of coproducts as product expansion system will not be covered. Whereas the utilization of residues and waste will be considered in the LCA analysis. Detailed explanation for the methods of collecting the data for LCI and LCIA on each type of feedstock can be found later in section 3.3.

3.2 Functional Unit

In order to achieve the goal and scope mentioned, functional unit that considered in this study is 1 ton of bioethanol produced. Besides, the primary energy usage and GHG emissions were estimated from 1 ton of bioethanol production. This functional unit is chosen because it will be convenient in comparing the results from LCI as different types of feedstock contain different amount of cellulose, i.e. the main component that used to convert into ethanol. On top of that, the cultivation of microalgae has very less impact on the LUC. Hence, the chosen functional unit is suitable when it is used in comparing the raw materials which have different composition of carbohydrates such as cellulose or starch.

3.3 Life Cycle System Boundary of EFB Based Bioethanol

As mentioned in the goal and scope, this LCA study will evaluate the environmental aspects and potential impacts throughout the palm EFB based bioethanol from cradle-to-grave. The life cycle of palm EFB based bioethanol is separated into three main stages. The first stage is the oil palm plantation, then palm oil milling and followed by the bioethanol processing. The system boundary for EFB bioethanol is as shown in Figure 3.1.

3.3.1 Oil Palm Plantation

According to Malaysian Palm Oil Council (2013), the oil palm cultivation occupied 4.49 million hectares of land in Malaysia. 17.73 million tonnes of palm oil and 2.13 tonnes of palm kernel oil are produced per annum.

The data that will be collected into LCI includes the area that used for oil palm plantation and the type of land used in oil palm seed cultivation. Besides, the average number of seeds used for cultivation per hectare will be collected as well. The fertilizers as the source of nitrogen and phosphorus for the growth of plants, pesticides, herbicides electricity and machinery input data for raw materials is needed. In addition, the output data such as the amount of FFB, fronds and trunks, carbon stock, soil emissions and fossil fuels consumed to transport FFB to the palm oil mill. All of these input and output data will be gathered from local palm oil companies for example Sime Darby, Hock Lee Group and Teck Guan Group and etc.

3.3.2 Palm Oil Milling

After the FFB being processed in the palm oil mill, the milling stage produces about 22% EFB, 9% shells, 14% fibers, 60% of palm oil mill effluent (POME), 5% palm kernel seeds and 20% crude palm oil (CPO) (Ibrahim, et al., 2014). The shells and fibers were generally fed into integrated biomass fired Combined Heat and Power (CHP) plant to generate power. Besides, the EFB will usually recycle back as organic fertilizer. However since EFB is the main raw material to produce bioethanol in this study, therefore it will not be used as organic fertilizer.

The coproducts such as CPO and palm kernel seeds will not be considered in

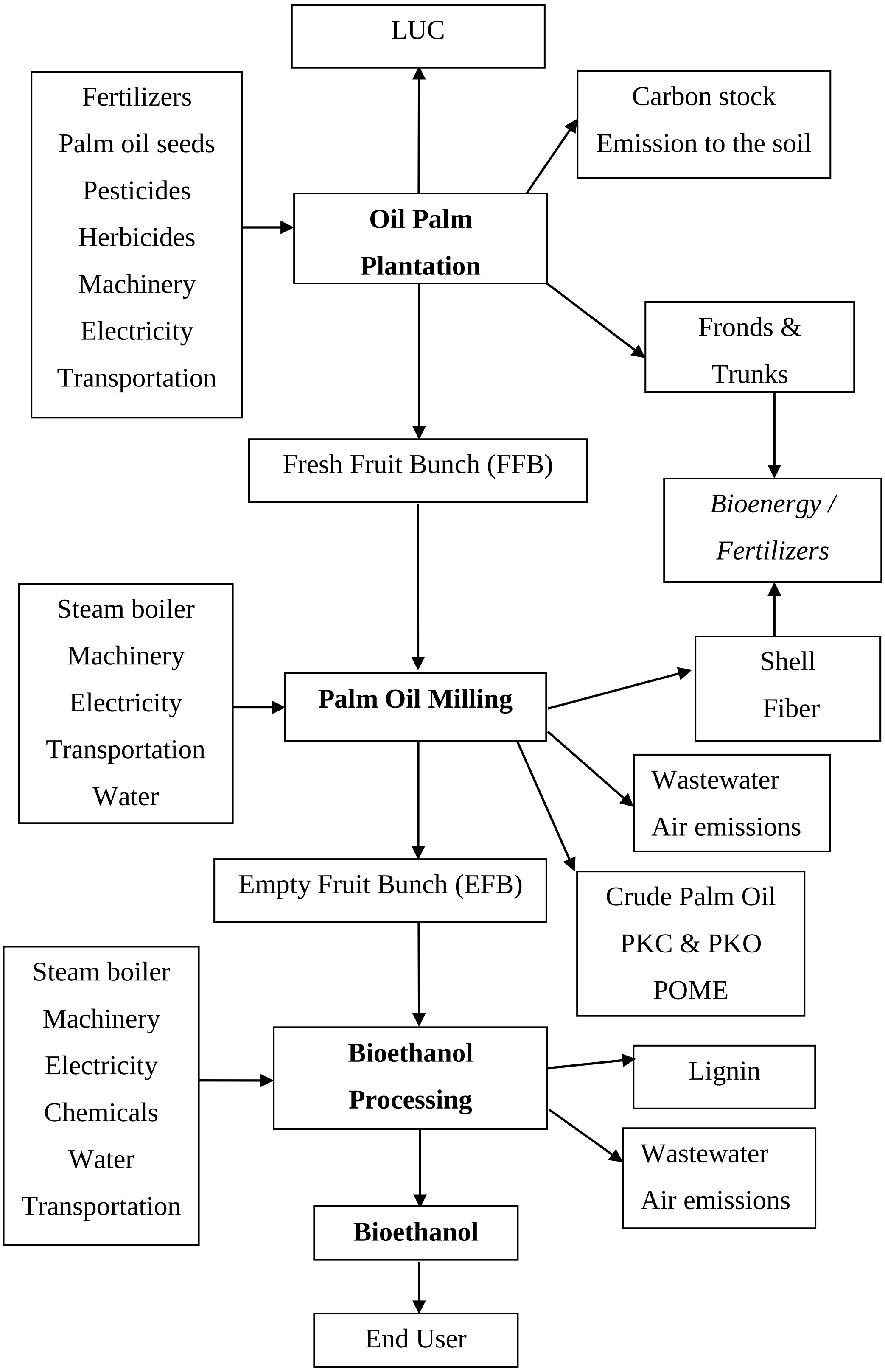


Figure 3.1: The System Boundary of Palm EFB based Bioethanol Process.

product expansion system as the main interest of this study is bioethanol production. However, the POME, shells and fibres were reused as the energy input for the palm oil mill. POME is a mixture of polluted effluent which contained high Chemical Oxygen Demand (COD) concentration and it can result in severe environmental impacts such as high GHG emissions (Delivand and Gnansounou, 2013). POME was treated under anaerobic conditions to produce biogas and these biogas were captured and fed into the CHP plant to generate power in palm oil mill. Hence, the energy produced and GHG emissions will be credited.

Apart from that, the input data that will be considered in this stage are the electricity, water and fossil fuels that consumed by the machinery, steam boilers and transportation included in the process. The output data such as carbon emissions and wastewater produced from electricity, machinery and transportation is required as well.

3.3.3 Bioethanol Processing from EFB

Due to the high content of carbohydrates such as cellulose in EFB, the EFB produced from the palm oil mill was considered as an ideal biomass for bioethanol production. However, there are no local manufacturers producing bioethanol in large scale or commercially in Malaysia. Therefore, the inventory data will be collected from pilot plant which is modelled by local company such as Sime Darby.

The input data that will be collected in bioethanol processing are electricity, water and fossil fuels that used in machinery, steam boilers and also the transportation of materials. The input of the most common chemicals used in stage such as dilute sulfuric acid, cellulose enzyme and yeast (*Saccharomyces cerevisiae*) will be gathered as well. The output from this stage is the lignin which can be combusted as fuel for steam generation. The wastewater and GHG emissions which mainly produced from steam boiler will also be investigated. The energy consumption for steam boiler is expected to be high as large amount of heat is necessary to hydrolyse the thick wall of lignocellulosic biomass.

3.4 Life Cycle System Boundary of Microalgae Based Bioethanol

The life cycle of microalgae based bioethanol is separated into three main stages. The first stage is the microalgae cultivation, then dewatering and components extraction and finally the bioethanol processing. The system boundary for microalgae-to- bioethanol is as shown in Figure 3.2.

3.4.1 The Cultivation of Microalgae

The microalgae cultivation is usually done in either open ponds (OP) or enclosed photo-bioreactors (PBR). Usually, marine microalgae is more preferable used in these large production of cultivation technologies. The types of microalgae that commonly used in cultivation are *Chlorella, Dunaliella, Chlamydomonas, Scenedesmus,* and *Spirulina***.** As mentioned, the most significant advantage of the microalgae cultivations compared to the agricultural crops cultivations is they do not require a large land area for cultivation activity. Therefore, the evaluations of land used by microalgae cultivation will not be considered in this LCA study.

The input data such as the cultures, nutrients, machinery, electricity, water, CO_2 and transportation of microalgae to extraction phase will be considered in this stage. The water produced from the dewatering or drying stage can be recycled back as the input of this stage (Collet, et al., 2014). Whilst the output data that will be collected are the microalgae produced and wastewater generated.

3.4.2 Dewatering/Drying and Components Extraction

The purpose of dewatering the microalgae is to separate the water from the solid (microalgae cake). Usually, microalgae comprises of 30% solid with 70% moisture content (Lee, et al., 2015). The dewatering of microalgae stage requires the input

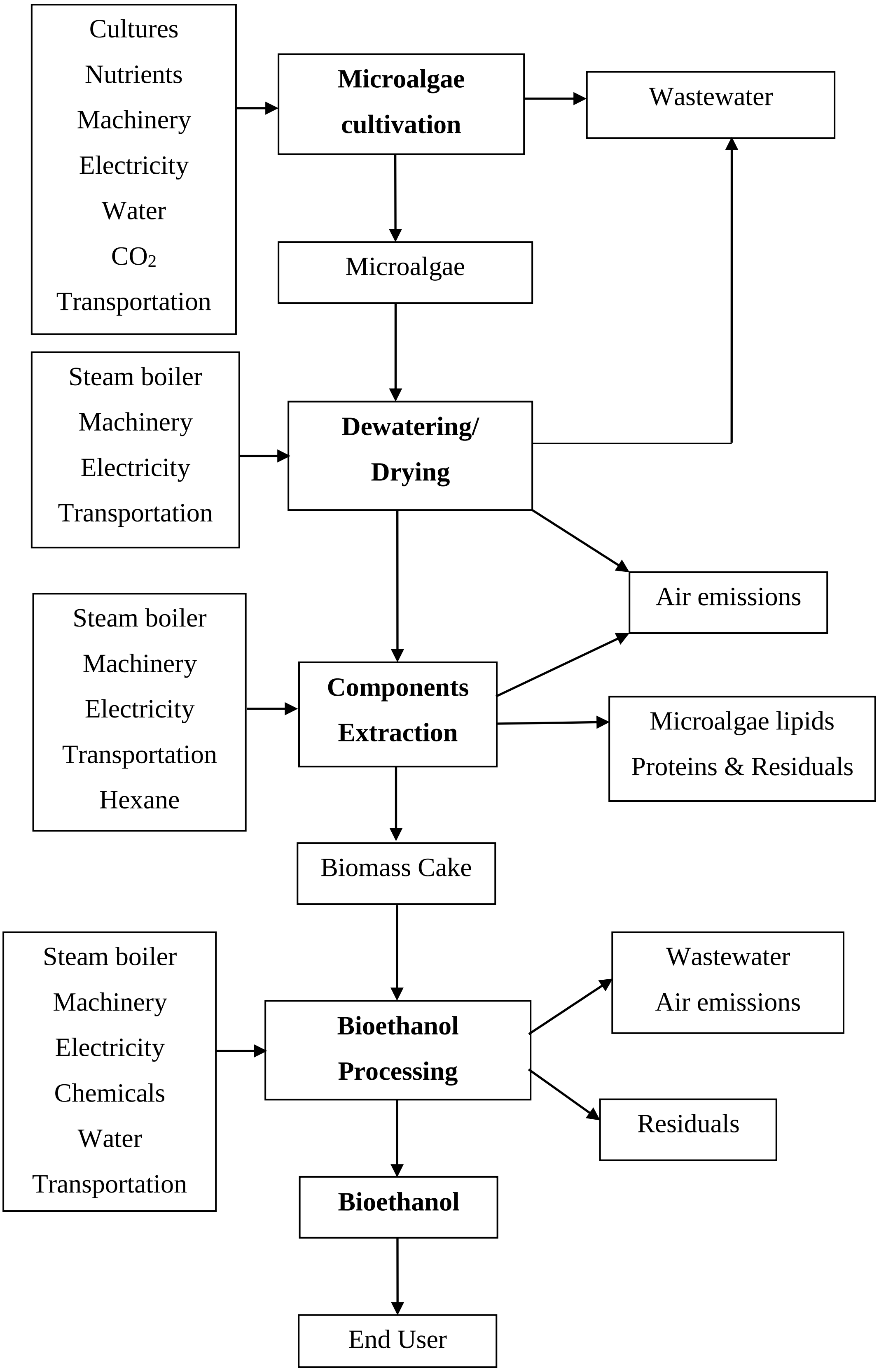


Figure 3.2: The System Boundary of Microalgae Based Bioethanol Process.

data such as the steam boiler, machinery and electricity while the output data needed are the biomass cake which contained the interested raw material i.e. carbohydrates, and output of water which will be reused in the cultivation stage. Lee, et al. (2015) claims that the energy required for dewatering process can be up to 84.9% of total energy consumption in biofuels production.

On the other hand, the components extraction phase is to extract the lipids and proteins from microalgae and leaving its biomass cake as a material for bioethanol production. The common technique for extracting lipid from microalgae is a solvent extraction using Hexane or methanol. However, the extraction of microalgae lipid by using solvent has very low efficiency. Ultrasonic-assisted extraction can be an alternative technique to organic solvent extraction (Zhao, et al., 2013).

Hence, the input data such as the microalgae paste, machinery, steam boiler, electricity and hexane used will be considered while the output data to be gathered are biomass cake, microalgae lipids, protein, residuals and GHG emissions. Microalgae lipids, protein and residuals were used in biodiesel, bio-oil and bio-char production. However, these are not considered in this LCA study as they are not the main interest.

3.4.3 Bioethanol Processing from Biomass Cake

The microalgae based bioethanol production is almost similar to the bioethanol processing from other agricultural waste feedstock. However, microalgae contain little or no lignin, which do not require biomass pre-treatment for the removal of lignin. The biomass cake containing up to 50% of carbohydrate per dry weight (Ho, et al., 2012).

The input data that will be collected in bioethanol processing are electricity, water, chemicals and fossil fuels that used in machinery, steam boilers and also the transportation of materials. The output from this stage is the residuals, wastewater and GHG emissions which mainly produced from steam boiler will also be investigated. The wastewater and GHG emissions would be less as compared to bioethanol processing from EFB as feedstock.

3.5 LCA Parameters Analysis Method

3.5.1 Energy Balance

The inventory data for the energy balance will be determined from the input and output of each stage of system boundary from the feedstock cultivation to the end of bioethanol production process. Some input and output parameters are in terms of mass basis or volume basis. These values are necessary to be converted into the form of energy parameter. For instance, from the research of Souza, et al. (2010), the energy intensity of 1 m^3 of water is approximately equals to 0.01MJ/L of water. Besides, the energy outputs can be gained through the multiplying of activity data available such as calorific value (CV) and lower heating value (LHV). At the same time, some of the input and output energy data will be obtained from the ASPEN PLUS simulation software.

The input energy from the manpower that involved in the life cycle of bioethanol production will not be included in this study. Nonetheless, the credits of energy from the coproduct expansion system will be considered. The overall energy flows of the production system from different feedstock is presented in terms of NER in which the sum of the net output energy divided by the net input energy. The net output energy will include the co-products and after the co-products have been regenerated as energy, it then will be removed and the input energy for generation of reused energy will be considered. The formula for NER is shown in equation 3.1.

$$\text{NER} = \frac{\sum Net\ Ouput\ energy}{\sum Net\ Input\ Energy\ include\ Product\ Expansion} \qquad (3.1)$$

Where,
NER = Net Energy Ratio

Apart from that, the residual waste and effluents generated from the processes will be sent for treatment. Abundant of biogas will be released from the effluent treatment plant and it can serve as the main source of GHG emissions. Therefore, capturing and reusing the biogas for energy consumption is one of the way to reduce GHG emissions.

3.5.2 GHG Emissions

There are four main GHG emissions: carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and fluorinated gases such as sulfur hexafluoride (SF_6), chloroflourocarbons (CFC) and hydrofluorocarbons (HFC) (EPA, 2013). In this research, the most important $CO_{2,}$ CH_4, and N_2O will be taken into account in the GHG emissions because they are commonly found in the life cycle of bioethanol production (Morales, et al., 2014). The N_2O come mainly from the application of fertilizers. According to Cooper, Butler and Leifert (2011), the GHG emissions from the usage of fertilizer (organic nitrogen (N) source) was calculated based on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The N_2O emission was calculated from the input of organic N into the soil multiplied with the emission factor for N in residues i.e. 0.01 kg N_2O-N/ kg N input. Then N_2O emission was converted to CO_2 equivalents (CO_2eq) using GWP on a 100-year time horizon of 310 times CO_2 (Cooper, Butler and Leifert, 2011).

In this study, it would be appropriate to list down the GHG emissions values in terms of kgCO_2eq per tonne bioethanol (kg CO_2 equivalent per functional unit of this study). The total GHG emissions of the life cycle of bioethanol production can be determined by using the equation 3.2.

$$GHG_{production} = GHG_{cultivation} + GHG_{transportation} + GHG_{combustion} + GHG_{electricity} + GHG_{other\_waste} \quad (3.2)$$

Where,

$GHG_{production}$ = total life cycle GHG emissions of the bioethanol production, kg CO_2eq/tonne

$GHG_{cultivation}$ = total GHG emissions from feedstock cultivation stage, kg CO_2eq/tonne

$GHG_{transportation}$ = total GHG emissions from transportation, kg CO_2eq/tonne

$GHG_{combustion}$ = total GHG emissions from the combustion involved in plant processing units, kg CO_2eq/tonne

GHG_{other_waste} = total GHG emissions from the waste produced and waste treatment, kg CO_2eq/tonne

GHG emissions can also be offset through the energy generation from the co-products. In the bioethanol production processes, one of the sources of GHG emissions is electricity from the grid. In Malaysia, the GHG emissions from the electricity grid is approximately 0.6 kg CO_2eq/kWh (Malaysia Energy Centre, 2004). Moreover, the avoided carbon can be determined due to utilizing the coproducts expansion in bioethanol production after knowing the emissions of the fossil fuel in transportation and combustion.

3.5.3 Sensitivity Analysis

A sensitivity analysis is necessary to be carried out to assess the effect of changes of the inputs such as composition of carbohydrates in feedstock, operating temperature for fermentation on the yield of ethanol, NER and GHG emissions presented in this study.

The effect of pesticides is not required to be evaluated as most of the LCA research often exclude it in sensitivity analysis. Besides, the pesticide has no relevant impacts to the energy and GHG emissions (Souza, et al., 2010). The equipment and transportation cannot be assessed as some of the approaches are different. For instance, the extraction processes of EFB from FFB and carbohydrate from microalgae are different. Hence their equipment used in that particular stage were different. Furthermore, the amount and weight of EFB are tremendous as compared to microalgae and this had led to the difference of fuel consumption in transporting the feedstock to processing plant.

During the sensitivity analysis, the data will be independently analysed. This means that each input will be varied while the others are held constant. Apart from that, the process parameters such as reactor size, rates of mixing, efficiency of extraction and etc. should remain unchanged (Batan, et al., 2010).

3.6 Simulation of Bioethanol Production from Different Feedstock

In this research, the bioethanol production from different type of feedstock will be simulated with ASPEN Plus. Basically, the simulation will focus only the cellulose conversion process in the bioethanol production, i.e. from the pre-treatment process of feedstock until a pure ethanol are produced. Besides, the parameters and conditions of the processes such as operating temperature, pressure, composition of components and others will be adopted from local industries or journals.

Furthermore, the yield of ethanol, energy consumptions of processing unit, source of GHG emissions will be identified and compared between the EFB and microalgae as the feedstock. Last but not least, the energy consumptions and GHG emissions data will be collected and compared with the LCI results obtained in LCA study.

3.7 The Assumptions and Limitations of this LCA Study

The assumptions that has been made in this LCA research are as followed:

- The functional unit chosen for this study is production of 1 tonne of bioethanol based on a plant with a raw EFB processing capacity of 1.25 tonnes per day (Chiew and Shimada, 2013).

  - The two types of bioethanol production feedstock i.e. EFB and microalgae are assumed to be cultivated on the same geographical location, i.e.: Malaysia.
  - The distance between the source of feedstock and the processing plants in this study is assumed to be 50 km.
  - The global warming potential (GWP) is based on kilogram of carbon dioxide equivalent per functional unit (kg CO_2 eq/ tonne bioethanol).
  - The waste disposal and its energy consumptions are not included in the system boundary of LCA.
  - Coproducts such as agricultural biomass, residues and biogas will be utilized to produce heat, energy and electricity which could replace all or part of the energy or electricity required by the processes. These will be included in the credit and debit of energy balance.

There are a few limitations that will constraint the interpretation of the inventory data obtained. In Malaysia, the production of bioethanol is still in development stage and is not being commercialized yet. Due to the limited assessable data available in Malaysia, a consistent scenario for each type of feedstock is difficult to be developed.

Several limitations and challenges that expected to be faced in this study are:

- The difficulty in collecting data from local industries and research companies as the data are strictly private and confidential. Therefore, some of the inventory data will be obtained from other LCA studies as references.
- The analysis will be conducted using secondary data obtained from other references and sources. No primary data from experiments or pilot plants to establish the results.
- The difficulty in estimating the distance to transport feedstock and raw materials such as fertilizer and seeds to the cultivation or processing stages due to the facts that all data were taken from different companies available.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Life Cycle Inventory

Life Cycle Inventory (LCI) is the key of LCA where the input and output of materials, energy and environmental emissions throughout the product system are compiled.

In this study, LCI includes the data of bioethanol production from cradle-to-grave. From the production of raw materials, water supplied into system, heat and energy used, GHG emissions to environment and etc. must be tracked in detail for the production of a defined amount of bioethanol from the previous chapter. Basically, bioethanol from two types of raw materials i.e. Oil Palm Empty Fruit Bunch (EFB) and Microalgae were studied in this LCA research. All the energy heating values and GHG emissions conversion factors were referred to Intergovernmental Panel Climate Change (IPCC) and Department of Environmental and Climate Change (DECC) standard conversion values.

4.1.1 The Life Cycle Inventory for Palm Empty Fruit Bunch based Bioethanol

The LCI for EFB based bioethanol were collected from local oil palm plantation, palm oil milling companies which located in Sarawak, and from journals and software simulations.

The data received from local industrial companies are primary data whereas for data gathered from journals and software simulations are secondary data.

4.1.1.1 LCI Data for Oil Palm Plantation

In this LCI, the input and output data of oil palm plantation was gathered from Fu Tian Agriculture and their oil palm plantation estate is located in Sungai Petai, Sarikei Sarawak. These data were collected in per month basis and some in per quarter basis as shown in Appendix B. However, the water irrigations information were extracted from weather forecast website and data of fronds and trunks were from Agensi Inovasi Malaysia (AIM). Table 4.1 shows the input and output information which related to oil palm platantion stage.

Table 4.1: The Input and Output Data for Oil Palm Plantation.

Oil Palm Cultivation Stage			
Input Data			
Items	**Unit**	**Value**	**Source**
Seedling	trees /ha	124	Fu Tian Agriculture
Fertilizers:			
Nitrogen	ton /yr	3.369	
P_2O_5	ton/yr	3.369	
K_2O	ton/yr	4.773	
MgO	ton/yr	0.561	
Borate (B)	ton/yr	1.965	
Total	**ton/yr**	**14.037**	
Fertilizers:	**GHG Emissions, kg CO_2 eq/yr/ha**		**Energy Intensity, MJ/yr/ha**
Nitrogen	699.955		5821.056
P_2O_5	120.230		2074.867

K_2O	96.125	1625.690
MgO	2.559	191.258
Borate (B)	186.794	669.402
Total	**1,105.663**	**10,382.270**

Pesticides	ton/ha/yr	0.032	Fu Tian Agriculture
	MJ/yr/ha	**8,194.24**	
	kg CO_2 eq/yr/ha	**351.082**	
Water source from rain water :			Fu Tian Agriculture Myweather2
Precipitation	**m/yr**	**3.285**	
	ML/yr/ha	**32.85**	
Electricity	**Unit/yr/ha**	**N/A**	

Output Data			
Items	**Unit**	**Value**	**Source**
FFB	ton/yr	690.432	Fu Tian Agriculture
	ton/yr/ha	**24.397**	
Fond & Trunks	ton/yr	994.290	Agensi Inovasi Malaysia
	MJ/yr/ha	**3033.814**	
	kg CO_2 eq/ yr/ ha	**715.98**	

Although the amount of water used for irrigation has been determined, however the input energy of irrigations does not include in life cycle energy balance as the precipitations are occurred naturally and no machines or labour involved. Besides, the electricity consumptions is not available in this stage as the usage was mainly for general administration buildings which located nearby the plantation.

4.1.1.2 LCI Data for Palm Oil Mill

The information of palm oil mill were collected from Ta Ann Manis Oil Mill and Wilmar International Plantation Palm Oil Mill as shown in Appendix D and E. Whilst the flue stack emissions and part of the Biogas productions were referred from Rashid, et al. (2013). Table 4.2 shows the input and output data for palm oil mill stage.

Table 4.2: The Input and Output Data for Palm Oil Mill Stage.

Palm Oil Mill Stage			
Input Data			
Items	**Unit**	**Value**	**Source**
FFB	ton/yr	**360,000**	Ta Ann Manis Oil Mill
Steam Boiler :			
Fibers & Shells	ton/yr	60,480	
	MJ/yr/ton FFB	**1023.792**	
	kg CO_2 eq/ yr/ ton FFB	**241.584**	
Water	ton/yr	285,120	
	MJ/yr/ton FFB	**7.920**	
	kg CO_2 eq/ yr/ ton FFB	**0.273**	
Electricity	kWh/yr	12,960,000	
	kWh/yr/ton FFB	36	
	MJ/yr/ton FFB	**129.6**	
	kg CO_2 eq/ yr/ ton FFB	**30.586**	
Sterilization Process			
Steam	ton/yr	241,920	
	MJ/yr/ton FFB	**1518.72**	
	kg CO_2/eq/ton FFB	**0.4748**	

Electricity	kWh/yr	1,555,200
	MJ/yr/ton FFB	**15.552**
	kg CO_2 eq/ yr/ ton FFB	**3.670**

<u>Transportation</u>	
Estate (From)	Naman Plantation
	Multi Maximum
	Pelita Durin
	Zumida
	Hariyama
Palm Oil Mill (To)	Ta Ann Manis Oil Mill
Total Amount of 40-ton Truck (Annually)	9,000
Total Distance, km	855,000
Total Diesel Consumption, L	256,500
Total Energy Consumed, MJ/yr/ton FFB	**25.92**
GHG Emissions, kg CO_2 eq /yr/ ton FFB	**2.31**

<u>Output</u>			
Items	**Unit**	**Value**	**Source**
<u>Product</u>			
CPO	ton/yr/ton FFB	0.200	1) Ta Ann Manis Oil Mill 2) Wilmar International Plantation Palm Oil Mill
PK	ton/yr/ton FFB	0.040	
EFB	**ton/yr/ton FFB**	**0.210**	
Fibers & Shells	ton/yr/ton FFB	0.176	

Emissions (Flue Stack):			
CO	kg CO_2 eq/yr/ton FFB	32.78	Rashid, et al.
CO_2	kg CO_2 eq/yr/ton FFB	46.35	
NOx	kg CO_2 eq/yr/ton FFB	1.11	
SOx	kg CO_2 eq/yr/ton FFB	1.88	
Total	**kg CO_2 eq/yr/ton FFB**	**82.12**	
Biogas System			
POME	**m^3/yr**	**288,000**	Ta Ann Manis Oil Mill
Biogas (62.5% CH_4, 37% CO_2)	m^3/yr	7,200,000	
Calorific Value	kWh/m^3	10	
	kWh/yr	17,100,000	
	MJ/yr/ton FFB	**171**	
	kg CO_2 eq/ yr/ ton FFB	**40.356**	

From Table 4.2, the amount of diesel consumed by a standard 40 ton truck is 30 liters per 100 km travelled (Goodyear, 2015). Moreover, according to Sarawak Energy (2015), 25 m^3 of biogas can be produced from each m^3 of POME. The biogas consists of 62.5% of CH_4 and 37% of CO_2.

4.1.1.3 LCI Data for EFB based Bioethanol Production

In Malaysia, there were no local manufacturers producing bioethanol from palm biomass in large scale or commercially. Hence, the information of this stage was extracted from the ASPEN PLUS simulation as it is difficult to get the primary data as no bioethanol production plants existed in Malaysia. However, the data of energy consumptions in processes such as pretreatment and hydrolysis were obtained from journals as shown in Table 4.3. Besides, the process flow diagram for bioethanol production starting from fermentation process until the purification of final product are shown in Figure 4.1. The stream tables and equipment details are shown in Appendix F.

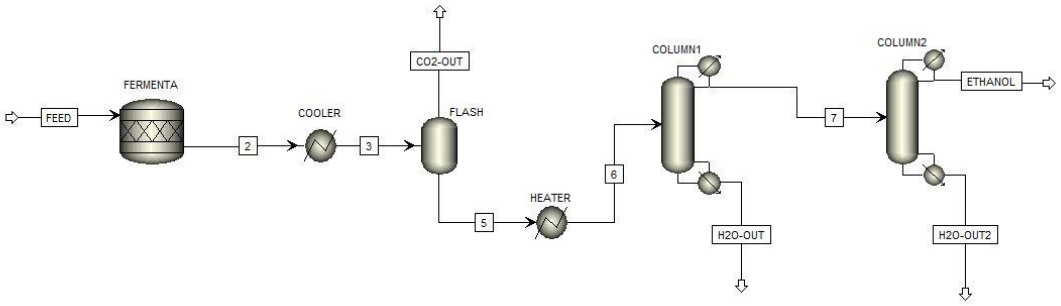


Figure 4.1: Process Flow Diagram of Bioethanol Production from ASPEN PLUS.

Table 4.3: The Input and Output Data for EFB based Bioethanol Production Stage.

<u>Bioethanol Production Stage</u>			
<u>Input Data</u>			
Items	Unit	Value	Source
EFB	ton/yr	31,458.24	
Energy Consumption **<u>From Process:</u>**			
Pretreatment	MJ/hr	8,089.2	Magnussan H.
Hydrolysis	MJ/hr	2,207.3	Nanda S.
Fermentation	MJ/hr	303.537	Aspen Plus
Heat Exchange	MJ/hr	237.813	
Distillation Columns	MJ/hr	7,249.61	
Total Energy Consumption	MJ/hr	18,087.46	

	MJ/yr/ton EtOH	**18,087**
	kg CO_2 eq/ yr/ ton EtOH	**4,269**
Water	kg/hr	4,119.16
	m3/hr	4.11916
	MJ/yr/ton EtOH	**0.04119**
	kg CO_2 eq/yr/ton EtOH	**1.4174**

Transportation	
Assumptions: Distance between palm oil mill and production plant is 50 km	
Total Amount of 40-ton Oil Tanker (Annually)	910
Total Distance, km	45,500
Total Diesel Consumption, L	13,650
Total Energy Consumed, MJ/yr/ton EtOH	**57.46**
GHG Emissions, kg CO_2 eq /yr/ ton EtOH	**5.12**

Output			
Items	Unit	Value	Source
Product			
Bioethanol	ton/yr	**8,640**	Aspen Plus
	MJ/ yr/ ton EtOH	**29,670.284**	
	kg CO_2 eq/ yr/ ton EtOH	**2,500**	
CO_2	ton/yr	8259.32	Aspen Plus
	kg CO_2 eq/ yr/ ton EtOH	**955.94**	
Lignin	ton/yr	5,933.02	1) Abdullah & Sulaiman
	MJ/ yr/ ton EtOH	**780.69**	

	kg CO_2 eq/ yr/ ton EtOH	**180.86**	2) Nanda S. 3) Isroi, et al.

4.1.2 The Life Cycle Inventory for Microalgae based Bioethanol

Microalgae cultivation and commercialization in Malaysia is rather limited due to insufficient research and lack of well-developed cultivation technology. Currently, the cultivations of microalgae in Malaysia were commonly done in lab scale and used as research purpose. Besides, there is not a single bioethanol plant and also using microalgae lipid as feedstock to produce biodiesel. Hence, it is impossible to obtain primary data for the LCI of microalgae based bioethanol.

In this report, all the LCI data for microalgae based bioethanol were collected from secondary data, which are from academic journals and simulation software Aspen Plus. These data are divided into three stages, they are cultivation, harvesting and extraction and bioethanol production stages.

4.1.2.1 LCI Data for Microalgae Cultivation Stage

In this stage, the information was collected from academic journals which were done by local researchers and others. Furthermore, some data were obtained from the assessments report of microalgae cultivation and LCA of microalgae lipid based biodiesel. Table 4.4 shows the input and output details for microalgae cultivation stage.

Table 4.4: The Input and Output Data for Microalgae Cultivation Stage.

Microalgae Cultivation Stage

Input Data

Items	**Unit**	**Value**	**Source**
Pond Area	ha	100	Lundquist, et al.
Wastewater	ML/yr	22,740	
	MJ/ yr/ ha	**2,274**	
	kg CO_2 eq/ yr/ ha	**78,248**	
Nutrients:			
Nitrogen	mg/L	35	1) Lundquist, et al. 2) Luo, et al.
	ton/yr	795.9	
	MJ/ yr/ ha	**389,195**	
	kg CO_2 eq/ yr/ ha	**46,799**	
Phosphorus	mg/L	35	
	ton/yr	795.9	
	MJ/ yr/ ha	**389,195**	
	kg CO_2 eq/ yr/ ha	**46,799**	
CO_2	kg/ kg biomass	2.0	1) Lundquist, et al. 2) Brennan & Owende 3) Medeiros, Sales & Kiperstok
	ton/yr	14,880	
	kg CO_2 eq/ yr/ ha	**148,800**	
Electricity Consumption:			
CO_2 distributions	kWh/yr	353,846	Lundquist, et al.
Wastewater pumping	kWh/yr	230,769	
Surfacewater pumping	kWh/yr	76,923	
Total Electricity Consumption	**kWh/yr**	**661,538**	
	MJ/yr/ha	**23,815**	
	kg CO_2 eq/ yr/ ha	**5,620**	

Output Data

Items	Unit	Value	Source
Microalgae	**ton/ yr**	**7,440**	Lundquist, et al.

4.1.2.2 LCI Data for Harvesting and Extraction Stage

The input and output data in this stage were collected from journals. All the values are tabulated in Table 4.5 below.

Table 4.5: The Input and Output Data for Harvesting and Extraction Stage.

Harvesting and Extraction Stage			
	Input Data		
Items	**Unit**	**Value**	**Source**
Microalgae	ton/yr	7,440	Lundquist, et al.
	Harvesting		
Water removed	ML/yr	239.824	1) Lundquist, et al. 2) Sander & Murthy
Thermal Dewatering	MJ/ L water	4.028	
Total Energy Dewatering	**MJ/yr/ton algae**	**129,840.20**	
	kg CO_2 eq/yr/ton algae	**30,642.287**	
Types of Dewatering:			
Filter Press	MJ/ ton algae	63,610	Sander & Murthy
	MJ/ yr	473,258,400	
Centrifuge	MJ/ ton algae	119,690	
	MJ/ yr	890,493,600	
Belt Dryer	MJ/ ton algae	13,800	Lardon, et al.

	MJ/ yr	102,672,000	
	Extraction		
Electricity	**MJ/ yr/ ton algae**	**1,197.30**	Lardon, et al.
	kg CO_2 eq/ yr/ ton algae	**282.563**	
Steam boiler	**MJ/ yr/ ton algae**	**252.95**	
	kg CO_2 eq/ yr/ ton algae	**59.70**	
n-Hexane	Btu/ lb lipid	205	Sazdanoff N.
	MJ/ ton lipid	476.83	
	MJ/ yr/ ton algae	**83.445**	
	kg CO_2 eq/ yr/ ton algae	**19.693**	
	Output Data		
Items	**Unit**	**Value**	**Source**
Carbohydrates	**ton/yr**	**3,682.8**	Lardon, et al.
Lipids	ton/yr	1,302	
Protein	ton/yr	2,098.08	

4.1.2.3 LCI Data for Microalgae based Bioethanol Production.

The input and output for microalgae based bioethanol production were extracted from Aspen Plus simulation. The input raw material for microalgae based bioethanol production is different from EFB based bioethanol. Furthermore, microalgae based bioethanol production stage does not require pretreatment as the lignin composition in microalgae such as Chlorella vulgaris is negligible. Table 4.6 shows the input and output information for microalgae based bioethanol production.

Table 4.6: The Input and Output Data for Microalgae based Bioethanol Production.

Bioethanol Production Stage			
Input Data			
Items	Unit	Value	Source
Carbohydrates	ton/yr	**10,692**	
Energy Consumption From Process:			
Pretreatment	MJ/hr	N/A	
Hydrolysis	MJ/hr	2,207.3	
Fermentation	MJ/hr	303.537	
Heat Exchange	MJ/hr	237.813	
Distillation Columns	MJ/hr	7,249.61	
Total Energy Consumption	MJ/hr	9,998.26	Aspen Plus
	MJ/yr/ton EtOH	**9,998**	
	kg CO_2 eq/ yr/ ton EtOH	**2,360**	
Water	kg/hr	4119.16	
	m3/hr	4.11916	
	MJ/yr/ton EtOH	**0.04119**	
	kg CO_2 eq/yr/ton EtOH	**1.4174**	
Transportation			

Assumptions: Distance between palm oil mill and production plant is 50 km			
Total Amount of 40-ton Oil Tanker (Annually)	267.3		
Total Distance, km	13,365		
Total Diesel Consumption, L	4,009.5		
Total Energy Consumed, MJ/yr/ton EtOH	**16.88**		
GHG Emissions, kg CO_2 eq /yr/ ton EtOH	**1.50**		
Output			
Items	Unit	Value	Source
Product			
Bioethanol	ton/yr	**8,640**	Aspen Plus
	MJ/ yr/ ton EtOH	**29,670.284**	
	kg CO_2 eq/ yr/ ton EtOH	**2,500**	
CO_2	ton/yr	8259.32	
	kg CO_2 eq/ yr/ ton EtOH	**955.94**	

4.2 Life Cycle Energy Balance

In order to have same basis in each stage of EFB and Microalgae based bioethanol production, the total energy consumptions tabulated in LCI are converted to functional unit of 1 ton bioethanol (ton EtOH). The energy inputs are categorized into direct and indirect energy. Direct energy is referred to the energies which were used in the form of electricity, steam and heat. Whereas indirect energy is the energy which was consumed in the transportation process. Besides, the output energy of a system is referred to product expansion energy.

The input and output energy data of oil palm cultivation stage were collected from Fu Tian Agriculture. The oil palm plantation area is approximately 28.3 hectares and produces around 24.397 tons of FFB per hectare per annum. The fertilizers which consist of five main nutrients were used in oil palm trees cultivation. They are nitrogen, phosphorus oxide (P_2O_5), potassium oxide (K_2O), magnesium oxide (MgO) and borate (B). The energy input from fertilizers is approximately 10,382.27 MJ/yr/ha and it is the highest energy consumption in cultivation stage. While the pesticides used in cultivation stage is 8,194.24 MJ per hectare annually. The calculated energy input of pesticides takes up 44.11% of total energy consumptions in cultivation stage. As comparing the pesticides usage in other local oil palm plantations such as United Plantation Berhad, the pesticides used in Fu Tian Agriculture was approximately 4 times lower than United Plantation. The amount of pesticides used in Fu Tian and United Plantation were 0.26 kg/tree and 1.08 kg/tree respectively. The high application of pesticides was due to lower crops production in the past 2 years and the production was increased significantly in replanting hectarage (United Plantation, 2013).

Rain water is the main water source for the irrigation of palm oil trees. According to Myweather2 (2015), the precipitation amount in Sarikei, Sarawak was 32.85 ML/ha throughout the year 2105. The rainfall was relatively less in the month of June to August as shown in Figure 4.2. Hence, water source for the irrigation was obtained from domestic water supply. However, the amount of domestic water supply used in irrigation is negligible and difficult to be traced. Besides, majority of the source of water irrigation are from natural resources. Therefore, the energy input in the form of water into cultivation stage is zero.

Furthermore, the usage of electricity in this stage was mainly for the administration buildings nearby the plantation which is indirectly involved in cultivation. Since there is no any heavy machinery involved in oil palm cultivation, the energy input in the form of electricity is zero as well.

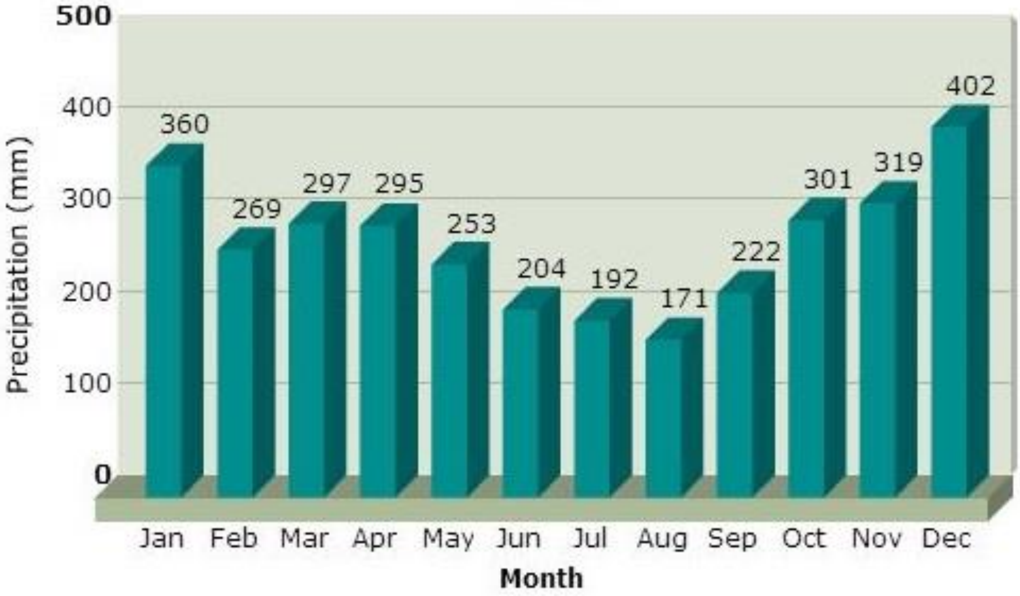


Figure 4.2: Precipitation Amount in Sarikei Sarawak, Malaysia (adapted from Myweather2, 2015).

From Table 4.1, the output of cultivation stage are FFB, fronds and trunks. Fronds and trunks are important in compensating the energy flowed into this stage. They are treated as the biomass which can be used in Biomass Heat Power Plant (BHPP) to generate electricity for self-usage or to national grid. Hence, the amount of energy which generated by reusing the co-products will be included in co-product expansion allocation system. The total input energy with functional unit of 1 ton bioethanol is subtracting the total co-product expansion energy with the same functional unit to give the total energy consumptions in a particular stage. In this case, the fronds and trunks are allocated to co-product expansion with an energy value of 3033.814 MJ/year/ha being offset. The biomass energy has successfully produced an electricity amount of 23,849 kWh.

In the stage of palm oil mill process, steam and electricity are consumed tremendously to produce Crude Palm Oil (CPO), Palm Kernel (PK) and EFB. The steam boiler played as an important role in generating steam and electricity to all the processes which involved in producing CPO, PK and EFB. The inputs of steam boiler are 285,120 ton per year of water and 60,480 ton per year of fibres and shells. The water sources are from reservoir pond in which the water are collected from rain water and rivers such as Sg. Rejang and Sg. Naman. The steam generated from the boiler is used in the sterilization process and electricity are produced from the turbine of steam boiler at the same time. The reused energy from fibres and shells are so useful where no electricity supply from third party is needed. Apart from that, electricity were used in sterilization and stripping process to separate out the EFB.

There are several suppliers of FFB to Ta Ann Manis Palm Oil Mill, such as Naman Plantation, Multi Maximum, Pelita Durin, Zumida, and Hariyama. Hence, the fuels consumed in FFB transportation were computed where 9000 trips of standard 40-ton trucks were used to transport the FFB from all the estates mentioned above to the palm oil mill. The total energy consumed in transportation of this stage was 25.92 MJ per ton of FFB annually.

As for the output data generated from palm oil mill stage, 0.21 ton of EFB is produced from 1 ton of FFB. Besides, 0.20 ton of CPO and 0.04 ton of PK are produced from 1 ton of FFB. However, the output of CPO and PK will not include in product expansion system because they required to be converted to energy fuels such as biodiesel to generate energy. Furthermore, POME which is the wastes produced from mill will be treated to yield biogas which will then use in regenerating power usage in the mill. According to Sarawak Energy (2015), the amount of biogas can be produced is 7,200,000 m^3 per annum from the amount of effluent of POME provided by Ta Ann Manis Oil Mill. The energy produced is as high as 622.61 MJ/year/ton EtOH which will be used in by-product expansion system to offset the energy used.

As for the palm based bioethanol production stage, there are several limitations and assumptions in this study due to the fact that bioethanol has yet to be commercialized in Malaysia. In addition, academic researches on second and third generation bioethanol productions are limited too as some of countries such as United States and Brazil are still using energy crops as the feedstock of ethanol fuels productions.

The input data are tabulated in Table 4.3 and the values were mostly adopted from Aspen Plus Simulation. It was reported that the energy spent in pretreatment process which including the lignin separation is 8089 MJ per ton of EtOH produced by Magnusson H. (2014). While Nanda S. (2014) reported that the energy consumed in hydrolysis process is 2207.3 MJ per ton of EtOH produced. For the energy consumptions in subsequent processes such as fermentation, heat exchanging and purification with distillation columns were obtained from Aspen Plus Simulation. In overall, the total energy consumptions is 18,087 MJ per ton EtOH produced annually. The pretreatment process and purification of final product showed the higher energy consumptions among the processes. Dilute acid was used by Mgnusson H. (2014) in pretreatment process, it is the most famous method and cheaper cost due to its availability. However, the energy consumption in pretreatment process can be reduced by using biological pretreatment because less mechanical supports are used (Gupta and Verma, 2014).

The output of bioethanol production stage has 8640 ton of EtOH annually. Besides, the CO_2 emissions and lignin are 8259.32 and 5933.02 ton per year respectively. The output energy which particularly from every ton of ethanol is 29670.284 MJ. These energy could be used as the alternative fuels to replace the conventional vehicle fossil fuels. Whereas the lignin can be included in co-product energy expansion system where it is burnt to generate electricity approximately 780.69 MJ per ton of EtOH produced.

Since there were no bioethanol production plant in Malaysia, the distance between palm oil mill and production plant was assumed 50 km long. The diesels consumed in EFB transportation were computed in which 910 trips of standard 40-ton trucks were used to transport the EFB to the production plant. The total energy consumed in transportation of this stage was 57.46 MJ per ton of EtOH annually.

For the comparison purposes in this LCA study, microalgae feedstock is also being studied by using the similar approach as palm oil. The reasons for microalgae being selected for the comparisons are microalgae cultivation was regarded as an important approach in reducing the GHG in environment (John, et al., 2010). CO_2 is consumed by microalgae in photosynthesis and microalgae also able to survive and grow municipal waste water. Nitrogen and phosphorus are the main nutrients for the growth of microalgae and they can be found abundantly in waste water. Hence, microalgae is important in CO_2 fixation, it is also helpful in biodegradation of organisms in waste water. However, since most of the microalgae cultivation was done in lab scale in Malaysia, all the energy input and output were extracted from academic journals and reports.

As for the microalgae cultivation stage, the studied pond area was 100 hectares with water depth of 35 cm. Furthermore, the species of cultivated microalgae in this study is Chlorella vulgaris. The amount of waste water supplied to the cultivation pond was 22,740 ML per year. The energy input from nutrients such as nitrogen and phosphorus are 389,195 MJ/ha and 46,799 MJ/ha respectively. Besides, the electricity consumed in this stage was 23,815 MJ/ha/year in cultivation stage. These electricity were used in CO_2 distributions, wastewater pumping and surface water pumping. Whereas the output of this stage is 7,440 ton of microalgae per year.

Next, the harvesting and extraction stage was tabulated in Table 4.5 and the main purposes of this stage are to remove water and separate the component carbohydrates from lipids and proteins. As computed in Table 4.5, the energy input for thermal dewatering is approximately 129,840.2 MJ per ton of microalgae per year. The energy consumed in thermal dewatering is significantly high as compared to other processes throughout all stages. Large amount of water was required to remove from 3 *wt* % of microalgae to 91 *wt* % of microalgae (Lundquist, et al, 2010). Besides that, Sander and Murthy (2010) have reported that another dewatering method which is centrifuge separators that have the almost same efficiency as thermal dewatering is required energy input 119,690 MJ per ton algae.

The electricity consumed in harvesting and extraction stage is 1197.3 MJ per ton of microalgae per annum. The energy input from steam boiler was 252.95 MJ per ton of microalgae and n-Hexane used in extracting lipids and proteins is 83.45 MJ/ton microalgae. No transportations were involved in this stage because harvesting and extraction processes are commonly done nearby the cultivation area. The main output of this stage is carbohydrates which is 3682.8 ton per year. The co-products lipids and proteins were not include in energy expansion system as they are unable to directly convert into energy by burning.

The microalgae based bioethanol production stage is almost similar as palm based bioethanol production stage. However, the input of this stage is carbohydrates instead of EFB. Besides, the microalgae based bioethanol production stage does not require pretreatment as the lignin composition in *Chlorella vulgaris* is negligible. Hence, the energy consumption in pretreatment can be excluded. The total input energy for all processes which adopted from Aspen Plus Simulation is 9,998.26 MJ per ton of EtOH produced annually. The purification of final product shown the highest energy consumptions among the processes.

The output of bioethanol production stage has also 8640 ton of EtOH and 8259.32 ton of CO_2 annually. However, there were no lignin produced and no co-product energy expansions in this stage.

For transportation, a similar assumption was made in microalgae based bioethanol production stage, i.e. the distance between palm oil mill and production plant was assumed 50 km long. The diesels consumed in carbohydrates transportation were computed in which 267.3 trips of standard 40-ton trucks were used to transport the carbohydrates to the production plant. The total energy consumed in transportation of this stage was 16.88 MJ per ton of EtOH annually.

All the input and output values were converted to the same functional unit which is 1 ton of bioethanol. The total life cycle energy balance and net energy ratio (NER) for both EFB and microalgae based bioethanol are tabulated in Table 4.7 and Table 4.8 below.

Table 4.7: Total Energy Balance of EFB based Bioethanol.

Oil Palm Cultivation	
Total Input Energy (MJ/yr/ton EtOH)	13,202.33
Total Co-product Expansion Energy (MJ/yr/ton EtOH)	-2156.13
Total Energy Consumption (MJ/yr/ton EtOH)	11,046.2

Palm Oil Mill	
Total Input Energy (MJ/yr/ton EtOH)	151.00

Total Co-product Expansion Energy (MJ/yr/ton EtOH)	-1094.485
Total Energy Consumption (MJ/yr/ton EtOH)	-943.485
Bioethanol Production	
Total Input Energy (MJ/yr/ton EtOH)	18,144.96
Total Co-product Expansion Energy (MJ/yr/ton EtOH)	-780.69
Total Energy Consumption (MJ/yr/ton EtOH)	17,364.28
Total Input Energy (MJ/yr/ton EtOH)	27,367.00
Total Output Energy (MJ/yr/ton EtOH)	29,670.28
NER	**1.08**

Table 4.8: Total Energy Balance of Microalgae based Bioethanol.

Microalgae Cultivation	
Total Input Energy (MJ/yr/ton EtOH)	14,952.38
Total Co-product Expansion Energy (MJ/yr/ton EtOH)	0
Total Energy Consumption (MJ/yr/ton EtOH)	14,952.38
Harvesting and Extraction	
Total Input Energy (MJ/yr/ton EtOH)	328,434.70
Total Co-product Expansion Energy (MJ/yr/ton EtOH)	0
Total Energy Consumption (MJ/yr/ton EtOH)	328,434.70
Bioethanol Production	
Total Input Energy (MJ/yr/ton EtOH)	10,015.00
Total Co-product Expansion Energy (MJ/yr/ton EtOH)	0
Total Energy Consumption (MJ/yr/ton EtOH)	10,015.00
Total Input Energy (MJ/yr/ton EtOH)	353,401.38

Total Output Energy (MJ/yr/ton EtOH)	29,670.28
NER	**0.084**

Based on Table 4.7 and Table 4.8, the estimated total life cycle energy consumptions for the EFB and microalgae based bioethanol production is equivalent to 27,367 MJ and 353,401 MJ per ton of EtOH yield respectively. Microalgae based bioethanol has significantly high amount of energy consumption is because large amount of water is required to be removed. The thermal dewatering has taken up approximately 85% of total energy consumptions. On the other hand, the total amount of energy being offset from palm EFB as feedstock is approximately 4031.3 MJ per ton EtOH annually. The microalgae feedstock has no co-product energy expansion as no by product which can be directly converted into reused energy. In addition, the NER calculated in this LCA study based on the production of 1 ton of EFB based and microalgae based bioethanol are 1.08 and 0.084 respectively. Hence, the production of EFB based bioethanol has a net positive energy while the microalgae based has a negative net energy. This shows that the production of bioethanol by using EFB as feedstock is more sustainable than using microalgae.

Figure 4.3 and Figure 4.4 show the total energy consumptions of EFB and microalgae bioethanol from each stage of processes involved. From Figure 4.2, only the palm oil mill shows a negative energy consumption. Whereas the bioethanol production stage shows the highest energy consumption for EFB feedstock. On the other hand, microalgae feedstock has a very high energy consumption in harvesting and extraction stage. The energy consumed in harvesting is far higher than other stages as shown in Figure 4.3. This is the main reason that microalgae as feedstock has a net negative energy.

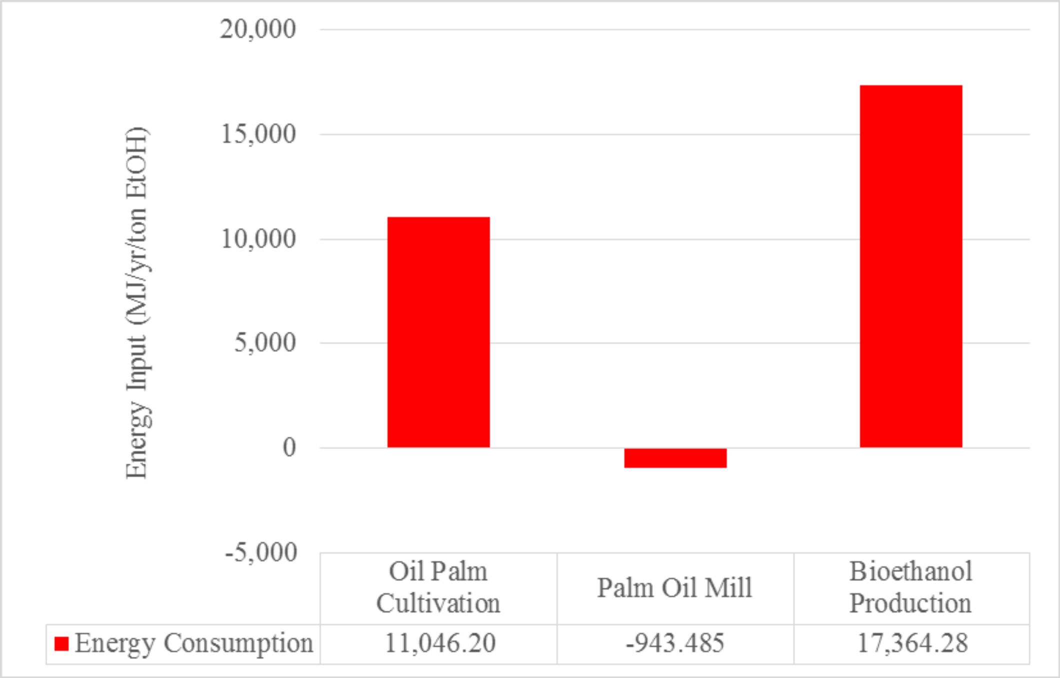


Figure 4.3: The Total Energy Consumptions of EFB based Bioethanol Processes.

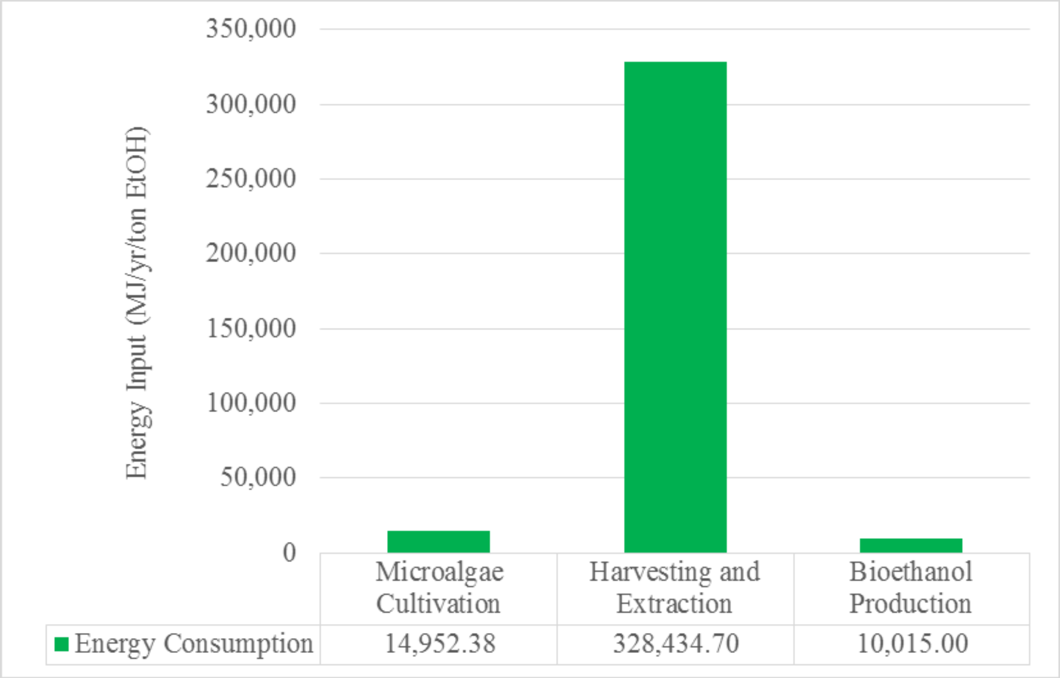


Figure 4.4: The Total Energy Consumptions of Microalgae based Bioethanol Processes.

4.3 Life Cycle GHG Emissions

In this section, the life cycle GHG emissions has been computed to compare the net GHG emissions of both bioethanol feedstock from their cultivation stage to bioethanol production stage. First and foremost, the main contribution of GHG emissions from oil palm cultivation stage was from the application of fertilizers, which is 1106 kg CO_2 eq per hectare. The second highest contribution of GHG emissions from cultivation stage was the biomass of fronds and trunks. The fronds and trunks was directly combusted in order to regenerate heat and electricity to offset the energy consumed. However, GHG are produced at the same time, which is 715.98 kg CO_2 eq per hectare.

On the other hand, the microalgae cultivation stage is the only stage which has a negative GHG emissions. This is because CO_2 was used as an input for the photosynthesis in microalgae cultivation stage. The CO_2 supplied is approximately 148,800 kg CO_2 eq per hectare and it is more than the total GHG emissions from electricity consumptions and pumping of wastewater and nutrients, which is 132,390 kg CO_2 eq per hectare. The GHG emissions results from electricity and power consumption are based on standard Malaysian electricity grid GHG conversion factor where the electrical power generation in Malaysia is mostly based on natural gas, coal and hydro power. On the other hand, the GHG contribution by steam is based on the standard industrial steam boiler.

As for the palm oil mill stage, the GHG emissions were contributed from electricity, steam boiler, biogas system and flue stacks. The emissions of flue stack such as CO, CO_2, NO_x and SO_x showed the significant CO_2 emissions, 82.12 kg CO_2 eq per ton of FFB handled. Besides, the co-product such as fibers, shells and POME which included in energy expansion system released even higher amount of GHG which is 241.584 kg CO_2 eq and 40.356 kg CO_2 eq per ton of FFB annually. The fibers and shells were treated as biomass and combusted in steam boiler where the water from reservoir pond was heated and converted to steam. Eventually, the flowing of steam spin the turbine and produced electricity. While the emissions from biogas system was produced during the anaerobic digestions of POME to biogas which consists of 37% of CO_2. Moreover, the transportations of FFB from all the estates to mill has contributed 2.31 kg CO_2 eq per ton of FFB.

In the harvesting and extraction stage of microalgae feedstock, thermal dewatering released tremendous amount of GHG, i.e. 30,642.87 kg CO_2 eq per ton of microalgae. This is because large amount of water was required to be removed and eventually a lot of electricity which from the electrical grid. Whereas the GHG emissions from electricity used in extraction process was 282.56 kg CO_2 eq, 59.69 kg CO2 eq from steam boiler, and 19.69 kg CO2 eq from n-Hexane for every single ton of microalgae processed. No transportations were involved in this stage.

Lastly, the total GHG emissions from EFB based bioethanol was higher than microalgae based bioethanol. This is because the energy consumption in producing EFB bioethanol was higher due to pretreatment process was involved. Besides, lignin was the co-product of EFB based bioethanol production and it was combusted to regenerate the energy for the production stage. The total life cycle GHG emissions and GHG offset for both EFB and microalgae based bioethanol are tabulated in Table 4.9 and Table 4.10.

Table 4.9: Total GHG Emissions of EFB based Bioethanol

Oil Palm Cultivation	
Total GHG Emissions (kg CO_2 eq/yr/ton EtOH)	1544.156
Total Offset GHG Emissions (kg CO_2 eq/yr/ton EtOH)	0
Net GHG Emissions (kg CO_2 eq/yr/ton EtOH)	1544.156

Palm Oil Mill	
Total GHG Emissions (kg CO_2 eq/yr/ton EtOH)	1447.05
Total Offset GHG Emissions (kg CO_2 eq/yr/ton EtOH)	0
Net GHG Emissions (kg CO_2 eq/yr/ton EtOH)	1447.05

Bioethanol Production	
Total GHG Emissions (kg CO_2 eq/yr/ton EtOH)	6,956.04
Total Offset GHG Emissions (kg CO_2 eq/yr/ton EtOH)	0

Net GHG Emissions (kg CO_2 eq/yr/ton EtOH)	6,956.04
Total Net GHG Emissions (kg CO_2 eq/yr/ton EtOH)	**9,947.246**

Table 4.10: Total GHG Emissions of Microalgae based Bioethanol

Microalgae Cultivation	
Total GHG Emissions (kg CO_2 eq/yr/ton EtOH)	4,448.312
Total Offset GHG Emissions (kg CO_2 eq/yr/ton EtOH)	-4,999.68
Net GHG Emissions (kg CO_2 eq/yr/ton EtOH)	-551.368
Harvesting and Extraction	
Total GHG Emissions (kg CO_2 eq/yr/ton EtOH)	77,510.6
Total Offset GHG Emissions (kg CO_2 eq/yr/ton EtOH)	0
Net GHG Emissions (kg CO_2 eq/yr/ton EtOH)	77,510.6
Bioethanol Production	
Total GHG Emissions (kg CO_2 eq/yr/ton EtOH)	4,862.51
Total Offset GHG Emissions (kg CO_2 eq/yr/ton EtOH)	0
Net GHG Emissions (kg CO_2 eq/yr/ton EtOH)	4,862.51
Total Net GHG Emissions (kg CO_2 eq/yr/ton EtOH)	**81,821.742**

From the results tabulated in Table 4.9 and Table 4.10, the estimated total life cycle GHG emissions produced from 1 ton of EFB and microalgae based bioethanol are 9,947.246 kg of CO_2 and 81,821.742 kg of CO_2 annually. The life cycle of microalgae based bioethanol production released 8 times more GHG emissions than

EFB based. However, this is not the expected results as more than 90% of GHG emissions from life cycle of microalgae feedstock were contributed by thermal dewatering. Hence, alternative ways or technologies such as solar drying should be used in order to reduce the energy consumption and has the same effect to remove water from harvested microalgae.

Figure 4.5 shows the total GHG emissions from every stage of EFB based bioethanol production cycle. From the figure, the bioethanol production stage released the highest amount of GHG among all the stages. This also indicates that the energy consumption in production stage is the highest. On the other hand, Figure 4.6 shows the total GHG emissions from every stage of microalgae based bioethanol production cycle. Microalgae has a negative GHG emissions as microalgae required large amount of carbon nutrients to grow. The bioethanol production stage in microalgae feedstock has relatively low GHG emissions as compared to EFB feedstock.

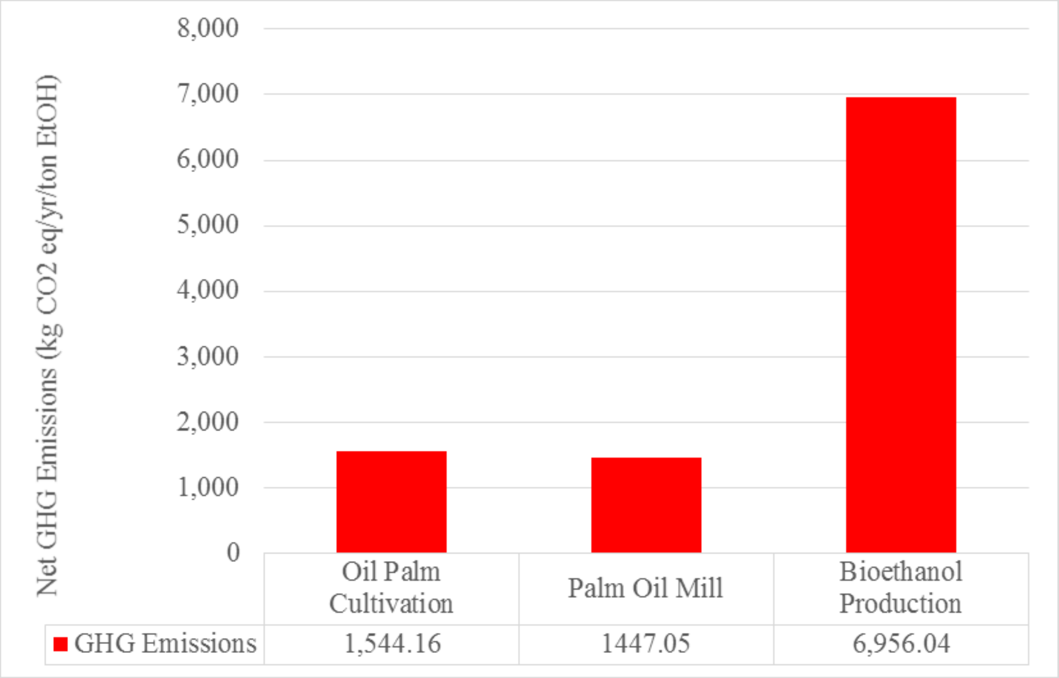
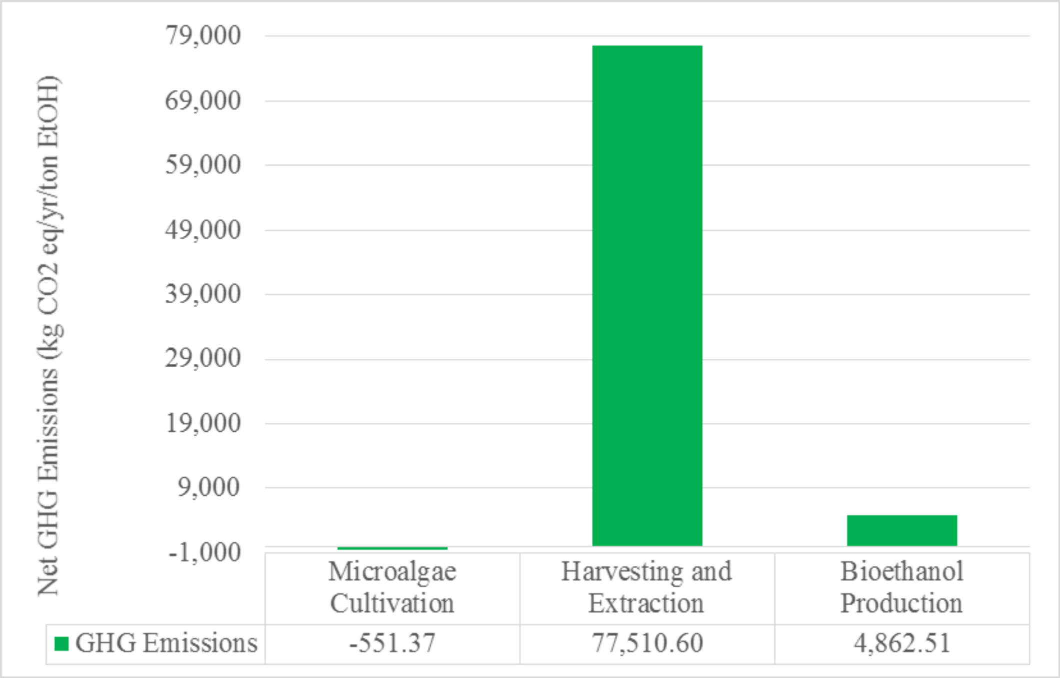


Figure 4.5: The Total GHG Emissions of EFB based Bioethanol Processes.



	Microalgae Cultivation	Harvesting and Extraction	Bioethanol Production
🟩 GHG Emissions	-551.37	77,510.60	4,862.51

Figure 4.6: The Total GHG Emissions of Microalgae based Bioethanol Processes.

4.4 Sensitivity Analysis

The energy efficiency of harvesting methods for removal of water from microalgae biomass is the one of the major barriers in the massive productions of microalgae as feedstock for bio-liquid fuels (Brink and Marx, 2012). In this LCA research, the energy consumption in harvesting is approximately 324,600 MJ/ ton of EtOH which took up 90% of the total energy consumption of microalgae based bioethanol life cycle. Hence, in order to improve the energy efficiency of the system. A new dewatering method in harvesting stage shall be implemented while maintaining the efficiency. Nowadays, besides of thermal dewatering, centrifuge separators and chamber filter press are also used in commercialized microalgae industry (Sander and Murthy, 2010). In addition, conventional method such as solar drying is another alternative to improve the energy efficiency of the system (Kadam K.L., 2001). However, solar drying method is a slow process as compared to other methods mentioned and it required 5 hours or above and weather dependent (Becker E. W., 1994) (Prakash, et al. 2007).

The energy consumptions for the particular harvesting stage with different methods are computed in Table 4.11. Besides, the NER and the GHG emissions were calculated again and compared.

Table 4.11: Energy Consumptions for Alternatives in Harvesting Stage .

Methods	**Energy Consumptions (MJ/yr/ton EtOH)**	**Reference**
Thermal Dewatering	324,600	Lunquist, et al.
Centrifuge Separators	299,225	Sander and Murthy
Chamber Filter Press	159,025	Sander and Murthy
Solar Drying	0	Kadam K.L.

Although the centrifuge separators and chamber filter press have the same effects and efficiency of dewatering. However, the energy involved in centrifuge separators does not show a significant drop. Although centrifugation technology does not require large of amount of heats to vaporize the moisture present in microalgae biomass, but big amount of electricity is required to drive the powerful centrifuge separators. Basically, water which contained algae biomass is continuously pumped into centrifuge separators. High gravitational force is utilized to sling out the heavier algae biomass which will get rid of as sludge during the ejection stage. At the same time, clear water is discharged from the centrifuge machine.

Whereas the chamber filter press consumed almost half less of the energy spent in thermal dewatering, which is 159,025 MJ/yr/ton EtOH. Chamber filter press helps in filtering solid containing liquid. A suitable filter membrane is used to make sure the undissolved solid, i.e. microalgae separated from liquid when high pressure is exerted on it. However, this method is slow and labors intensive as it requires emptying periods and labors to remove filter cake.

Lastly, solar drying is an old method which utilize the sun’s energy to dry foods or crops. Hence, it could be a great method in improving the energy efficiency of the system. One of example of solar dryer is flat plate collector with cover. In this method, the solar heat energy can be used directly and indirectly to vaporize the moisture. For direct dryer, the microalgae which placed on a plate that covered with transparent glass or black metal will be exposed to sun and heated up by solar energy (Kadam K.L., 2001). While indirect dryer, drying air will be warmed in a space then channeled to the chamber where the product is stacked (Kadam K.L., 2001). The disadvantage of this method is the solar energy can only be collected during day time. Besides, a very big opened area is required for commercialized size cultivation plant.

The NER and GHG emissions from each alternatives mentioned above were calculated again and compared. The results are tabulated in Table 4.12.

Table 4.12: NER and Total GHG Emissions after Applying the Alternatives in Harvesting Stage.

Method	NER	Total GHG Emissions (kg CO_2 eq/yr/ton EtOH)
Thermal Dewatering	0.084	81,821.742
Centrifuge Separators	0.090	75,833.122
Chamber Filter Press	0.158	42,745.922
Solar Drying	1.188	4,311.142

From Table 4.12, the NER of using centrifuge separators and chamber filter press are showing negative net energy even though the energy consumptions have been reduced by 8% and 50%. However, by using solar drying the NER has been increased to 1.188 which is even higher than the NER of EFB based bioethanol production life cycle. Besides, the GHG emissions is directly proportional to the energy consumptions. From the table above, the GHG emissions for implementing solar drying has a very significant drop as compared to thermal dewatering, centrifuge separators and chamber filter press. The GHG emissions of microalgae based bioethanol life cycle has been decreased by approximately 94.73%.

Although the conventional solar drying seems to be a promising method to improve the energy efficiency of the microalgae life cycle and to conserve the environment as it is using natural resources as energy. However, some parameters such as land availability, weather dependency and etc. shall be considered.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Report Summary

In this LCA study, the life cycle of bioethanol production from using palm EFB as feedstock gives a NER of 1.08 which it implies that the life cycle energy output is higher than the energy input. In contrast, bioethanol production from using microalgae as feedstock produces a NER of 0.084 which indicates that the life cycle energy output is significantly less than the energy input. Thus, EFB as feedstock has shown to be more reliable and sustainable as compared to microalgae. Besides, this report had showed the importance of co-product expansion energy involved in the life cycle of bioethanol production. From the life cycle of EFB based bioethanol production, the co-products which could be reused and utilized as energy or electricity has contributed to higher NER. On the other hand, the lack of co-products from microalgae life cycle shows no energy could be offset in all stages of microalgae bioethanol production.

The estimated total life cycle GHG emissions produced from 1 ton of EFB based and microalgae based bioethanol are 9,947.246 kg of CO_2 and 81,821.742 kg of CO_2 respectively per year. The life cycle of microalgae based bioethanol production released 8 times more GHG emissions than EFB based and this indicates that EFB bioethanol brings much lesser environmental impact overall. This is due to high energy was particularly consumed in thermal dewatering process in harvesting stage. The amount of GHG emissions is directly proportional to the electricity consumptions in dewatering process. Moreover, alternative of dewatering methods which can replace thermal dewatering have been studied and conventional solar drying is able to improve the energy efficiency of the system. The NER has net positive life cycle energy and GHG emissions were greatly reduced. However, solar drying method is a slow process as compared to other alternatives and it is weather dependent. Therefore, the results of this LCA research has shown that EFB bioethanol has the potential to become a major renewable fuel energy source in the near future of Malaysia.

5.2 Future LCA Research Recommendations

A few recommendations shall be implemented in order to improve the precision of the data in this study. Firstly, a LCA research for an industry shall be done by compiling all inputs and outputs into a transparent inventory. This can provide the industry with outstanding overview of areas in which the materials and cost that can be made for environmental improvement application. Besides, in order to conduct an accurate LCA study on bioethanol feedstock in Malaysia in near future, it is important to have and apply Malaysian normalization and weighting conversion standards to produce excellent input and output data of life cycle. This issue should be addressed by the panel of local experts or biofuel energy organizations with the purpose of making a set of standard Malaysian energy and GHG conversion values. This can be achieved if the responsible group of LCA researchers had convinced the biofuel industries to record all available local standard conversion data to improve the accuracy of data generated.

Furthermore, only primary data should be collected from actual industries and included in future LCA research of bioethanol feedstock in order to have a more realistic research findings. Moreover, the data should be obtained from the known feedstock processing company that supply its raw materials to that particular biofuels company, the results and scenarios chosen can be traced from the beginning stage to the end stage of the production.

Other than that, other possible environmental impacts that involved in the life cycle bioethanol production process such as eutrophication values, acidification values and impacts to the biodiversity should be further evaluated. Lastly, the waste disposals and management should be explicitly provided by each industry so that not to overlook some environmental impacts that could found in this research.

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