# LIFE CYCLE ASSESSMENT ON THE PALM-BASED POLYOL PRODUCTION

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FACULTY OF ENGINEERING
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**DISSERTATION SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING SCIENCE**

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# ABSTRACT

The search for renewable resources as a feedstock in the polyol production inspired polyol makers to expand their focus on vegetable-based feedstock rather than just concentrating on petroleum-based feedstock only. Currently, there are a few comprehensive studies on polyol production from palm oil as a feedstock. Palm-based polyol has been proven to have similar or even better characteristic and performance than petroleum-based polyol by several polyol manufacturers. This study is intended to evaluate and identify the environmental impacts from the production of palm-based polyol carried out in MPOB Polyol Pilot Plant through four different scenarios studies. The outcome from this study is important to support the use of renewable raw material in the production of bio-based polyol, and hence will further boost the application of palm oil and its derivatives. The 'cradle-to-gate' system boundary utilizing the LCA methodology for the production of palm-based polyol shows that the most significant impact from the production comes from the energy use at the polyol plant. This impact is mainly contributed by the use of electricity and productions of hydrogen peroxide. There are also impact contribution from palm-based products which were used as a feedstock during the production. The result obtained from the alternative scenario (Scenario 2), indicated a reduction of around 63-65% of the GHG emissions produced from the overall palm-based polyol production. There is not much difference on impacts and GHG values if glycerol is use to replace diol during the alcoholysis stage as in Scenario 3. However, the results at the pilot plant study will be more interesting if future work can be carried out at a commercial plant with larger scale production.

# ABSTRAK

Penerokaan sumber yang boleh diperbaharui sebagai bahan mentah dalam pengeluaran polyol telah diilhamkan oleh pengeluar poliol untuk mengembangkan pengeluaran poliol yang berasaskan sayur-sayuran mentah dan tidak hanya tertumpu kepada bahan mentah yang berasaskan petroleum sahaja. Pada masa ini, terdapat beberapa kajian yang komprehensif mengenai pengeluaran poliol yang menggunakan minyak sawit sebagai bahan mentah. Poliol berasaskan sawit telah dibuktikan mempunyai prestasi dan ciri yang sama atau lebih baik daripada poliol berasaskan petroleum. Kajian ini dijalankan bertujuan untuk menilai dan mengenal pasti kesan alam sekitar daripada pengeluaran poliol berasaskan sawit yang telah dijalankan di Loji Rintis Poliol MPOB yang diterjemahkan menggunakan empat senario kajian yang berlainan. Hasil daripada kajian ini adalah penting bagi menyokong penggunaan bahan mentah yang boleh diperbaharui dalam pengeluaran bio-poliol, dan secara tidak langsung akan turut meningkatkan penggunaan minyak sawit dan terbitannya. Sempadan sistem *'cradle-to-gate'* yang telah ditentukan dalam pengeluaran poliol berasaskan sawit menunjukkan kesan yang paling ketara daripada pengeluaran tersebut adalah daripada penggunaan tenaga di loji rintis poliol tersebut. Kesan ini sebahagian besarnya disumbangkan oleh penggunaan elektrik, ia turut disumbangkan oleh proses pengeluaran hidrogen peroksida itu sendiri. Manakala, terdapat juga kesan impak yang berpunca daripada proses pengeluaran produk berasaskan sawit yang digunakan sebagai bahan mentah dalam penghasilan poliol. Senario alternatif (Senario 2) didapati dapat membantu untuk mengurangkan pelepasan gas rumah hijau (GHG) yang terhasil daripada pengeluaran poliol berasaskan sawit iaitu sebanyak 63-65% daripada jumlah keseluruhan. Tiada banyak perbezaan diperhatikan pada kesan dan nilai-nilai GHG apabila gliserol digunakan untuk menggantikan diol pada peringkat alkoholisis poliol seperti dalam Scenario 3. Walau

bagaimanapun, pemerhatian dan hasil keputusan kajian pada skala loji rintis ini akan menjadi lebih menarik sekiranya analisa dan kajian turut dapat dijalankan menggunakan skala komersial bagi pengeluaran poliol yang lebih besar pada masa hadapan.

# ACKNOWLEDGEMENT

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| AV | : | Acid value |
| $CO_2$ | : | Carbon dioxide |
| DALY | : | Disability adjusted life years |
| GJ | : | Giga joule |
| ISO | : | International Organization for Standardization |
| IV | : | Iodine value |
| KOH | : | Kalium hydroxide |
| LAS | : | Linear alkylbenzene sulphonates |
| LCA | : | Life cycle assessment |
| LCI | : | Life cycle inventory |
| LCIA | : | Life cycle impact assessment |
| MES | : | Methyl ester sulphonates |
| MJ | : | Mega joule |
| MPOB | : | Malaysian Palm Oil Board |
| OHV | : | Hydroxyl value |
| PAF | : | Potentially affected fraction |
| PDF | : | Potentially disappeared fraction |
| POP | : | Palm oil polyol |
| PU | : | Polyurethane |

## LIST OF APPENDICES

# CHAPTER 1: INTRODUCTION

## 1.1 The Oil Palm and Oleochemical Industries in Malaysia

Presently, palm oil is one of the major vegetable oils produced in the world. Malaysia is the second largest producer and exporter of palm oil in the world after Indonesia and contributed about 39.7% of the world's palm oil exports in year 2014. The total exports of oil palm products (which consist of palm oil, palm kernel oil, palm kernel cake, oleochemicals, biodiesel and finished products) from Malaysia declined by 2.5% to 25.07 million tonnes in 2014 from 25.70 million tonnes exported in 2013. However, total export revenue was increased by 3.7% to RM63.62 billion compared to RM61.36 billion achieved in 2013 due to higher export prices (MPOB, 2014). Figure 1.1 shows the graph for the export volume of palm oil, palm kernel oil and oleochemical products in Malaysia from the year 2001 until year 2014.

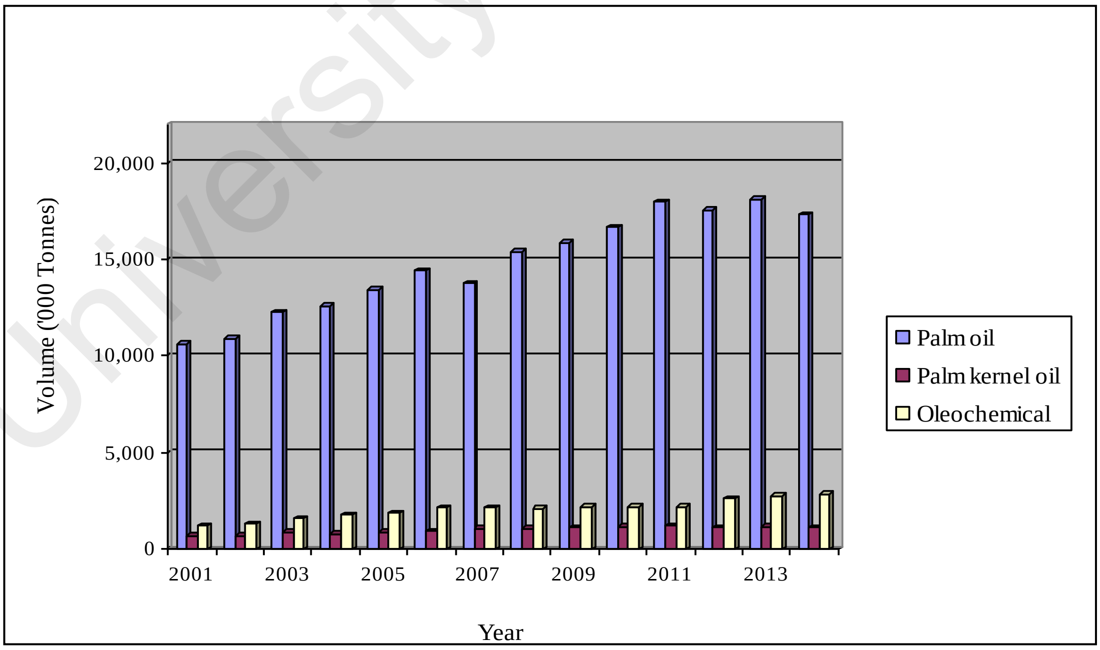


**Figure 1.1: Export volume of palm oil, palm kernel oil and oleochemicals in Malaysia from year 2001 to 2014 (MPOB, 2015).**

The rapid development of the oil palm industry has also influenced the development of oleochemical industry in Malaysia where most of the basic feedstock/material to produce oleochemical products were derived from palm oil products. Generally, oleochemicals are chemicals derived from plant and animal fats which are analogous to petrochemicals derived from petroleum. As the price of crude oil rose in the late 1970s, manufacturers switched from petrochemicals to oleochemicals because plant-based lauric oils processed from palm kernel oil were cheaper (NPCS, 2013). Then, it has expanded significantly since the establishment of the first oleochemical plant in 1979 in Malaysia (Mohtar et al., 2001).

In Malaysia, the oleochemical industry has started in the early 1980's by the establishment of IOI Oleochemicals as the one and only oleochemical plant that produces exclusively palm-based oleochemical products. This sector is one of the most important non-food uses for palm oil products. The production of basic oleochemicals such as fatty acids, methyl esters, fatty alcohol, glycerine and others oleochemical products e.g. sodium soap, polyol and polyurethane has increased steadily over the years. Oleochemical derivatives like polyol and polyurethane also have their own role in the oleochemical industry. In 2014, the export of oleochemical products rose by 4% to 2.83 million tonnes against 2.73 million tonnes in the previous year. The major export markets for oleochemicals were the EU with 22.6% of total oleochemical exports or 0.64 million tonnes, China, P. R (0.43 million tonnes), USA (0.0.26 million tonnes) and Japan with 0.22 million tonnes. Since the early eighties, this industry expanded rapidly and today the Malaysian oleochemical industry is one of the largest oleochemical industries among the Asean countries.

## 1.2 Environmental Issues and Sustainability Development

Within the last few years, environmental issues are becoming more important in Malaysia and around the world (Sumiani et al., 2007). Various international status reports on the condition of the environment have been reported over the last few decades (Wenzel et al., 2000). Global warming, climate change, greenhouse gases and the latest is on desertification are some examples of the environmental problems. From the US EPA observation, glaciers around the world now are shrinking, and the amount of sea ice in the Arctic Ocean has decreased since the 1970s. The average sea level worldwide is also projected to rise up to two feet by the end of this century. In other parts of the world, some migratory birds are spending their winter in average of 35 miles further north than they did 40 years ago due to the rise in temperature. All these scenarios happened because of climate change. The situation will worsen if no mitigation is carried out to overcome these problems.

The oil palm industry also faces many challenges and issues on sustainability and the environment. Because of that, the oil palm industry has now become aware of all these environmental issues and has started to strive towards improving the environmental quality through sustainable development and cleaner technology approach. The sustainability of the oil palm industry has now become part and parcel of the business which requires more involvement among the industry players itself. In order to have a sustainable palm oil, Round Table on Sustainable Palm Oil (RSPO) was established in 2004 and was participated by a number of Malaysian plantation companies. The oil palm industry is expected to adopt the principles and criteria of the RSPO to produce palm oil in a sustainable manner (Yusof, 2007).

At the same time, the Government has also pointed out some initiatives to provide a green image for oil palm industry through the implementation of Good Agricultural Practices (GAP). In oil palm industry, some of the GAP include the use of zero burning, integrated pest management, treatment of wastewater at palm oil mills had been practised by the industry (Yusof et al., 2009). The oil palm industry started to adopt zero burning and replanting policy to avoid the carbon dioxide emission and provide the better carbon footprint for industry. At the same time, it also reduces the accumulation of soil carbon in the plantation. Leguminous cover crops are also planted at the plantation to preserve the environment. Other than that, the oil palm biomass which was identified as waste from the oil palm production is recycled and then converted and utilized as a fertilizer input and energy source, which can make profit to the industry itself. The industry also treated the wastewater and uses integrated pest management to reduce the need for pesticides by using natural predators like owls, snakes, and insects to control pests especially in oil palm plantation.

Other initiatives included overcoming the biogas issue where the palm oil producers in Malaysia started implementing the biogas trapping systems to collect the biogas and then convert it into renewable energy in palm oil mills. Currently, the industry is moving towards either harnessing biogas from POME or producing value-added products such as fertilizer from POME which avoids methane generation. This move is visible with the gradual annual increase in the number of palm oil mills capturing their biogas (Vijaya et al., 2010). In recent year, the palm oil industry has embarked on trapping methane when it was realised that this is a GHG with high global warming potential. Mills that trap methane also gain carbon credits as the activity qualifies as a Clean Development Mechanism (CDM) project under the Kyoto Protocol (Yusof et al., 2009). Capturing methane at palm oil mills also can produce electricity for supply to the national grid or for their own use at the mills. This is one reason why palm oil mill was encouraged to capture their biogas and later use it as a renewable energy that is greener and friendly to the environment.

Today, the Malaysian oil palm industry is constantly being scrutinized on its environmental performance. Based on what the industry is facing right now, it is important to find the best approach and solution to support the industry. This can be achieved by the continuous environmental improvements and efforts are necessary and to remain competitive the oil palm industry must be prepared for new challenges ahead (Sumiani et al., 2007).

### 1.3 Life Cycle Assessment (LCA) Approach

From the history, LCA started during the energy shortages of the early 1970s as a systems-oriented tool for tracking material and energy flows in industrial systems (Joseph, 1996). The first examples of environmental assessments of products were carried out on packaging and published at the end of the 1960s and beginning of the 1970s in the USA. They were called "Resource and Environmental Profile Analyses' (REPAs) and focused primarily on energy consumption, resource consumption and generation of waste, in accordance with the focus in the environmental debate of the time. At that time there was still too little knowledge on processes' emission of environmentally hazardous substances and their possible impacts on the environment to permit assessment of a potential environmental impact (Wenzel et al., 2000)

The Society for Environmental Toxicology and Chemistry (SETAC) Code of Practice defined LCA as a process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment, to assess the impact of those energy and materials used and released to the environment, and to identify and evaluate opportunities to effect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials, manufacturing, transportation and distribution, use, reuse, maintenance, recycling and final disposal (SETAC, 1993).

LCA can be used as a tool for environmental improvement on the targeted product. LCA study can also be used as a decision-making tool for industries, government and non-government organizations. Based on a survey of LCA practitioners carried out in 2006 (Cooper et al., 2006), LCA is mostly used to support business strategy (18%) and R&D (18%), as input to product or process design (15%), in education (13%) and for labelling or product declarations (11%). Major corporations all over the world are either undertaking LCA in house or commissioning studies, while governments support the development of national databases to support LCA. Of particular note is the growing use of LCA for ISO Type III labels called Environmental Product Declarations, defined as "quantified environmental data for a product with pre-set categories of parameters based on the ISO 14040 series of standards, but not excluding additional environmental information". These third-party certified LCA-based labels provide an increasingly important basis for assessing the relative environmental merits of competing products. Third-party certification plays a major role in today's industry. Independent certification can show a company's dedication to safer and environmental friendlier products to customers and NGOs.

In the oil palm industry, the LCA approach is not a new thing since several LCA studies on palm oil have been conducted using this approach in order to overcome all the issues on sustainability and environment. LCA became as a good tool to help the industry to promote their products and to give a good perspective to the oil palm industry.

### 1.4 Problem Statement

During the last few years, the interest in palm oil products and its derivatives are increasing. One of the products are polyols which is derived from natural oils and has been constantly increasingly used for a variety polyurethane (PU) applications. Previously, most of the commercial polyols available in the market are originated from petroleum-based. Due to the escalating price of crude petroleum and increasing global awareness about sustainable development, there is a search for renewable resources to produce polyols from the renewable resources. Generally, there are many organization which have been trying for a long time to replace petro-polyols with more environmental-friendly analogs based on vegetable oils (Ricardo et al., 2008). So far, the most successful and interesting substitutes or resources for crude petroleum are vegetable oils which are palm oil, soy bean oil, castor oil and canola oil (Luo et al., 2008). These renewable potential resources can help the polymer industry to reduce their dependency on petroleum source in making polyol, polyurethane and other application in polymer. Escalating concern to the environmental issues like global warming, carbon footprint and depletion on fossil fuels, encourage most of the consumers today are more responsible with their choice and decision to have an environmental-friendly product.

This effort and approach can help to reduce the environmental footprint that come from the product process especially from petroleum by replacing it with something that is renewable and friendly to the environment. Polyol from the renewable resources e.g.

vegetable oils can be use as alternative resources to give a good potential for commercial polyol market in the future. In commercial use, polyols can be used to produce various types of polyurethane products such as ceiling panel, flora foams, cushion, car seats, mattress, wall panels, pillow, automotive parts, flexible foams, windows encapsulation and *etc*. In the other perspective, the research and development of polyol using renewable resources will bring the bright prospects to the new market segment in the polymer industry.

Technologies to produce polyols from palm oil and palm kernel oil that are economically competitive to petroleum-based polyols have been developed in Malaysia. They involve reacting palm oil and palm kernel oil with any polyhydric alcohols including glycerol to produce the longer-chain polyols, which are then reacted with polyisocyanates to generate polyurethanes in the presence of only water or other low boiling chemicals as the blowing agents (Salmiah and Yusof, 2003). The technologies on the polyol production are evolving and many good findings were achieved from this great research and development in this area. Even now, Cargill also offered the polyurethane industry a large scale, and reliable supply of bio-based polyols (Biobased Solutions, 2008). This is a good sign and a right time for this industry to grow and expand their market globally.

At present, numerous LCA studies have been conducted on the production of palm-based polyol. Previously, most of the LCA studies on the polyol production are limited to petroleum-based polyol and soy-based polyol. As the direction of bio-based polyol especially from palm has increased, the interest in evaluating the environmental performance from the production also is increasing. So, this study is important to help and support our national export of palm-based polyol and also give credit to the oil palm industry. Actually, it is very challenging task for the bio-based polyol industry especially in Malaysia to promote their product in order to make it competitive with petroleum-based polyol. In Malaysia, three palm-based polyol producers still remaining produce the bio-based polyol namely as Maskimi Polyol, Wansern Biotechnology Sdn. Bhd and PolyGreen Chemicals (Malaysia) Sdn. Bhd.

By establishing the LCA on the palm-based polyol production, it becomes easier for Malaysia to promote our palm-based polyol products in the global market. Moreover, this palm-based polyol can be used as an alternative renewable resource and has very good commercial market potential in the future.

## 1.5 Objectives of the Study

This study was carried out based on several objectives. The objectives of this study are:

i) To establish life cycle inventory (LCI) of palm-based polyol production using inventory data collected.

ii) To evaluate and identify the environmental impacts through the life cycle impact assessment (LCIA) for palm-based polyol production at the pilot plant scale.

iii) To determine and suggest the way/solution to reduce the environmental impacts from the palm-based polyol production.

## 1.6 Scope and Limitation of the Study

### 1.6.1 Scope of the Study

The scope of this study covers the LCA of palm-based polyol production at a pilot plant scale. In this study, the chosen site system boundary in the production of the palm-based polyol is at the Advanced Oleochemical Technology Division (AOTD) pilot plant, Malaysian Palm Oil Board (MPOB). The functional unit of this study is 1 tonne of palm-based polyol production. The study also covers Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) of palm-based polyol production.

The purpose of this study is to carry out a 'cradle-to-gate' LCA, based on the inventory data collected i. e. from oil palm nursery until the production of palm-based polyol. In the same time, it also can be use as a marketing tool for palm-based polyol to penetrate into the global market using eco-labelling and etc.

### 1.6.2 Limitation of the Study

The system boundary excludes the production of capital goods e.g. machineries, buildings, vehicle manufacturing, vehicle maintenance and disposal, transport infrastructure and waste treatment. All the data was based on the pilot plant operation.

## 1.7 Benefits from the Study

This study is expected to benefit the polyol industry with the development of a LCA database for the palm-based polyol. On other hand, it will help to promote the palm-based polyol and other products like polyurethane as an environmental friendly product which is can be introduced as an alternative product in polymer industry besides of petroleum-based and soy-based polyol.

## 1.8 Thesis Outline

This thesis comprised of five chapters which are:

**Chapter 1: Introduction**

Chapter 1 describes the introduction of the study, significance of the study and the problem statement. The scope, limitation, objectives and expected benefits of this study are also clearly stated in this chapter.

**Chapter 2: Literature Review**

This chapter focuses on literature review starting from the basic definition of LCA, issues related to palm oil industry, polyol and polyurethane background. It also includes previous researches related to the LCA studies on polyol and polyurethane which are critically reviewed.

**Chapter 3: Methodology**

This LCA study is compiled of several interrelated components which are goal definition and scope, inventory analysis, impact assessment and interpretation for palm-based polyol products. In the goal definition and scope, functional unit and system boundary of the study are included. The inventory data obtained from this study was analyzed using the SimaPro software version 8.0.2. The results on environmental impacts from the palm-based polyol production are performed with the Eco-Indicator 99 methodology.

**Chapter 4: Results and Discussion**

In chapter 4, results are presented and discussed. This chapter is divided into two parts which is life cycle inventory (LCI) and life cycle impact assessment (LCIA). The results are presented in graphs and charts to highlight the significant impacts from palm-based polyol production. Four scenarios were carried out for each palm-based polyol product including sensitivity analysis scenario. Qualitative analysis has been made for the pilot plant scale of palm-based polyol and the commercial scale of soy-based polyol production in order to seek the significant impact on the impact categories. The greenhouse gas (GHG) evaluation for each palm-based polyol are also discussed under this chapter.

**Chapter 5: Conclusions and Recommendations**

This chapter summarize all the results which are followed by a list of recommendations for future work in terms of the scope of work and LCA approach as a management tools especially for oil palm industry and palm-based polyol production.

# CHAPTER 2: LITERATURE REVIEW

This chapter is a review of the background research on Life Cycle Assessment (LCA) including the definition and methodology, issues on oil palm industry, application and market on polyol and polyurethane and also LCA status in Malaysia.

## 2.1 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a common environmental management tool and a good analytical tool for assessing and optimizing the environmental quality of a production system over the whole life cycle (Stalmans et al., 1995). It has been applied in many ways either in public or private sectors. Generally, LCA was used by the manufacturers to identify their processes, raw materials or a system that might be perform as a major contributor to the environmental impacts. By using LCA tools, the manufacturers can search or establish another option to minimize their environmental impacts. Other than that, LCA also can be used for environmental labelling (ecolabels) by the public policymakers. Some of ecolabels from around the world are listed here:

i) Blue Angel (Germany)
ii) Nordic swan (Nordic countries)
iii) Environmental Choice (Canada)
iv) Eco Mark (Japan)
v) Green Seal (United States)
vi) Environmental Choice New Zealand (New Zealand)
vii) SIRIM Eco Label (Malaysia)

Referring to the ISO Standard, LCA can be found in the ISO 14000 Series as shown in the Table 2.1.

**Table 2.1: List of ISO 14000 series of standard.**

| Description | ISO |
|---|---|
| Organizational risk management | ISO 14001,ISO 14004, ISO 14005, ISO 14006, ISO 14015, ISO 14061 and ISO 14063 |
| Environmental labelling | ISO 14020, ISO 14021, ISO 14024 and ISO 14025 |
| Environmental performance | ISO 14031, ISO 14032, ISO 14033 and ISO 14034 |
| Life cycle assessment | ISO 14040-14049, ISO 14051, ISO 14062, ISO 14071-14073, ISO 21929-1 and ISO Guide 64 |
| Environmental terms and definitions | ISO 14050 |
| Greenhouse gas and carbon footprinting | ISO 14064, ISO 14065, ISO 14066, ISO 14067 and ISO 14069 |
| Auditing of management systems | ISO 19011 |
| Energy management systems and audits | ISO 50001-50004, ISO 50006 and ISO 50015 |

(Source: Burden, 2014)



The development of the International Standards for life cycle assessment is an important step to consolidate procedures and methods of LCA. The contribution of ISO is crucial to the general acceptance of LCA by all stakeholders and by the international community.

There are two main LCA standards under the ISO 14040-14044 series which are ISO 14040:2006 and ISO14044:2006. This ISO 14040:2006 covers on the principles and framework of LCA, at the same time provides a clear overview of the practice, applications and limitations of LCA to a broad range of potential users and stakeholders, including those with a limited knowledge of life cycle assessment.

Meanwhile, ISO 14044:2006 provides the requirement and guidelines on LCA, where it is designed for the preparation of, conduct of, and critical review of life cycle inventory analysis. It also provides guidance on the impact assessment phase of LCA and on the interpretation of LCA results, as well as the nature and quality of the data collected. Both of these standards are important for any LCA practitioners in order to conduct their LCA study.

This life cycle based environmental initiative or also known as Life Cycle Assessment (LCA) focuses on improvement to the product in all phases, from raw material extraction and transport, to production and consumption or use up to re-use or disposal.

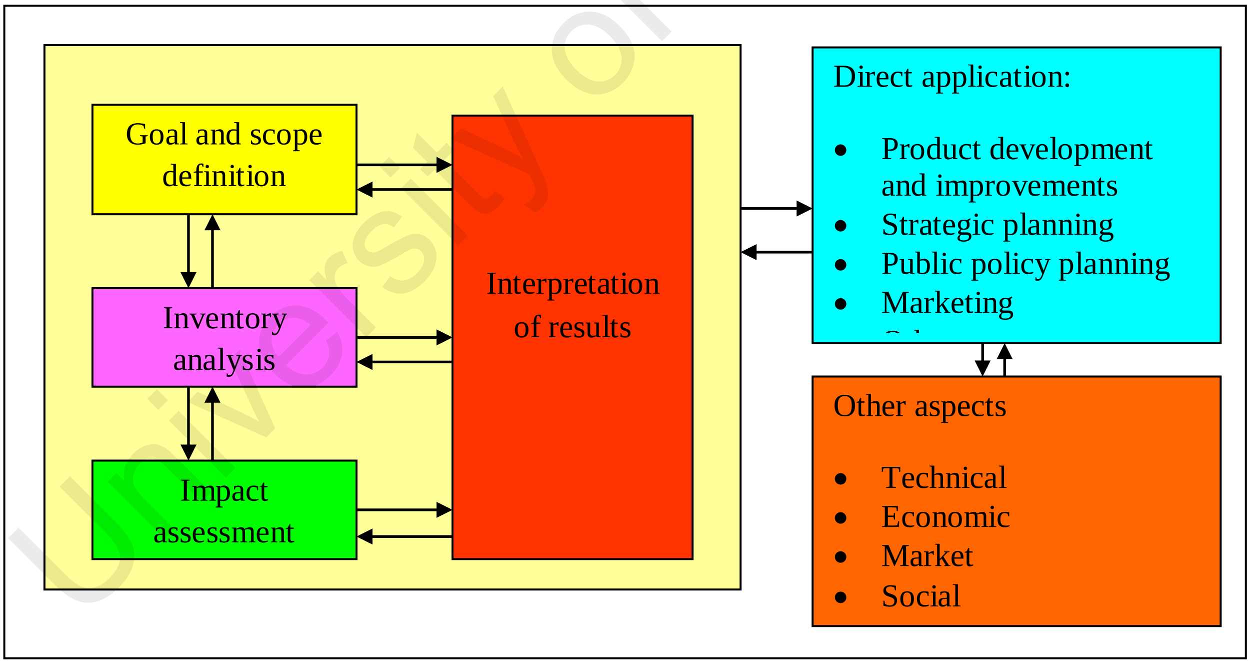


**Figure 2.1: Life cycle assessment framework - phases of an LCA (Source: ISO 2006, ISO 14040:2006(E)).**

According to ISO 14040, LCA can be divided into four phases which are as followed i) goal and scope definition, ii) inventory analysis, iii)impact assessment and iv) interpretation. All these phases are shown in Figure 2.1. The LCA result becomes more useful, credible and close to reality when all these four phases are repeated several times.

Meanwhile, the ‘cradle-to-gate’ is known as an assessment of a partial product life cycle from resource extraction (cradle) to the factory gate (i.e., before it is transported to the consumer). The use phase and disposal phase of the product are omitted in this case. Cradle-to-gate assessments are sometimes used as the basis for environmental product declarations (EPD), termed business-to-business EDPs. One of the significant uses of the cradle-to-gate approach is compilation of the life cycle inventory (LCI) data. This allows the LCA to collect all of the impacts leading up to resources being purchased by the facility. Then can add the steps involved in the transport of raw materials to plant and manufacture process, and then can produce own cradle-to-gate values for specific products.

## 2.2 Life Cycle Assessment Framework

### 2.2.1 Goal and Scope Definition

This is the first phase that needs to identify before any of LCA study can be carried out. Goal definition consists of clarifying what the LCA can and cannot be used for, including the decisions which it must support and the environmental consequences to which these decisions can lead (Wenzel et al., 2000). While, scope definition is purposely to identify and to define the objective of the assessment and to limit it to include that which is significant for the goal of the LCA. System boundary, functional unit, assumptions, limitations, allocation, type of methodology that will be performed, data quality requirement and type of critical review, if any is another item that need to described and identified before second phase of LCA can be proceed. The definition of the functional unit is an important step in order to indicate the specific unit that will be used in LCA study.

### 2.2.2 Life Cycle Inventory Analysis

This phase will be more time consuming compared to other phase. In this phase, all data on raw material, every single material consumption, energy consumption, emissions, discharges or wastes to environment will be taken into account. This phase is more on collection, measurement and quantifying the inventory data for the whole production. The quality of data is also crucial and important. Figure 2.2 shows the procedure of preparing the life cycle inventory (LCI) based on ISO 14044:2006(E).

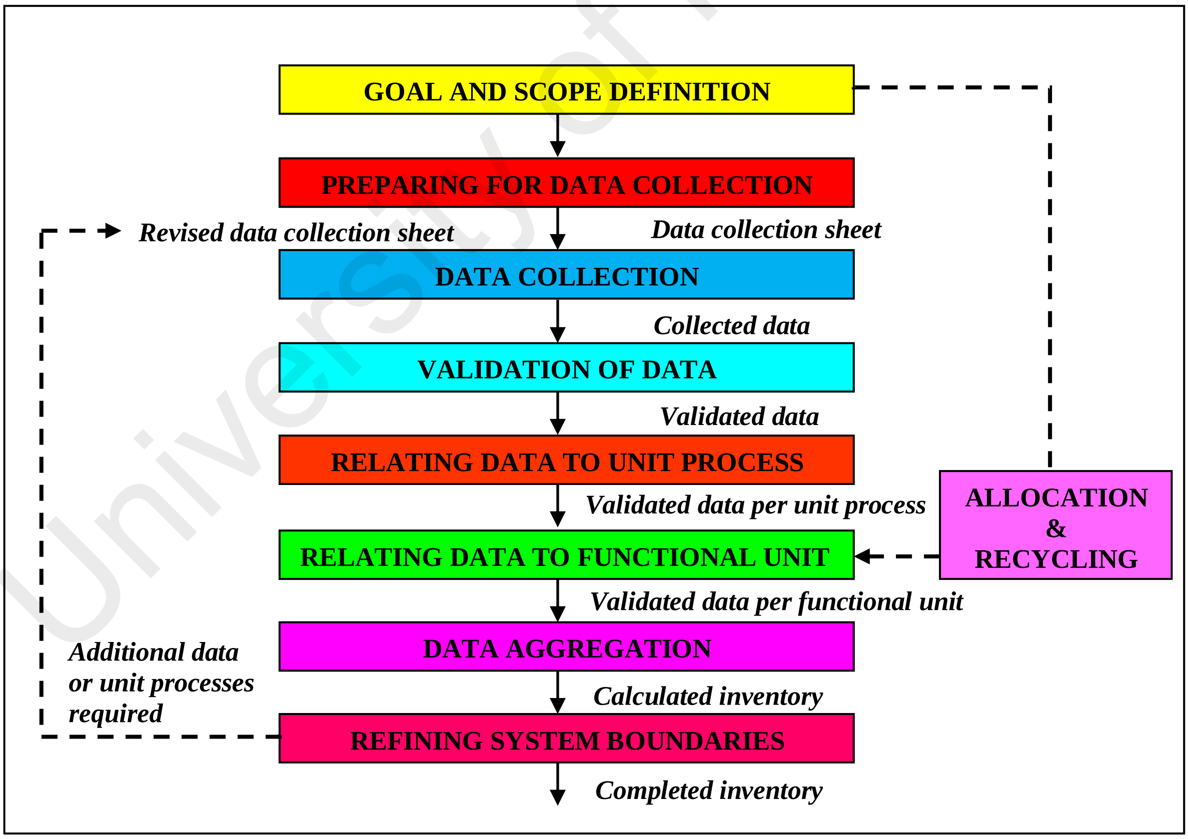


**Figure 2.2: Flow of life cycle inventory.**

Reuse of data from other studies can simplify the work but this must be made with great care so that the data is representative. The quality aspect is therefore also crucial. The data must be related to the functional unit defined in the goal and scope definition. Data can be presented in tables and some interpretations can be made already at this stage. The results of the inventory is an LCI which provides information about all inputs and outputs in the form of elementary flow to and from the environment from all the unit processes involved in the study.

### 2.2.3 Life Cycle Impact Assessment

Information on the Life Cycle Inventory (LCI) is used for the Life Cycle Impact Assessment (LCIA). According to ISO 14040, the goal of balancing the system is the assessment of the potential environmental impact. Potential contributions to various environmental impacts are calculated. The potential impacts on the environment, working environment and resources consumption are weighted in relation to one another in order to increase the suitability of the inventory as a basis for decisions. LCIA aims to evaluate the significance of potential environmental impacts that come out from the LCI phase.

### 2.2.4 Life Cycle Interpretation

This phase aims to reach the significant conclusions and recommendations from the study to aid in decision-making. Results from LCI and LCIA are combined together and reported in order to give a complete and unbiased report of study. Interpretation also performed through each of the other steps in the LCA to ensure the quality of the LCA study. The outcome of the interpretation phase is a set of conclusions and recommendations for the study. According to ISO 14040:2006, the interpretation should include:

- identification of significant issues based on the results of the LCI and LCIA phases of an LCA;
- evaluation of the study considering completeness, sensitivity and consistency checks; and
- conclusions, limitations and recommendations.

### 2.2.5 Life Cycle Impact Assessment Software

There are several LCA softwares which are available in the market. This study uses one of the LCA software as stated here, which is SimaPro that originated from Netherlands. Others LCA software are GaBi (Germany), JEMAI (Japan), LCAiT (Sweden), Umberto NXT LCA (Germany), openLCA (Germany), Quantis SUITE 2.0 (Swiss), Eco-it 1.4 (Netherlands), BEES (USA), CMLCA (Netherlands) and LCAPIX (USA).

### 2.2.6 Life Cycle Impact Assessment Methodologies

LCIA methodology shall be determined which impact categories, category indicators and characterization models are included within the LCA study (ISO 14044:2006). There are several of LCIA methodologies which can be applied as mentioned by Hannele et al. (2011).

i) CML 2002

ii) Eco-indicator 99

iii) Ecological Scarcity Method (Ecopoints 2006)

iv) EDIP 97

v) EDIP 2003

vi) EPS 2000

vii) IMPACT 2002+

viii) LIME

ix) LUCAS

x) ReCiPe

xi) TRACI

xii) MEEup

There are also other LCIA methodologies that are used by the LCA practitioners to support their results and findings in LCA study such as:

i) Cumulative Energy Demand

ii) IPCC Greenhouse gas emissions

According to ISO (2000), LCI results are first classified into into impact categories. A category indicator, representing the amount of impact potential, can be located at any place between the LCI results and the category endpoint. Based on that, there were two methods developed, i. e. the mid-point oriented methods and damage-oriented methods (Jolliet et al., 2004). Mid-point impact category are also known as problem-oriented method that translates impacts into environmental themes such as climate change, acidification, human toxicity and etc. The EDIP, TRACI or CML 2000 methods are examples of problem-oriented methods. While damage-oriented method or end-point impact category translates environmental impacts into issues of concern such as human health, ecosystem health or damage to resources. Eco-indicator 99, EPS and LIME methods are example of damage-oriented method (Itsubo and Inaba, 2012). Based on all these facts, Eco-indicator 99 methodology was preferred to be selected for this study. Other than that, all the upstream and midstream studies on oil palm industry also used this methodology to conclude their findings.

### 2.2.7 Eco-indicator 99 Methodology

There are several methodologies which have been suggested and described by the LCA practitioners. One of the methodologies is Eco-indicator 99. The Eco-indicator 99 is a state of the art impact assessment method for LCA, with many conceptual breakthroughs. The method is also the basis for the calculation of eco-indicator scores for materials and processes. Other than that, Eco-indicator 99 has fully consistent and almost complete modelling of the damage caused by a large number of relevant impact categories and almost completes specification of all the technical uncertainties. The most practical application is the calculation of single scores for commonly used materials and processes. Such standard list has proven to be a very useful tool for practitioners, as they can perform their own LCA in a matter of minutes (Goedkoop and Spriensma, 2001). Table 2.2 shows the assessment parameter that was included in Eco-indicator 99.

**Table 2.2: Assessment parameters (Eco-indicator 99).**

| Impact category | Characterization | Damage category |
|---|---|---|
| **Emission** | | |
| Carcinogens | DALY/kg | Human health |
| Respiratory organics | DALY/kg | Human health |
| Respiratory inorganics | DALY/kg | Human health |
| Climate change | DALY/kg | Human health |
| Radiation | DALY/kg | Human health |
| Ozone layer | DALY/kg | Human health |
| Ecotoxicology | PAF.$m^2$.year/kg | Ecosystem quality |
| Acidification | PDF.$m^2$.year/kg | Ecosystem quality |
| Eutrophication | PDF.$m^2$.year/kg | Ecosystem quality |
| **Land use** | | |
| Decrease diversity | PDF.$m^2$.year/kg | Ecosystem quality |
| **Resource depletion** | | |
| Metals/Minerals | SE/kg | Resources |
| Fossil fuels | SE/kg | Resources |

*Source:* Sumiani and Sune (2007)

*Note:*

DALY : disability adjusted life years (years of disabled living or years of life lost due to the impacts)

PAF : potentially affected fraction (animals affected by the impacts)

PDF : potentially disappeared fraction (plant species which disappear as result of the impacts)

SE : surplus energy (MJ) (extra energy that future generations must use to excavate scarce resources)



According to Goedkoop and Spriensma (2001), there are three version of Eco-indicator 99 which are:

i) Egalitarian (E)

This version uses a precautionary principle. It is the most comprehensive version, but it also has the largest data uncertainties and sometimes have include data on which consensus is lacking.

ii) Individualist (I)

This version only proven cause effect relations is included. The preference for proven relationships is the attitude of individualists to consider each limit as negotiable.

iii) Hierarchist (H)

This version includes facts that are backed up by scientific and political bodies with sufficient recognition. The hierarchical attitude is rather common in the scientific community, and among policy makers.

Louise et. al (2003) had mentioned that Eco-indicator 99 methodology considers three damage categories which are human health, ecosystem quality and resources. Table 2.3 shows the three damage categories and the concomitant impact categories modeled in Eco-indicator 99.

**Table 2.3: The damage categories and the underlying impact categories modelled in Eco-indicator 99.**

| Damage Categories | Impact Categories |
|---|---|
| Human Health | Carcinogenic effects on humans<br>Respiratory effects caused by organic substances<br>Respiratory effects caused by inorganic substances<br>Damage caused by climate change<br>Effects caused by ionizing radiation<br>Effects caused by ozone layer depletion |
| Ecosystem Quality | Damage caused by ecotoxic effects<br>Damage caused by the combined effect of acidification and eutrophication<br>Damage caused by land occupation and land conversion |
| Resources | Damages caused by extraction of minerals<br>Damages caused by extraction of fossil fuels |

#### 2.2.7.1 Damage Category to Human Health

This damage is focused to the health of any human individual, being a member of the present or a future generations that may cause temporary or permanent disabilities. As mentioned by Goedkoop and Spriensma (2001), the environmental sources for such damages are listed below:

i) Infectious diseases, cardiovascular and respiratory diseases, as well as forced displacement due to the climate change

ii) Cancer as result of ionising radiation

iii) Cancer and eye damages due to ozone layer depletion

iv) Respiratory diseases and cancer due to toxic chemicals in air, drinking water and food.

The damage to human health has involve six impact categories as mentioned in Table 2.2, which are carcinogenic, respiratory organic, respiratory inorganic, climate change, radiation and ozone layer depletion. To aggregate different types of damages to human health, DALY (Disability Adjusted Life Years) scale is used for Eco-indicator 99. The scale lists many different disabilities on a scale between 0 and 1 (0 meanig being perfectly healthy and 1 meaning death).

#### 2.2.7.2 Damage Category to Ecosystem Quality

The ecosystems are very complex and it is very difficult to determine all damages inflicted upon them. An important difference with human health is that even if we could, we are not really concerned with the individual organism, plant or animal Goedkoop and Spriensma (2001). The ecosystem damage was expressed as a percentage of species that are threatened or that disappear from a given area during a certain time.

There are three impact categories under this damage category of ecosystem quality which are:

i) Ecotoxicity

For ecotoxicity, the Potentially Affected Fraction (PAF) of species in relation to the concentration of toxic substances was determined using method developed by RIVM. The PAFs are determined on the basis of toxicity data for terrestrial and aquatic organism like micro-organism, plants, worms, algae, amphibians, molluscs, crustaceans and fish. The PAF expresses the percentage of species that is exposed to a concentration above the No Observed Effect Concentration (NOEC). The higher the concentration, the larger the number of species that is affected. Being based on NOEC, a PAF does not necessarily produce observable damage. Therefore, even a high PAF value of 50% or even 90% does not have to result in a really observable effect. PAF should be interpreted as toxic stress and not as a measure to model disappearance or extinction of species (Goedkoop and Spriensma, 2001).

ii) Acidification and euthrophication

For this impact category, the PAF concept cannot be used directly since the damage from acidification and eutrophication is caused by an entirely different and complex of biochemical mechanism. Instead, there is a need to observed effects from acidification and eutrophication on plants, so the probability that a plant species stills occurs in an area can be determined. This is called the Probability of Occurrence or POO which is translated using this method into Potentially Disappeared Fraction (PDF): PDF = 1 – POO (Goedkoop and Spriensma, 2001).

iii) Land use

For land use impact category, the Potentially Disappeared Fraction (PDF) was chosen as indicator. Since the damage complex is complex, so there are four different models is needed which are the local effect of land occupation, the local effect of land conversion, the regional effect of land occupation and the regional effect of land conversion. The local effect refers to the change in species numbers occurring on the occupied or converted land itself, while the region effect refers to the changes on the natural areas outside the occupied or converted area (Goedkoop and Spriensma, 2001).

The unit for the damage to Ecosystem Quality is the PDF times area times year [$m^2$.yr]. For land use this unit is easy to explain. The damage increases with an increase in area size, an increase in occupation time or an increase in restoration time for a formerly converted area (Goedkoop and Spriensma, 2001).

#### 2.2.7.3 Damage Category to Resources

In the Eco-indicator 99, only minerals and fossil fuels will be considered under this damage category. The use of agricultural and silvicultural biotic resources and the mining of resources such as sand or gravel are considered to be adequately covered by the effects on land use. Biotics resources which are extracted directly from nature, like fish and tame or wild plants, are not modelled in Eco-indicator 99 (Goedkoop and Spriensma, 2001).

In the case of non-renewable resources (minerals and fossil fuels), it is obvious that there is a limit on the human use of these resources, but it is rather arbitrary to give figures on the total quantity per resource existing in the accessible part of the earth crust. If we sum up only the known and easily exploitable deposits, the quantities are quite small in comparison to current yearly extractions. If include occurrences of very low concentrations or with very difficult access, the resource figures become huge. It is difficult to fix convincing boundaries for including or not-including occurrences between the two extremes, as quantity and quality are directly linked. Because of this problem, the Eco-indicator 99 methodology does not consider the quantity of resources as such, but rather the qualitative structure of resources (Goedkoop and Spriensma, 2001).

### 2.3 Sustainability of Oil Palm

The escalating development on the growth of oil palm industry, which is known as a renewable resource, has cause the industry to face and confront with new challenges i.e. to be environmentally sustainable. The sustainability of the oil palm industry has now become part and parcel of the business which requires more involvement among the industry players. Malaysian Palm oil Board (MPOB) as the leading organization in research and development of palm oil, has done much efforts to counter the sustainability issues raised by NGOs. Due to this scenario, MPOB has been actively embarking into LCA studies for various oil palm products to achieve the target on environmental sustainability. Moreover, MPOB has also established Malaysian Palm Oil Sustainability Manual that shows the principles and procedures along the oil palm supply chain towards sustainability.

To have a sustainable oil palm industry, Malaysia together with other stakeholder organizations which include multinationals, private companies and NGO's, initiated the RSPO in 2004 as a strategy to improve the sustainability performance of the palm oil industry. RSPO has more than 300 members from growers, processors, traders, manufacturers, retailers, banks, environmental NGOs and also social NGOs (Yusof et. al, 2009). RSPO seeks to promote the production, procurement and use of sustainable palm oil through the development, implementation and verification of creditable global standards, supported by engagement of and communication to stakeholders along the supply chain.

In a global state where land is a finite resource, the development of oil palm plantations is a sustainable and environmentally beneficial activity. In addition, the production and processing of palm oil is, in itself, a sustainable process. Almost all by-products from oil palm plantations can be used. Empty shell husks can be used as fertilizer, to generate electricity or to fortify concrete. More importantly, palm oil mill effluent (POME) is an increasing important source for rural electricity generation. Internal studies have found that by utilizing POME and empty fruit bunches to capture emissions and generate electricity, emissions from the palm oil extraction process can be reduced from 59 percent to 99 percent when compared to fossil fuels (MPOC, 2013). Even the methyl ester from biodiesel production can be used as a fuel for temperate climate country. In addition, it is an excellent feedstock for polyurethane production from palm oil which is palm-based polyol. Therefore, the continuous and total usage of oil palm right from the upstream until the downstream along the value chain was shown to be environmentally friendly and sustainable.

Although the framework on sustainability contains business values, customer focus, management systems and stakeholder involvement, the effort over the next few years is to make the sustainability framework workable in the industry (Yusof and Chan, 2004).

Yusof and Chan (2004) had highlighted that palm oil also can be used directly or indirectly as oleochemicals. The products are soap, epoxidized palm oil, polyols and polyurethane, polyacrylate coatings, printing ink, engineering thermoplastic, fuel (as diesel substitute) and drilling mud.

### 2.3.1 Trends and Challenges between Food and Fuel Demand

The Malaysian oil palm industry has shown the stability performance with good records in several key performance indicators such as price of palm oil products, crude palm oil production, exports and imports volume as well as revenue. Total export of oil palm products in 2014 (consisting palm oil, palm kernel oil, palm kernel cake, oleochemicals, biodiesel, finished products and others) has earning RM 63.62 billion with the total export volume about 25.07 million tonnes. The export contribution for each product is shown in Figure 2.3.

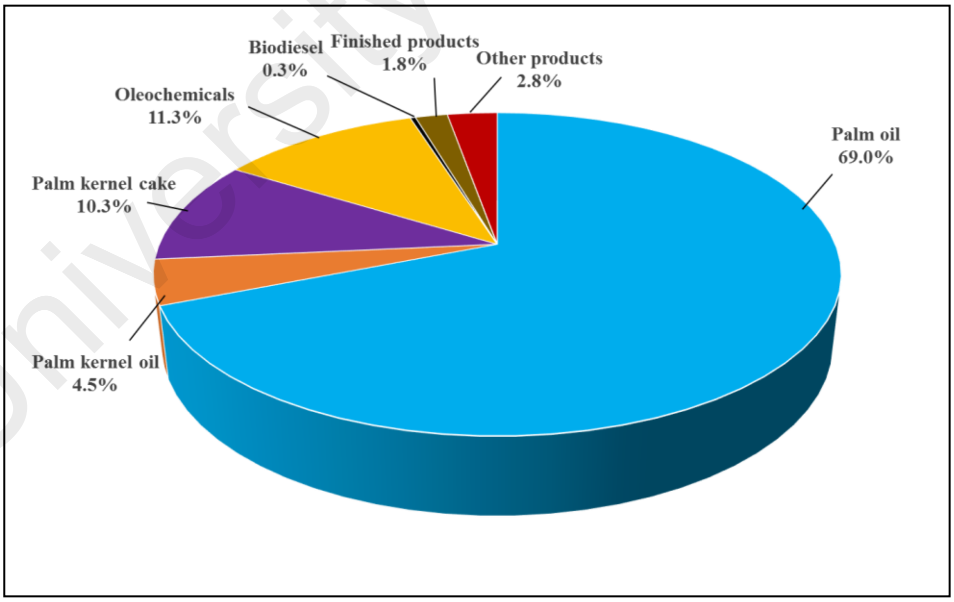


**Figure 2.3: Malaysian oil palm products export in 2014.**

Among the vegetable oils produced in the world in 2014 as in Figure 2.4, palm oil production ranked number one with the total production of 59.08 million tonnes followed by soy bean oil with the total production of 45.51 million tonnes (MPOB, 2015). Palm oil, rapeseed oil and sunflower oil are the vegetable oil crops grown for their oil content and production by these has responded more directly to the changes in world demand for oils and fats. For the other major vegetable oil crop, soybean, the oil is produced as a by-product to soybean meal, a product that is directed at the world protein market (R.E.A. Holdings PLC, 2012).

In Malaysia, there also has been interest in the utilization of palm oil and oil palm biomass for the production of environmental-friendly biofuels. The biofuel option is often seen as a safety net project for the palm oil sector, especially when the price of crude palm oil (CPO) is about to hit rock bottom and the palm oil stockpile sits above the critical two million tonne mark.

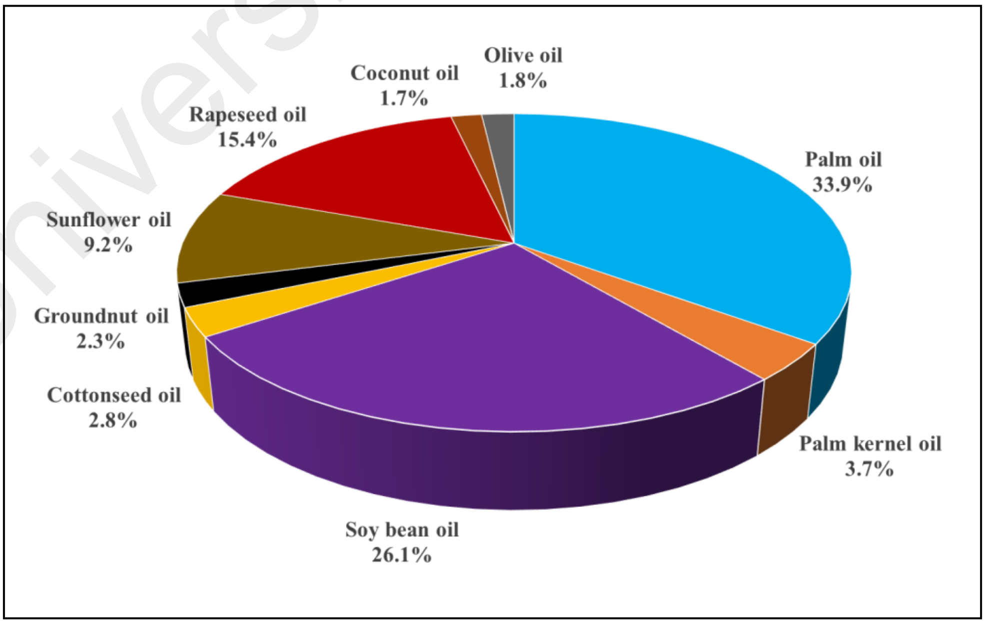


**Figure 2.4. World vegetable oils production in 2014.**

During the first half of 2012, the oil palm industry was faced with lower CPO production compared to the 2011 production. While, in second half of the 2012, the palm oil prices was declined due to the weaker export demand. To date, the B5 biodiesel is now sold only in Kuala Lumpur, Putrajaya, Selangor, Negeri Sembilan and Malacca, powering diesel vehicles, especially government-owned ones (Mohd Nasir, 2013).

From the economic point of view, the utilization of the bioenergy such as biodiesel may not be as economically attractive as using conventional energy, but this should not prevent its widespread use as the concern towards depletion of the fossil fuels and increasing environmental concerns must also be addressed (MPOB, 2011).

As mentioned by Yusof and Yew (2009), the use of biofuels to replace fossil fuels must result in a reduction of LCA GHG emissions. The EU, for instance, expects saving of at least 35% relative to use of fossil fuels. Palm biofuels is the most environment friendly products with the GHG emissions of 835 kg $CO_2$ eq comparing with 1,387 kg $CO_2$ eq from soybean, 1,562 kg $CO_2$ eq from canola and 4,288kg $CO_2$ eq from fossil fuels.

The versatile oil palm can be used for food, fibre and biofuels (Yusof and Yew, 2009). As far as people concern, the main proportion of palm oil will still be used for food. Malaysia together with Indonesia has agreed to gazette a total of 6 million tonnes of palm oil to be used as biofuel. Malaysia and Indonesia being the two largest palm oil producers in the world produced a total of 36 million tonnes of palm oil in 2007. In 2011, the combined production of palm oil for Malaysia and Indonesia was 42.81

million tonnes out of 50.32 million tonnes of the Global Production (MPOB, 2011). However, the competitiveness of palm oil implies that it will remain an important source of sustainable and renewable raw material for food, oleochemical and biofuels industries of the future (Yusof et al., 2007).

## 2.4 Oleochemical Industry in Malaysia

The demand of the oleochemical products has increase due to the expanding of the oleochemical sector and its applications**.** The consistency production and supply in CPO and CPKO successes has made Malaysian the biggest oleochemical producer in South East Asia with 20% production capacity of world capacity. In 2012, the major oleochemical products exported were fatty acids (33.1% of total oleochemical exports), followed by fatty alcohol (21.5%), methyl ester (18.5%), soap noodles (13.9%) and others (10.4%). The increase in exports of oleochemical products was due to the higher demand from the EU, China, USA and Japan (MPOB, 2012).

In Malaysia, Malaysian Oleochemical Manufacturers Group (MOMG) was established in January 1984 with the aim to attract more producers among the industry. It is also a product group of the Chemical Industries Council of Malaysia (CICM) and its members are committed to conduct its business in a socially responsible manner, i.e. through Responsible Care, a global initiative representing the chemical industry's commitment to continuous improvement of all aspects of safety, health and environment protection of their operations.

The oleochemical industry in Malaysia is nearly totally dependent on indigenous raw materials, i.e. palm oil and its derivatives and palm kernel oil as the feedstocks for the various basic oleochemical products. In this respect, the Malaysian oleochemical industry is contributing significant additional revenue over the basic value of the commodity oils.

### 2.4.1 Polyol and Polyurethane

Vegetable oil-based polyols contain a higher proportion of renewable raw materials and will continue to grow in importance as they are regarded as more sustainable than conventional materials based on fossil fuels (Hazimah et. al, 2011). Polyol is known as an alcohol with more than two reactive hydroxyl groups per molecule. The structure, molecular weights and functional groups of the polyols play an important role in determining the properties of the final urethane polymers (Ooi *et. al.,* 2006). Polyol is reacted to isocyanates to make polyurethane. A polyol of low functionality usually have around 2-3 hydroxyl groups/mol and with a high molecular weight of 2000-10000 daltons, leads to an elastic polyurethane. While, polyol with high functionality of around 3-8 hydroxyl groups/mol leads to a rigid crosslinked polyurethane (Ionescu, 2005). A wide range of polyol is available, but about 90% of these used in making polyurethanes are polyethers with terminal hydroxyl group. Hydroxyl terminated polyesters are also used to produce polyurethanes with special properties but they are usually more expensive. While, polyurethane is one of the most versatile polymeric materials with regard to both processing methods and mechanical properties. Polyurethane produced form vegetable oil polyols have a higher thermal properties than polyols prepared from propylene oxide polyols (Javni et. al, 2000).

Currently, there are many research carried out to synthesize polyol and polyurethane using renewable resources form vegetable oils, i. e. palm oil, palm kernel oil, soy-bean oil, sunflower oil, rapeseed oil, linseed oil and castor oil. In term of price, soy-bean oil, palm oil and rapeseed oil are the most attractive ones for the large-scale industrial products (Uldis et. al, 2013).

### 2.4.2 Application of Polyol and Polyurethane Products

Polyols can be used to produce various types of polyurethane products such as ceiling panels, flora foams, wall panels, cushion, flexible foams, automotive parts etc. (Hazimah et. al, 2011). The largest polyurethane production are flexible foams manufacturing. Due to this demand, the application of bio-renewable polyols to manufacture flexible foams is more desirable. Polyurethane produced from palm-based polyol also can be formulated to produce several part to be used in automotive industry such as carpet underlay, pad dash panels and molded car seats.

In fertilizer industry, many efforts were done to produce a fertilizer product that has a coating material and give advantages of slow release of the nutrient and maintain it effectiveness over a long period of time after application. Research carried out by MPOB found that palm-based coated fertilizer have better appearance than uncoated fertilizers and have comparable performance with other coated fertilizers from soy-based and petroleum-based. This development can give a good benefit to the agriculture industry that is involved widely with fertilizer.

All the above applications can be produced using palm-based polyol Apart from that, other products also can be produced using fatty acid-based polyol such as coatings, adhesives and rigid polyurethane foams.

### 2.4.3 Market on Polyol and Polyurethane

The market for vegetable oil-based polyols is growing due to the economic, environment and availability advantages (Kiatsimkul et al., 2008). Polyol are major feedstock material used in the manufacturing of polyurethane. Global polyol market was estimated at $14.4 billion in 2011 and is expected to reach $22.4 billion by 2017. Apart from polyurethanes, polyol also can be use in CASE (coating, adhesive, sealants and elastomers) manufacturing. Some of the major players are BASF, Bayer MaterialScience, Dow Chemical Company, Huntsman Corporation, Perstorp AB, Shell Chemicals, Stepan Company and etc. The evolution of the polyols industry, its expansion to new applications with the success in matching new market and also the sustainability requirements is strongly related to the continuous development of the polyol chemistry.

Generally, polyol is a major feedstock material used in the production of polyurethane. Polyurethane (PU) is any polymer consisting of a chain of organic units joined by urethane (carbamate) links. Polyurethane polymers are formed through polymerization process by reacting a monomer containing at least two isocyanate functional group with another monomer containing at least two hydroxyl groups in the presence of a catalyst. PU foams constitute the largest category of cellular polymeric materials. They are produced, for the most part, either in flexible or in rigid form. Within these major groups, the density and other properties vary depending on the end use. PU foams offer an attractive balance of performance characteristics (aging properties, mechanical strength, elastic properties, chemical resistance and insulating properties) and cost.

For some applications, foams that have some stiffness and some elasticity are produced; in the trade, they are called semi flexible or semi rigid foams. Flexible polyurethane foam is used primarily as a cushioning material in furniture, transportation and bedding applications. Rigid polyurethane foam is utilized mainly as an insulation material in construction and refrigeration/freezer applications. Flexible polyurethane foams account for 54% of global consumption, but the split with rigid polyurethane foams varies by region. Rigid foams constitute more than 50% of total polyurethane foam consumption in China and Mexico, which are important manufacturing sites for refrigerators and freezers.

**Table 2.4: Global production of polyurethane by regions.**

| Region | 2005 (%) | 2006 (%) |
|---|---|---|
| Asia Pacific | 14 | 14 |
| Eastern Europe | 3 | 5 |
| Western Europe | 24 | 21 |
| China | 21 | 26 |
| NAFTA | 28 | 24 |
| South America | 3 | 3 |
| Middle East & Africa | 6 | 7 |
| Total (in million tonnes) | 13.7 | 16.9 |

Note: NAFTA = North American Free Trade Agreement

Form a survey by IAL Consultants, world production of polyurethane in 2005 was about 13.7 million tonnes and it will be estimated to 16.9 million tonnes in 2010. The growth is driven by demands in Eastern Europe, China and Middle East (Table 2.4). The following pie chart (Figure 2.5) shows the world consumption of polyurethane foams by the survey from SRI Consulting in 2009.

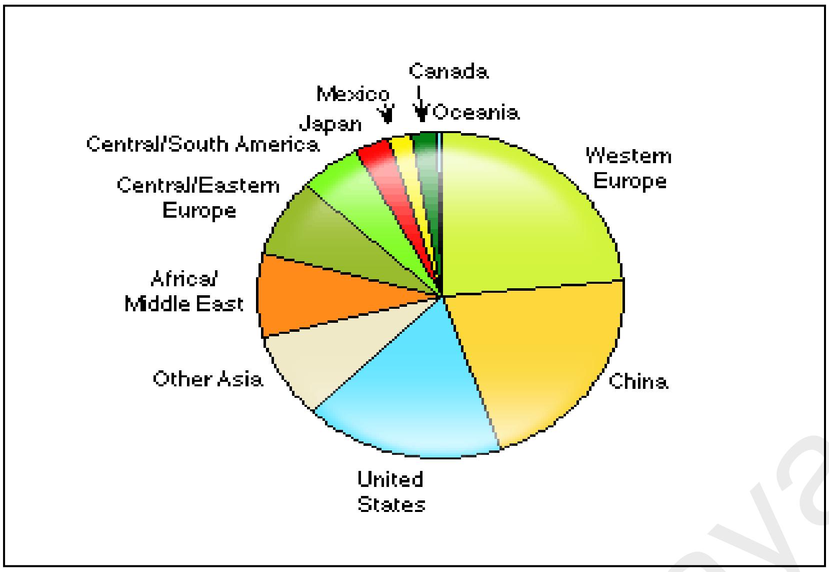


**Figure 2.5: World consumption of polyurethane foams in 2008.**

The global recession of 2008 to 2009 has significantly reduced demand for polyurethane foams in most countries and regions. Demand in 2009 was down by 3–35% depending on the product and country or region. Some companies, especially old and/or small production facilities, are expected to shut down permanently and others with multiple manufacturing sites could close some capacity. For most regions of the world, demand for flexible polyurethane foams is expected to grow at an average annual rate of about 2–4% from 2008 to 2013. Demand for rigid foams will grow at a faster rate. However, assuming that most countries will face drastic drops in 2009 demand (0–5% in the strongest economies to 5–20% in the United States and Western Europe), average annual growth rates of 5–15% are forecast for 2009–2013 (Chinn *et. al.*, 2009). Huge opportunities lie in Asia Pacific for polyol as the demand for PU is growing at a rapid pace there mainly from emerging economies like China and India. North America and Europe are considered to be mature markets for PU and polyol since there are market is growing at a slower rate. But, the demand from Asia Pacific, Latin America and Eastern Europe will be drive the polyol market in the future (Sheela, 2012).

The polyol and polyurethane market has grown well in several previous years. According to the IAL Consultant (2011), the production of the polyols has increased quickly in East Asia, especially in China. Total production capacity of the polyols is estimated to be 352 kilotonne per annum in East Asia in 2009; about 60% of this capacity is in China. In Malaysia, three large manufacturers on polyol which are Maskimi Polyol, Wansern Biotechnology Sdn. Bhd and PolyGreen Chemicals (Malaysia) Sdn. Bhd. have successfully develop palm oil based polyols to serve the local foamers as well as exports. The estimate supply and demand for standard polyether polyols and polyester polyols in South East Asia as for 2014 is shown in Table 2.5.

**Table 2.5: Forecast polyol demand in South East Asia by country, 2014 (tonnes).**

| Country | Standard Polyether Polyol | Polyether Graft Copolymer Polyol | PTHF Polyol | Acrylic Polyol | Polyester Polyol | Total |
|---|---|---|---|---|---|---|
| Australia | 23,561 | 2,171 | 308 | 1,722 | 4,254 | 32,016 |
| Indonesia | 18,769 | 656 | 606 | 3,821 | 5,741 | 29,593 |
| Malaysia | 35,381 | 1,685 | 1,016 | 1,528 | 3,572 | 43,182 |
| Philippines | 8,892 | 471 | 21 | 347 | 554 | 10,285 |
| Singapore | 14,830 | 621 | 6,219 | 4,947 | 26,909 | 53,526 |
| Thailand | 46,295 | 2,413 | 20 | 9,491 | 10,561 | 68,780 |
| Vietnam | 11,133 | 286 | 11,166 | 1,670 | 12,186 | 36,441 |
| New Zealand | 1,786 | 171 | 0 | 15 | 25 | 1,997 |
| **Total** | **160,647** | **8,474** | **19,356** | **23,541** | **63,802** | **275,820** |

*Note: PTHF – polytetrahydrofuran*

Global polyol market now is expecting to reach 10.4 million tonnes by 2018 and PU market also expecting to reach USD 66.4 billion in 2018 (Transparency Market Search, 2013). The market growth for both polyol and polyurethane is a good sign for the polyol industry to expanding and promoting their product.

## 2.5 Previous Study on LCA for Oil Palm Industry

There are several studies have been carried out for oil palm crop. In 2006, Malaysian Palm Oil Board (MPOB) embarked on a full LCA study of the Malaysian oil palm products from mineral soils including palm biodiesel (Figure 2.6). Halimah et al. (2010) had performed LCA study on oil palm seedling production which produced for the cultivation of palms in plantations. The production of high quality oil palm seedlings is very much dependent on good nursery management and practices. The study starts at the pre-nursery stage, before transferred to the main nursery then to plantation for transplantation. The major or significant impact from the study is ecotoxicity, mainly due to emissions from pesticides that used for fungi, insects and weeds infesting oil palm seedlings at the nursery stage. Then, it followed by fossil fuels and respiratory inorganics impact categories. In general, the production of oil palm seedlings has no significant impact to the environment.

The LCA study on oil palm industry also carried out on the oil palm plantation. Zulkifli et al. (2010) had identified the potential environmental impacts associated with the production of fresh fruit bunches (FFB) from specific operations in Malaysian oil palm plantations by considering continued land use as scenario study. The study found that the fossil fuels, respiratory inorganics and climate change are the hotspots in the FFB production. These impacts related to the contribution from the various fertilizers production and usage, use of machinery and transportation during the operations in the plantation.

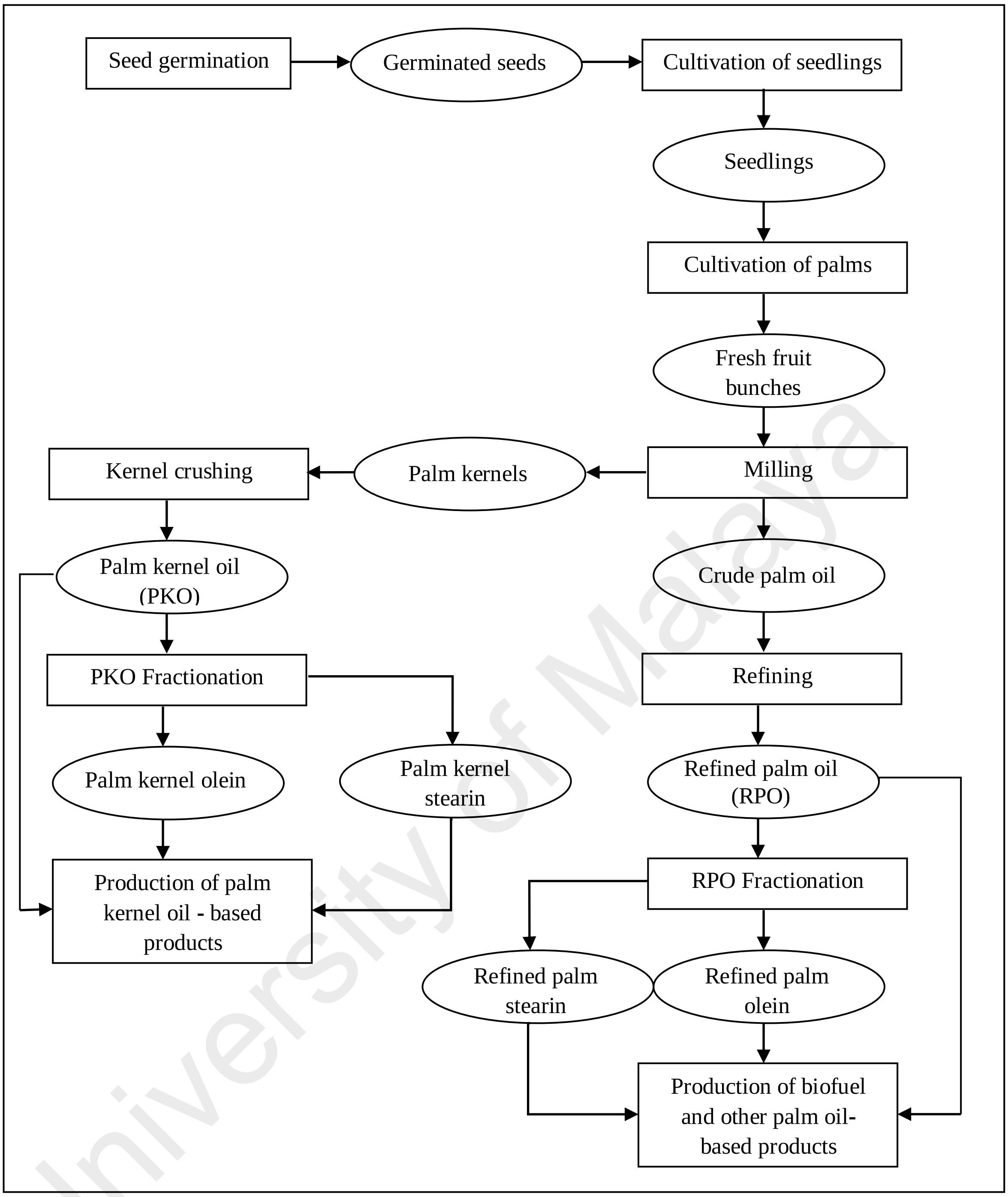


**Figure 2.6: System boundary of the Malaysian oil palm LCA studies.**

LCA study by Jannick (2010) also showed that palm oil is environmentally preferable to rapeseed oil within ozone depletion, acidification, eutrophication, photochemical smog and land use. The most significant process contributing to global warming are oil palm cultivation and palm oil mill (effluent treatment). However, study by Vijaya et al. (2010) showed that global warming caused by the palm oil mill effluent

(POME) can be reduced by implementing the biogas capture facility/system at the palm oil mill. The GHG emissions that contribute to the global warming will drop significantly if biogas is captured.

Through LCA studies, the sustainability of oil palm supply chain with the best scenario and approach has been proven. As mentioned by Vijaya et al. (2010), a better alternative to achieve the best environmental performance in the production of crude palm oil (CPO) is to process fresh fruit bunch (FFB) from plantations that have been replanted with oil palm practicing continued land use, to capture biogas at the palm oil mill effluent (POME) anaerobic ponds and then to use it to generate renewable energy.

This LCA study on oil palm was supported by Sumiani and Sune (2007) which was carried out on the feasibility study on CPO performance in Malaysia. In her study, she found that the continuous environmental improvements are necessary for oil palm industry in order to remain competitive for new challenges ahead. It also stated that the most significant impact categories with crude palm oil production are mainly from fossil fuels and respiratory inorganics with global warming and acidification/eutrophication as outsider impacts. This fact was also proven by Vijaya et al. (2010) through her study on the crude palm oil production. All the necessary point that was highlighted in Sumiani's study has been considered in Vijaya's study.

Apart of that, Vijaya et al. (2010) also conducted LCA study on the production of crude palm kernel oil (CPKO) that produced from palm kernel which are a by-product from the CPO production. CPKO is obtained by a simple mechanical pressing method using a continuous screw press. The study reported that the main impact contributors to the CPKO production were from upstream activities which were identified as fertilizer production and application plus biogas emissions. Vijaya et al. (2010) also suggested that the best approach for CPKO production with the least environmental impact is by integration of kernel-crushing plant with palm oil mill.

There also have some LCA studies on midstream product such as refined palm oil (RPO), refined palm olein (RPOo) and refined palm stearin (RPOs) which were reported by Yew et al. (2010). In RPO production, the impact to the environment is associated with the upstream activities at the oil palm plantation and palm oil mill. However, there is a minor impacts on the environment have be found in the productions of RPOo and RPOs. Even biodiesel form palm-based also had been studied (Puah et al., 2010). The study observed that the environmental impact from the production of palm biodiesel is related to the use of methanol, while the use of palm biodiesel contributes impact to the respiratory inorganics and acidification/eutrophication impact categories. It also showed that the production and use of palm biodiesel is more environmental-friendly as compared to petroleum diesel.

## 2.6 LCA on Polyol and Polyurethane

Globally, people are looking to develop renewable feedstock mainly for polyurethane (PU) products. The PU market aims for the feedstock that can have a lowest volatile organic carbon (VOC) and also can reduce the carbon dioxide that can contribute to GHG emissions. This kind of PU products will be benefit the consumers and it will provide advantages to the environment and also our society. However, it is a challenge to fulfill all the requirements in order to provide the sustainable PU product ahead. Cost effectiveness, performance, sustainability issues are the aspects that they need to be considered. So, most of the polyol or PU manufacturers work on the LCA is to show how good their products and encourage consumers to choose the better product with better environmental consequences.

To date, there has been no LCA study carried out comprehensively on palm-based polyol. Most of the LCA studies on polyol only covered soybean-based polyol and petroleum-based polyol. Even though there were some LCA reports on polyol from palm feedstock, the information is still minimal.

Pollack (2004) compared the environmental impacts of two soy polyol materials with a conventional petroleum-based polyol. In this study, all stages in the life cycle of a product area were analyzed which included raw material acquisition, manufacture, transportation, use and end of life. The results showed that the environmental impact scores for the two soy polyols is only about one quarter of the petro polyol scores level. The most significant environmental impact was noted for global warming, smog formation, eutrophication, ecological toxicity and fossil fuels depletion. For total fuel energy, soy polyol represented about 11.58 MJ/kg while petroleum-based polyol represented about 61.54 MJ/kg. Based on this value, the lower energy value (MJ/kg) favors the soy polyol material.

Analysis report by Five Winds International for Cargill (2005) found that the total primary energy demand of the soy-based polyol production reduced about 23% compared to the primary energy demand used to manufacture petrol-based polyol product. This reductions are due to the substituting the primary feedstock material, fossil hydrocarbons and with the usage of renewable biogenic material feedstock of soybeans. The potential impact on global climate change were also reduced as well, which was associated with the contribution of the reductions in nonrenewable fossil based fuels. The LCA analysis also found that the production of soy-based polyol product produces 36% less global warming potential emissions than the petrol-based polyol.

In another study, Franklin Associates (2007) conducted life cycle inventory (LCI) on the production of polyether polyol used for rigid foam polyurethane (PU). The average gross energy required to produce the polyether polyol for rigid foam PU is 74.3 GJ per 1,000 kg. The study also reported three atmospheric emissions that contributed to global warming potential, which are carbon dioxide from fossil fuels, methane and nitrous oxide with 2942, 410 and 25.1 kg$CO_2$ equivalents respectively. Carbon dioxide from fossil fuels also contributed the highest impact on atmospheric emissions followed with sulphur dioxide, methane, sulphur oxides, carbon monoxide and nitrogen oxides. While for waterborne emissions, dissolved solids become a main contributor and followed by chlorides.

Franklin Asociates (2007) also conducted a study on the production of polyether polyol used for flexible foam PU. The average gross energy on this production is slightly higher compared to rigid foam PU which is about 85.2 GJ per 1,000 kg. Carbon dioxide from fossil fuels is a main contributor to global warming potential that is about 3105 $CO_2$ equivalent, while methane and nitrous oxide contributed about 507 and 21.1 $CO_2$ equivalent respectively.

Cargill Inc. (2008) reported that their bio-based polyol can reduced about 23% of total primary energy demand with a value of 67.3 MJ/kg polyol. This amount is slightly lower than polyol from petrol-based with a value of 87.9 MJ/kg polyol. The Cargill process also claimed only required 61% less non-renewable primary energy to produce polyol than the polyol from petro-based with 33 MJ/kg and 85 MJ/kg, respectively. The most important is production of Cargill's polyol can reduce about 36% of global warming potential compared to the petro-based polyol.

In 2009, Helling and Russel conducted LCA study on three types of polyol from different feedstock which are petro-based polyol, soy-based polyol and castor-based polyol. This study was carried out as a 'cradle-to-gate' using Boustead Model. The study show the environmental benefits for flexible foam polyols made from soy or castor oil compared to petrochemical. As compared to petro-based polyol, both of the seed oil based polyols managed to used about 33% to 64% of the fossil resources and also generate very low GHG emissions, which is about 46%. The farming model also gives a significant impact to the gas emissions and water use for polyols from soy oil.

Omni Tech International (2010) conducted LCA study for The United Soybean Board to perform an update the cradle-to-gate data for soybean production including soybean processing, refining and conversion into key soy-derived feedstocks (methyl soyate, soy lube base stock, soy polyol and soy resin). It was found that soy-based polyol production is better than the petro-based polyol in most impact categories that was highlighted in the analysis. Result showed that soy-based polyol had much better global warming potential rather than petro-based polyol while it worse than petro-based polyol on ozone depletion potential. The analysis shows that the soy-based feedstock significantly reduced greenhouse gas emissions and cut the use of petroleum compared with similar petroleum-based products (Omni Tech International Ltd., 2010).

In 2011, with the continued innovation due to the increasingly awareness of energy consumption and dependency on the fossil fuels, Cargill has successfully found manufactured soy-based polyol with the 48% to 57% reduction in non-renewable energy comparing to the traditional petroleum-based polyols.

Due to the concern to reduce greenhouse gas (GHG) emissions and fossil fuels depletion, Niklos and Andre (2014) initiated and carried out LCA study of polyols for polyurethane using $CO_2$ as alternative carbon feedstock. They have found that the production of polyols with 20 wt% $CO_2$ in the polymer chains causes GHG emissions of 2.65-2.86 kg $CO_2$ eq per kg polyol and thus, does not act as GHG sink. However, if compared to production of conventional polyether polyols, production of polyols with 20 wt% $CO_2$ allows for GHG reduction of 11-19% and the use of fossil resources can be reduced by 13-16%. They also observed that the impacts reduction increase with the increasing of $CO_2$ content in the polyols. Therefore, the synthesis of polyethercarbonate polyols from $CO_2$ is clearly favorable compared to conventional polyether polyols from an environmental point of view.

In summary, based on the previous LCA studies conducted on polyol and polyurethane production, it can be concluded that LCA findings can be used as one of the tool to evaluate environmental impacts or performance for the specific product production. Most of the studies have shown that the main issue related to the polyol production was from fossil fuels, which can be obtained either from the fossil fuels used (if polyol is produced from petro-based feedstock) or from the energy used during the production itself. The findings also showed that vegetable oil polyols have better environment impact compared to the polyol from non-renewable fossil resources.

# CHAPTER 3: METHODOLOGY

As mentioned in Chapter 1, LCA is one of the technique that had been used to evaluate the performance of products or services. The objectives of this study are to establish life cycle inventory (LCI) of palm-based polyol production using inventory data collected at MPOB Polyol Pilot Plant and also to evaluate and identify the environmental impacts through the life cycle impact assessment (LCIA) for palm-based polyol production at the pilot plant scale as described in Chapter 1. Apart of that, a suggestion to improve the palm-based polyol production also will be highlighted at the end of the study based on the findings obtain through the study. The flow chart of the research process for this study was shown in Figure 3.1. This figure was included all the necessary steps taken during the study from the beginning until the end of the study.

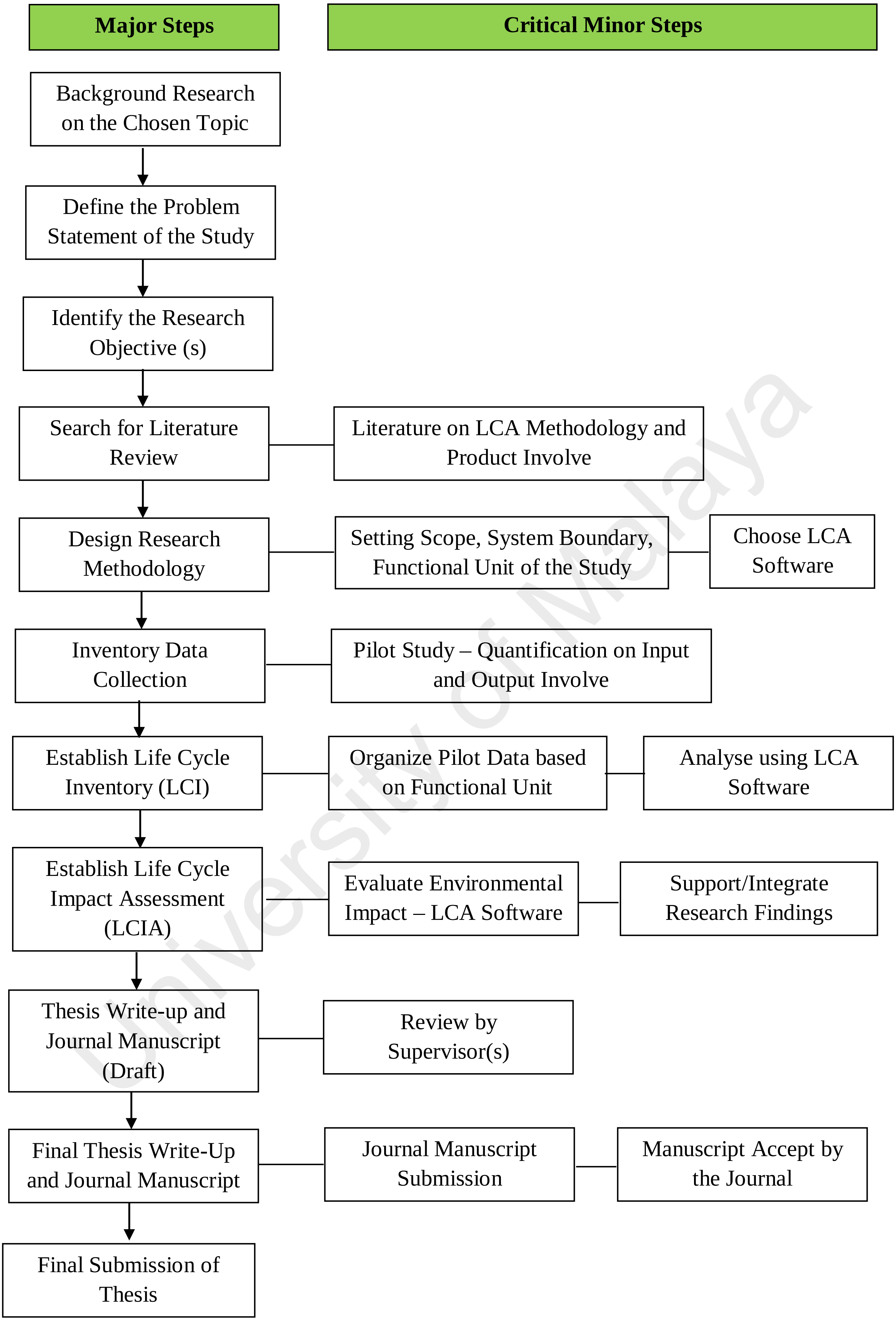


**Figure 3.1: Research process flow chart.**

This methodology follows the steps in the ISO 14040: 2006 Standard on LCA as described in Chapter 2. The flow chart of the methodology that will be used to conduct this LCA study is shown in Figure 3.2.

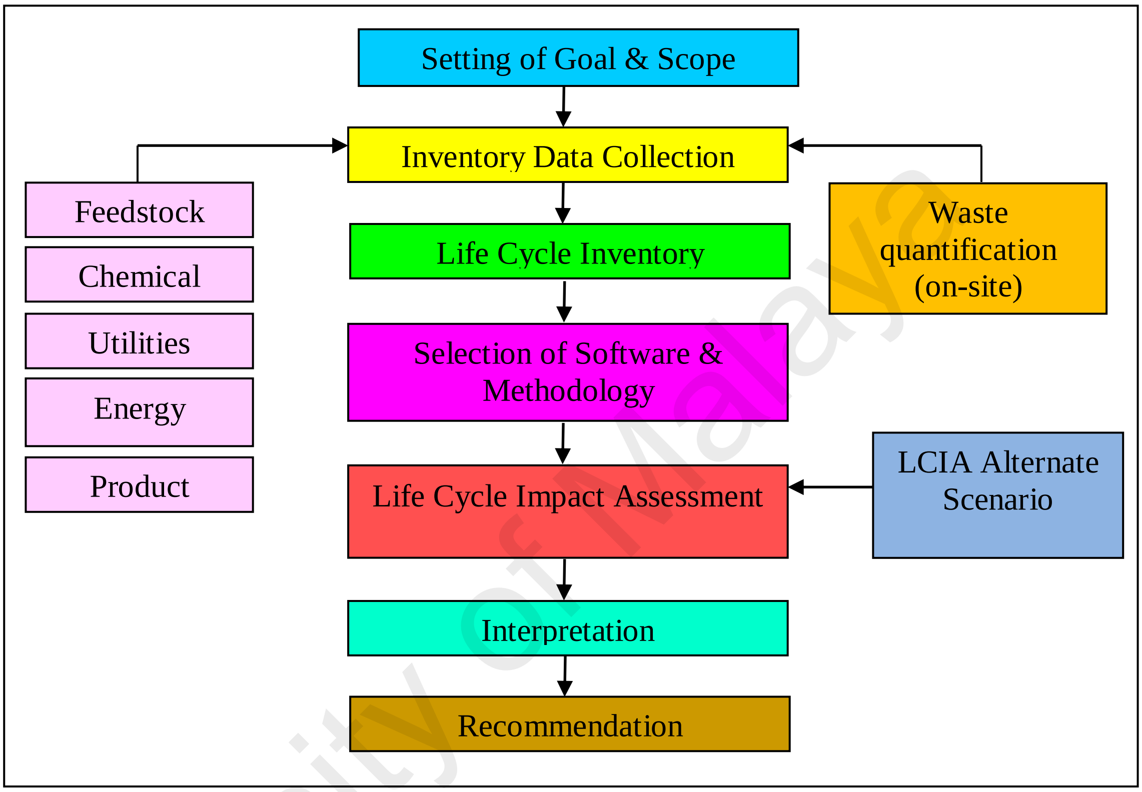


**Figure 3.2: Flow chart of methodology of LCA study.**

## 3.1 Setting Goal and Scope Definition

The goal and scope had been described in Chapter 1 section 1.6. In this study, the system boundary will be the production of the palm-based polyol at the Advanced Oleochemical Technology Division (AOTD) pilot plant as shown in Figure 3.3.

**Figure 3.3: MPOB Pilot Plant Polyol with 500 kg production per batch.**

## 3.2 Functional Unit

In order to conduct this study under the ISO guidelines, data of each unit processes on palm-based polyol feedstock were based on mass basis. The functional unit of this study is 1 tonne of palm-based polyol production.

The study also covers Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) of palm-based polyol production. It focuses on inventory data of production at polyol pilot plant only. This study has been conducted in accordance with the ISO 14040/14044 standards on LCA, which are:

i) ISO 14040:2006 – the International Standard of the International Standardization Organization, Environment management. Life cycle assessment. Principles and framework.

ii) ISO 14044:2006 – Environmental management – Life cycle assessment – Requirements and guidelines.

### 3.3 System Boundary

The LCI data gathered for this study are from gate-to-gate where selected life cycle stages are included in the system boundary. These stages are those within the dotted boundary shown in Figure 3.4.

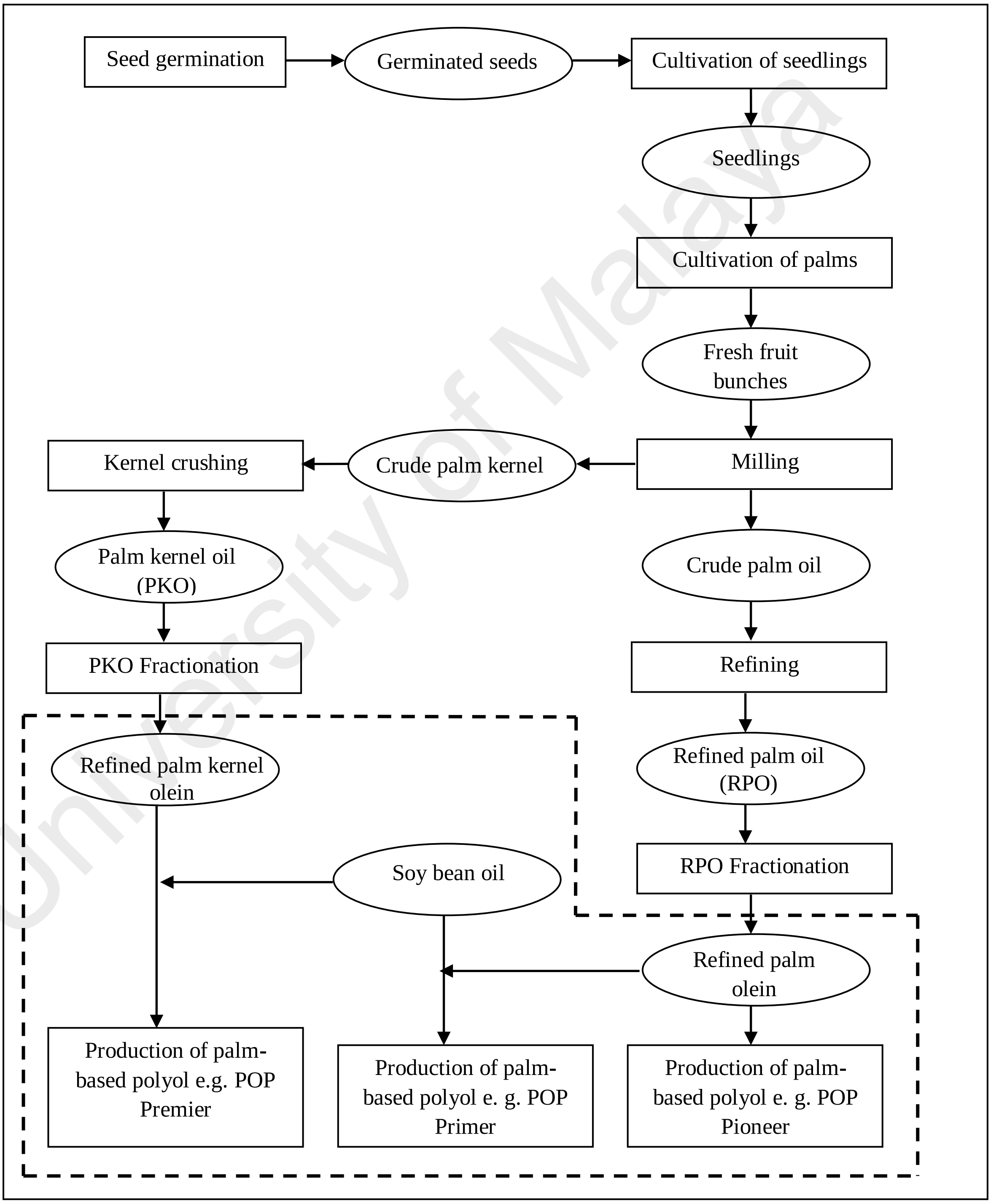


**Figure 3.4: System boundary of palm-based polyol production.**

Generally, the oil palm seedlings are planted in polybags at the oil palm nurseries which are located in Peninsular Malaysia. Basically, all the nurseries practised double-stage nursery system and the seedlings are kept under the shade to protect them from direct sunlight for 10 to 12 months before they are ready for planting in the plantation (Halimah et. al, 2010). In Malaysia, most of the plantations have a continued land use where it take 25 years for one cycle duration of oil palm from planting to replanting trees. Data for the plantations were collected from a detailed survey of the estates throughout Malaysia including private, smallholders and government estates (Zulkifli et. al, 2010). The system boundary also covers the production of crude palm oil at the palm oil mill and crude palm kernel oil at the crushing plant (Figure 3.4) before it is transferred to the refinery. Both of these products finally will be used as feedstocks in the production of palm-based polyol.

### 3.4 Inventory Data Collection

This study has a cradle-to-gate study which covers the whole production which is from upstream oil palm activities (including nursery, plantation, milling and refinery) until the dried polyol production (including epoxidation and alcoholysis processes). All the input and output for this study are as shown in Figure 3.5.

All the data was collected for palm-based polyol production at MPOB Pilot Plant Polyol. All the wastes and emissions from this production will be taken into consideration for impact assessment quantification. Later, the LCA study on 'gate-to-gate' of palm-based polyol production will be linked to the upstream production in order to produce the complete cycle of 'cradle-to-gate' of palm-based polyol production. The upstream input and output data were from MPOB palm oil database which is representing Malaysian database on oil palm industry.

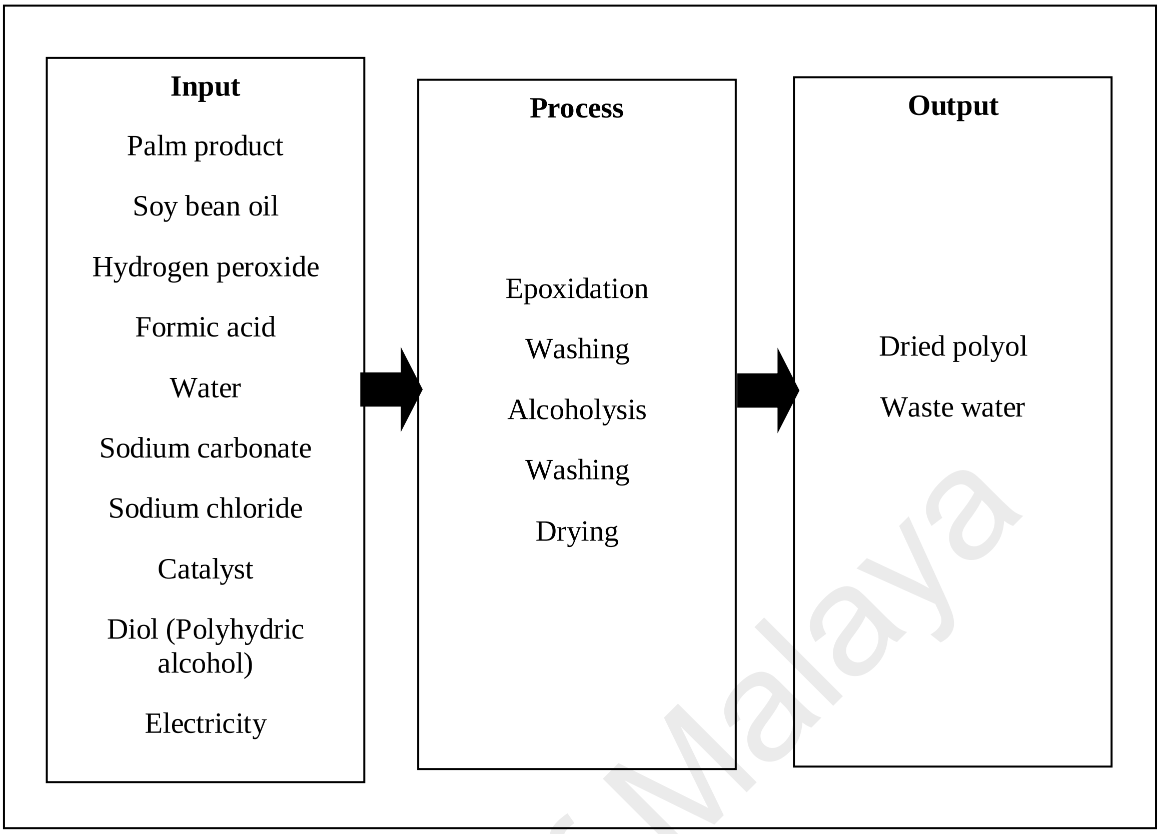


**Figure 3.5: Input and output for 'gate-to-gate' of palm-based polyol production.**

In general, a process for producing oleochemical polyols involves epoxidizing unsaturated oil using an organic acid together with oxygenated water or a per-acid to obtain epoxidized oil. Then the epoxidized oil will be washed using salt water to remove unused organic acid together with oxygenated water or per-acid. After the washing process, the washed epoxidized oil will be neutralized to acidic condition with a base. The neutralized epoxidized oil will be re-washed with a salt solution until the pH of the neutralized epoxidized oil reaches 6.5 to 7.5 to ensure the base residue is removed. The washed neutralized epoxidized oil will be dried under vacuum before it is reacted with the polyhydric alcohol in the presence of catalyst to obtain the polyols. A summary of the general process for the production of polyols is as shown in Figure 3.6. (Abu Hassan et al., 2011).

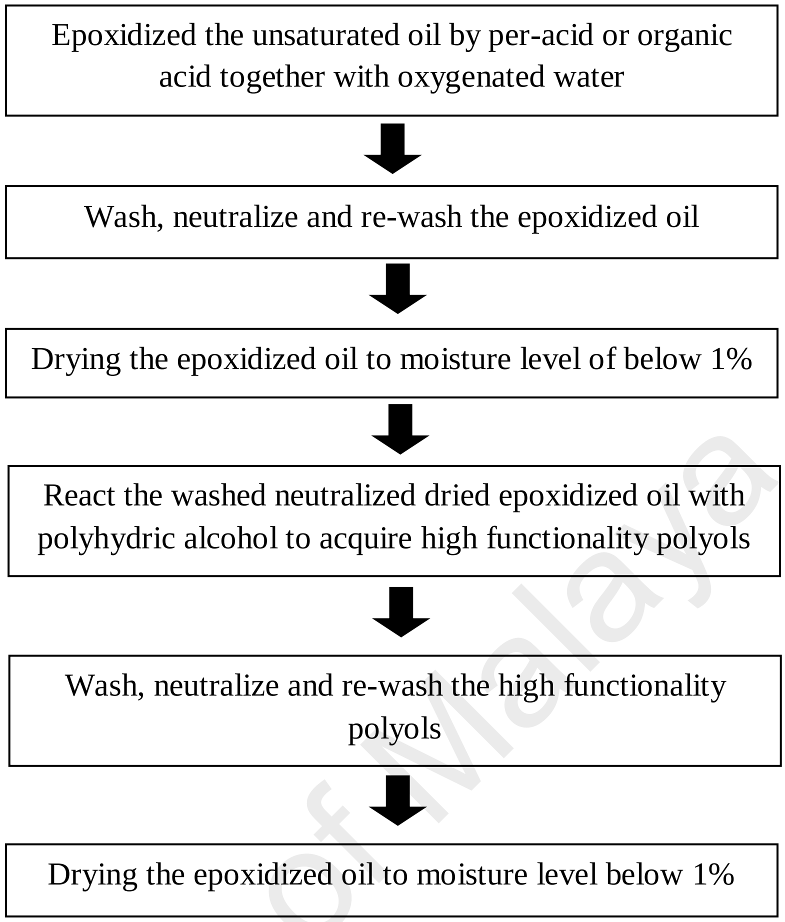


**Figure 3.6: General process of production of polyols (Abu Hassan et al., 2011).**

For this study, the iodine value is one of the important parameter that needs to be considered for each of the feedstocks which are refined palm olein, refined palm kernel olein and soy bean oil. The suggested iodine value for the above feedstocks is as shown in Table 3.1 below.

**Table 3.1: Iodine value for palm-based polyol feedstocks.**

| Feedstock | Range of iodine value (IV) (g $I_2$/100g sample) |
|---|---|
| Refined palm olein | 56 - 60 |
| Refined palm kernel olein | 25 – 29 |
| Soy bean oil | 130 - 135 |

The amount of chemicals i. e. formic acid and hydrogen peroxide were directly proportional with the amount of feedstock use during the production. Temperature during the epoxidation reaction was set-up between 55°C to 65°C. Since, this reaction is an exothermic reaction, so the reaction temperature needs to be controlled to avoid the overheating during the reaction. During the epoxidation process, hydrogen peroxide was added slowly (one kg for every minute) to a mixture of oil and formic acid through in-situ reaction inside the reactor with the pressure of 0.7 to 0.8 bar. The flow rate of hydrogen peroxide was set at 10kg/10min. If the flow rate is exceeding, the reaction can be exploded. Spent acid was collected at this stage which is then accumulated as waste water from epoxidation process.

Epoxidized palm oil (EPO) obtained from the epoxidation reaction needs to wash using a base i. e. sodium chloride and sodium carbonate until it reaches pH 6 to 7. Before washing the EPO with the base solution, the EPO was firstly washed using water to remove the excess acid solution from the reaction. Water used for the whole production is from tap water that is supplied by SYABAS. The electricity used is from the national grid which is from Tenaga Nasional Berhad (TNB) and is used for several equipments which are reactors, pumps, cooling tower motor, and electrical boiler.

## 3.5 Data Sources and Data Quality

Background data which include information on generic materials such as soy bean oil, hydrogen peroxide, formic acid, sodium carbonate, sodium chloride, catalyst, polyethylene glycol, water and energy were obtained from published sources or proxies which have the same operation but are mainly used in another country, and also have validated life cycle inventory database with specific laboratory test results, equipment and processes. Sources of data were also obtained from Ecoinvent database (Swiss

Centre for Life Cycle Inventories, 2005) packaged in SimaPro version 8.0.2 (**S**ystem for **I**ntegrated environ**M**ental **A**ssessment of **PRO**ducts).

Foreground data for each unit process were collected directly from the polyol pilot plant (site-specific). Inventory data was collected for three cycles (which is associated with waste quantification) for each type of polyol. In order to ensure the credibility and validity of the data, another three cycle's data production was taken into account for each type of polyol. The period of data collection was from year 2010 until year 2013. The data were then averaged to derive a set of generic data representing the polyol production at pilot plant scale. For each data set, the period during which the data were collected and how the data were collected were documented (Table 3.2).

**Table 3.2: Polyol product system and the associated data type/source (data collected in the period 2010-2013).**

| Process gate | Unit process | Process starts | Nature of transmission | Process ends | Data type (B/F)/ data source |
|---|---|---|---|---|---|
| Epoxidation process | Transportation refined palm/ palm kernel olein from the refinery | Collection of refined palm/ palm kernel olein from the refinery | Physical | Delivery of refined palm/ palm kernel olein to pilot plant polyol gate | F / site specific data |
| Epoxidation process | Refined palm / palm kernel olein production | Cradle-to-gate of palm/ palm kernel olein production | Physical and chemical processing | Refined palm/ palm kernel olein at the production unit gate | F/ Palm Oil database (in Ecoinvent database) |
| Epoxidation process | Transportation soy bean oil from the supplier | Collection of soy bean oil from the supplier | Physical | Delivery of soy bean oil to pilot plant polyol gate | F / Ecoinvent database |
| Epoxidation process | Soy bean oil production | Cradle-to-gate of soy bean oil production | Physical and chemical processing | Soy bean oil at the production unit gate | B/ Ecoinvent database |

**Table 3.2, continued**

| Process gate | Unit process | Process starts | Nature of transmission | Process ends | Data type (B/F)/ data source |
|---|---|---|---|---|---|
| Epoxidation process | Electricity production | Mining and extraction of fossil fuels | Physical | Distribution to grid at the points of use | B/ Ecoinvent database |
| Epoxidation process | Electricity usage | Pilot plant polyol gate | Energy conversion | Points of use at the epoxidation and other process unit gate | F/ site specific data |
| Epoxidation process | Hydrogen peroxide production | Acquisition of raw materials | Physical and chemical processing | Hydrogen peroxide at the production unit gate | B/ Ecoinvent database |
| Epoxidation process | Hydrogen peroxide usage | Hydrogen peroxide at pilot plant store | Physical | Hydrogen peroxide at epoxidation reaction gate | F/ site specific data |
| Epoxidation process | Formic acid production | Acquisition of raw materials | Physical and chemical processing | Formic acid at the production unit gate | B/ Ecoinvent database (adopted acetic acid data background) |
| Epoxidation process | Formic acid usage | Formic acid at pilot plant store | Physical | Formic acid at epoxidation reaction gate | F/ site specific data |
| Washing process | Water supply (for washing purpose) | From tap water source | Physical and chemical processing | Delivery water at water usage gate | B/ Ecoinvent database |
| Washing process | Water usage | Pilot plant polyol gate | Physical | Water consumption at epoxidation and alcoholysis reaction gate | F/ site specific data |
| Washing process | Sodium chloride production | Acquisition of raw materials | Physical and chemical processing | Sodium chloride at the production unit gate | B/ Ecoinvent database |

**Table 3.2, continued**

| Process gate | Unit process | Process starts | Nature of transmission | Process ends | Data type (B/F)/ data source |
|---|---|---|---|---|---|
| Washing process | Sodium chloride usage | Sodium chloride at pilot plant store | Physical | Sodium chloride at washing gate | F/ site specific data |
| Washing process | Sodium carbonate production | Acquisition of raw materials | Physical and chemical processing | Sodium carbonate at the production unit gate | B/ Ecoinvent database |
| Washing process | Sodium carbonate usage | Sodium chloride at pilot plant store | Physical | Sodium carbonate at washing gate | F/ site specific data |
| Washing process | Waste water production | Waste water from washing process of EPO and crude polyol | Physical | Waste water at washing gate | F/ site specific data |
| Alcoholysis process | Diol production | Acquisition of raw materials | Physical and chemical processing | Diol at the production unit gate | B/ Ecoinvent database |
| Alcoholysis process | Diol usage | Diol at pilot plant store | Physical | Diol at alcoholysis gate | F/ site specific data |
| Alcoholysis process | Catalyst production | Acquisition of raw materials | Physical and chemical processing | Catalyst at the production unit gate | B/ Ecoinvent database |
| Alcoholysis process | Catalyst usage | Catalyst at pilot plant store | Physical | Catalyst at alcoholysis gate | F/ site specific data |
| Drying process | Dried polyol production | Crude polyol from washing gate | Physical | Dried polyol and waste water at drying gate | F/ site specific data |
| Drying process | Waste water collection | Waste water from drying of dried polyol | Physical | Waste water (to discharge) | F/ site specific data |

### 3.6 Items Excluded from the Study

In the environmental assessment, processes are excluded if they are judged to have an insignificant contribution (<1%) to the overall environmental load; if representative data for the processes are extremely difficult or impractical to gather; if the processes are clearly part of a separate product system; and if the processes are not relevant to the goal of the study. The production of capital goods as machineries, buildings, vehicle manufacturing, vehicle maintenance and disposal, transport infrastructure and waste treatment also excluded as mentioned earlier in Chapter 1.

### 3.7 Sampling of Palm-based Polyol

There are three types of palm-based polyol which was identified as a final product from the production which are POP Pioneer, POP Primer and POP Premier. The palm-based polyol production has two separate reactions where the first is epoxidation of palm oil and followed by the alcoholysis of the epoxidized palm oil before the production of palm-based polyol. The reaction using palm kernel oil as an example is as shown in Figures 3.7, 3.8 and 3.9:

$$\underset{\text{Hydrogen peroxide}}{H_2O_2} + \underset{\text{Formic acid}}{HCOOH} \longrightarrow \underset{\text{Water}}{H_2O} + \underset{\text{Performic acid}}{HCOOOH}$$

**Figure 3.7: Oxidation reaction between hydrogen peroxide and formic acid to form performic acid.**

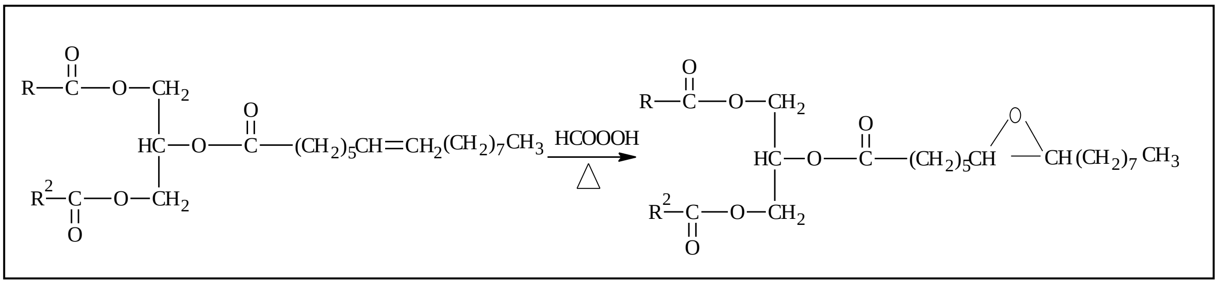

**Figure 3.8: Epoxidation reaction of palm kernel oil with performic acid.**

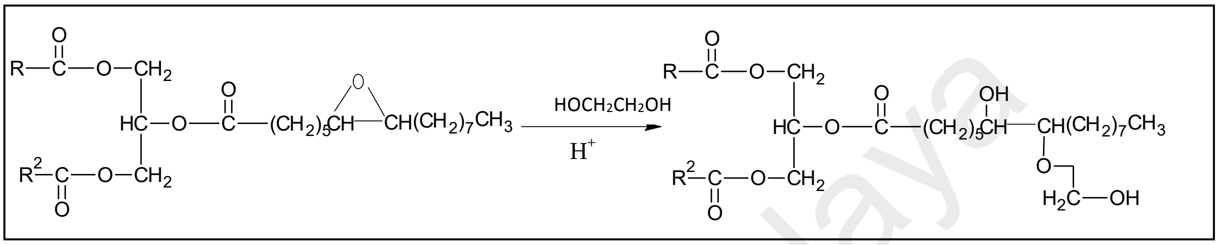

**Figure 3.9: Alcoholysis reaction of epoxidized palm oil to form polyester polyol.**

During the epoxidation process (Figure 3.8), the palm products or their oil blending will be reacted with hydrogen peroxide with the presence of formic acid to form epoxidized palm oil (EPO). The EPO will react with diol (as example: polyethylene glycol (PEG)) during the alcoholysis to form polyester polyol. This alcoholysis reaction involves breaking the epoxy ring by PEG to form polyol with OH group. The energy for the production is calculated from the electricity consumption during the production including electricity and power for machinery and others facilities in the polyol pilot plant. Three different case studies were carried out for this study and they are as follows:

i) POP Pioneer production.

ii) POP Primer production.

iii) POP Premier production.

### 3.7.1 POP Pioneer Production

POP Pioneer is a palm-based polyol that is produced from totally refined palm olein as a feedstock. The process flow chart of POP Pioneer is as shown in Figure 3.10.

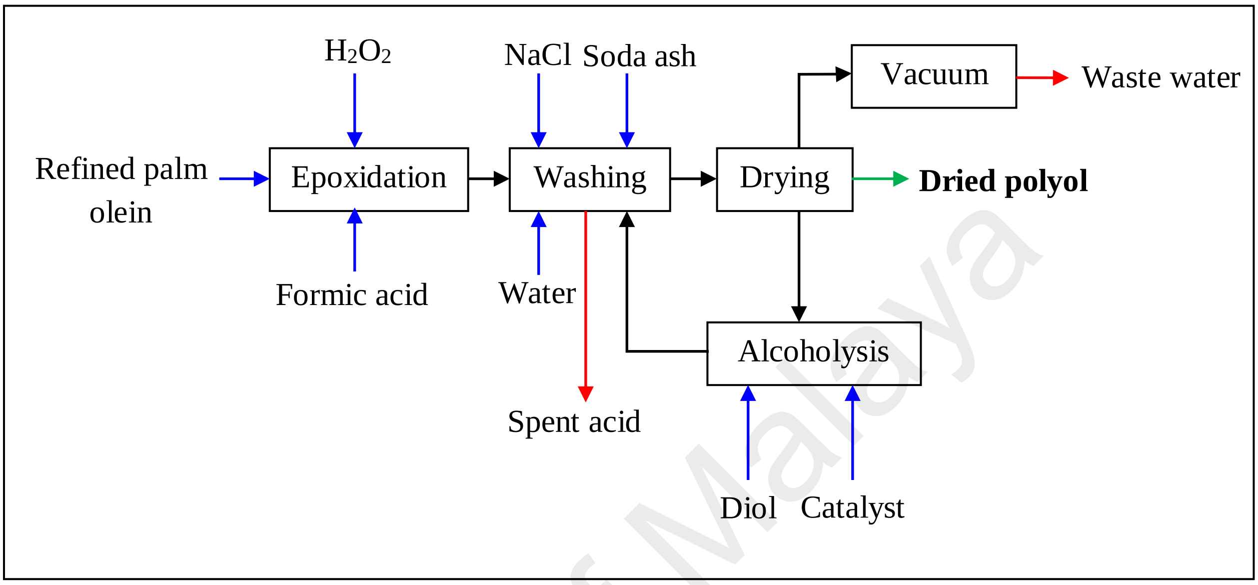


**Figure 3.10: Process flow chart for POP Pioneer production.**

### 3.7.2 POP Primer Production

POP Primer is a palm-based polyol that is produced using two types of feedstock, i. e. refined palm olein and soy bean oil with specific blending ratio. The process flow chart of POP Primer is as shown in Figure 3.11.

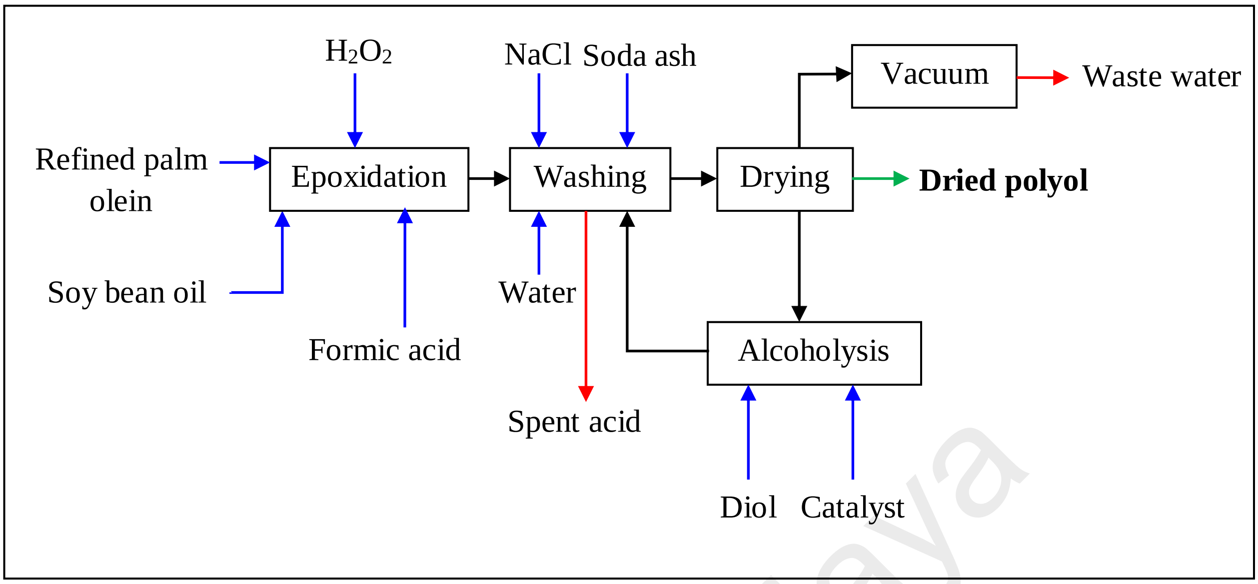


**Figure 3.11: Process flow chart for POP Primer production.**

### 3.7.3 POP Premier Production

POP Premier is a palm-based polyol that is produced from specific blending ratio between two types of feedstock, i. e. refined palm kernel olein and soy bean oil. The process flow chart of POP Primer is as shown in Figure 3.12.

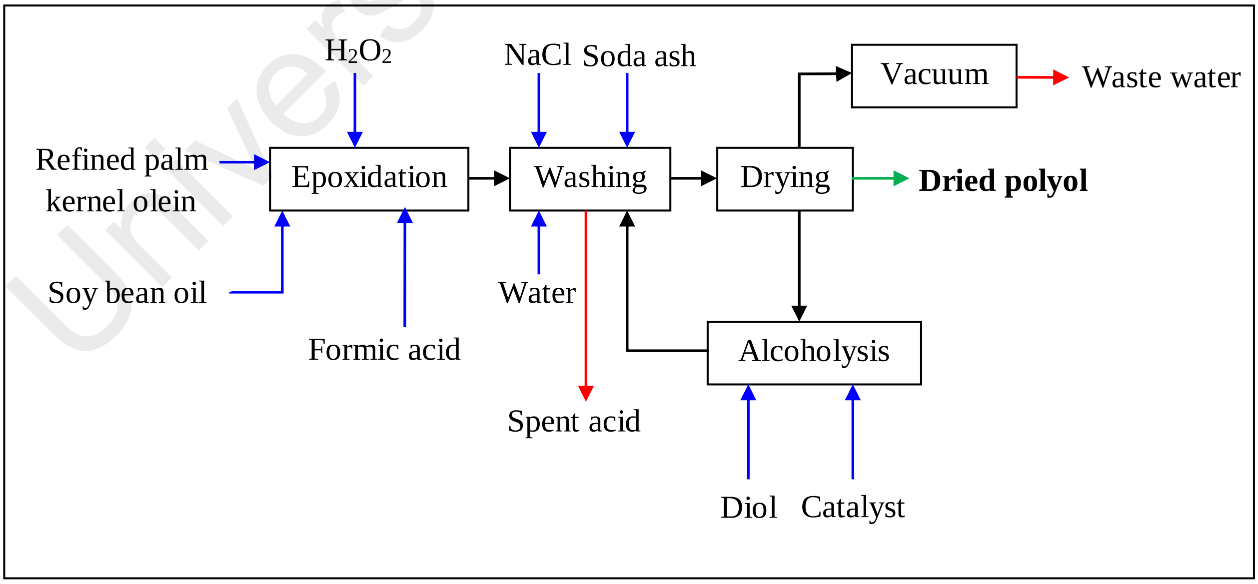


**Figure 3.12: Process flow chart for POP Premier production.**

## 3.8 Scenarios Study

Four scenarios were carried out for each palm-based polyol products (POP Pioneer, POP Primer and POP Premier) based on the methodology chosen for this study as shown in Table 3.3.

**Table 3.3: Scenarios study of palm-based polyol production.**

| Scenario | Criteria | Rationale |
|---|---|---|
| Scenario 1 | Production of palm-based polyol using continued land use (oil palm to oil palm) with biogas capture | Base case study for palm polyol (using common practice for oil palm upstream studies) |
| Scenario 2 | Production of palm-based polyol using continued land use with biogas capture and substitution of electricity with oil palm biomass as an energy source | Alternative scenario – electricity contribute highest impact; replacement of energy source (energy from national grid) to reduce GHG |
| Scenario 3 | Production of palm-based polyol using continued land use with biogas capture and substitution of diol with glycerol | Alternative scenario – use of glycerol to substitute diol in the production due to abundant source of glycerol |
| Scenario 4 | Production of palm-based polyol using continued land use (oil palm to oil palm) with biogas emissions at the palm oil mill | Sensitivity analysis scenario |

## 3.9 Selection of LCA Software

There are many LCA softwares that can be used to conduct LCA as mentioned in Chapter 2 section 2.4. The SimaPro software was selected for this study since all the upstream oil palm studies were carried out using this software and Eco-indicator 99 was chosen as methodology. In MPOB, SimaPro was used to evaluate all LCA studies from nursery, plantation, milling, refinery, biodiesel and etc. Thus, the continuous use of this software can harmonize the result of this study by linking up the current study on palm-based polyol with the other upstream and midstream studies of oil palm industry.

### 3.10 Selection of Impact Categories

Eco-indicator 99 was chosen for this LCA study. As mentioned in Table 2.1, there are several impact categories that are normally used to evaluate the environmental performance of products. So, for this study 11 of the impact categories was considered as listed below:

i) Carcinogens
ii) Respiratory organics
iii) Respiratory inorganics
iv) Climate change
v) Radiation
vi) Ozone layer
vii) Ecotoxicity
viii) Acidification
ix) Land use
x) Mineral
xi) Fossil fuels

The details of each impact category have been described in detail in Chapter 2.

### 3.11 Malaysian Database in SimaPro version 8.0.2

SimaPro version 8.0.2 was used for this study and this software was developed in Europe specifically for the use in Europe. The database is all European based data with some global data. Due to this all the normalization and weighting factors are on European levels. However, the data on oil palm database was from Malaysian Palm Oil Board (MPOB) and it was accepted and established as National Database for Oil Palm Industry. Some of these data was used in this study especially in the upstream study.

### 3.12 Greenhouse Gas (GHG) Inventory

GHG is a gas in the atmosphere that absorbs and emits radiation within the thermal infrared range. Each GHG has active radiative or heat-trapping properties. Water vapour (H2O), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4) and ozone (O3) are the primary greenhouse gases in the Earth's atmosphere (Vijaya et. al., 2010). Beside CO2, N2O and CH4, the Kyoto Protocal also deals with the sulphur hexafluoride (SF6), hydrofluorocarbon (HFCs) and perfluorocarbons (PFCs).

The GHG will be calculated using the Global Warming Potential (GWP) index. GWP is the ability of a GHG to trap heat in the atmosphere relative to an equal amount of carbon dioxide. The GWP indexes are as shown in Table 3.4 which was taken from IPCC TAR, 2007. Meanwhile, GHG for electricity will be calculated using the Emission Factor which was taken from Wisions Sustainable Energy Support Program SEPS, 2009 as shown in Table 3.5.

**Table 3.4: Global warming potentials for selected greenhouse gases.**

| Greenhouse Gas (GHG) | Global Warming Potential (GWP) for 100 years |
|---|---|
| CO2 | 1 |
| CH4 | 23 |
| N2O | 296 |
| HFC-23 | 12000 |
| HFC-134a | 1300 |
| SF6 | 22200 |

**Table 3.5: Emission factor.**

| Energy | Emission Factor |
|---|---|
| Electricity | 0.000594 t $CO_2$ eq kWh-1 |

## 3.13 Interpretation of the Results

Using the results and the methodology, the LCIA for the study was interpreted. The results and interpretation will be discussed in detail in Chapter 4.

# CHAPTER 4: RESULTS AND DISCUSSION

As mentioned in Chapter 3, there are three types of palm-based polyol products which are POP Pioneer, POP Primer and POP Premier which will be assessed using the LCA approach. For this study, three production cycles were carried out in order to obtain a constant and reliable data set for each palm-based polyol production.

The functional unit for this study is one tonne of palm-based polyol product. This choice was made because most of the LCA studies on polyol from petro-based and soy-based are based per on one tonne of product. Therefore, this functional unit was chosen to make it compatible and standardized with other LCA polyol studies. The discussion for each of palm-based polyol products were explained based on their case study respectively.

## 4.1 Data Sources and Data Quality of Palm-based Polyol Production

The inventory data was collected for a period of three years. The data validation procedure was carried out by on-site and actual measurements. Data used in this study are a combination of primary and secondary data. Primary data were obtained during the actual plant production such as raw materials, wastes and energy consumption. Secondary data are related to the processes used, for example process manufacturing of raw materials and some of the data which was derived from Ecoinvent database. All relevant background data such as energy, transport and auxiliary material are taken from the Ecoinvent database. For each data set, the period during which the data were collected and how the data were collected were documented as shown in Chapter 3 Table 3.1.

## 4.2 Life Cycle Inventory (LCI)

The inventory data was based on the three types of polyol production. As mentioned in Chapter 3, the LCI study was based on gate-to-gate of palm-based polyol production without considering inventory data from upstream and midstream oil palm studies. Thus, the study gate begins with the transportation of refined palm olein/ refined palm kernel olein/ soy bean oil to the pilot plant gate, and ends with the production of palm-based polyol.

In the analysis under the contribution from transport, all distances are considered as half of a round trip and truck (lorry) loads are full load weight and make empty return trips. The transportation involved is an important component in this LCA study as it is a significant resource consumption and GHG emitting process. Quantification of the environmental load from transportation is determined by using the Ecoinvent database.

Transportation of chemicals i. e. formic acid, hydrogen peroxide, sodium chloride, sodium carbonate and diol were accumulated between these five chemicals since it was purchased from the same chemical manufacturer. Energy used by chemical processes in the production of palm polyol i. e. epoxidation, washing, drying and alcoholysis, was calculated based on operating hour for all the equipments and utilities at palm-based polyol plant. There were no emissions produced during the chemical processes; assuming the chemical reactions during the production were under control and completely reacted.

Apart from the data within the palm-based polyol boundary itself, this study also used primary data from the upstream and midstream activities of the oil palm industry as listed in Table 4.1.

**Table 4.1: Inventory data sources for palm-based polyol study.**

| Life cycle stage | Data source |
|---|---|
| Oil palm nursery | Halimah et. al. (2010)[11] |
| Oil palm plantation | Zulkifli et. al. (2010)[12] |
| Palm oil mill | Vijaya et. al. (2010)[13] |
| Fractionation of palm product | Tan et. al. (2010)[14] |

Data from these studies were linked to the palm-based polyol processes to obtain the complete data set for each palm-based polyol products.

### 4.2.1 LCI for POP Pioneer Production

The focus of the LCI is on the inventory data for POP Pioneer production that has been calculated to quantify all the environmental inputs and outputs based on the functional unit within the system boundary. Table 4.2 shows the inventory data for palm-based POP Pioneer produced using pilot plant polyol.

Several assumptions were carried out during the LCA analysis regarding the inventory data obtained from the production. To obtain the LCI data for one tonne of palm-based polyol, several calculations were made to ensure that the LCI data presented is close to the actual production data (Table 4.3). According to the normal process for palm-based polyol, about 91% to 95% yield will be obtained from the feedstock. So, to produce one tonne of palm-based polyol, the highest yield percentage was used, which is 95%.

**Table 4.2: Inventory data of POP Pioneer from pilot study.**

| Parameter | Unit | Average amount |
|---|---|---|
| Refined palm olein (RPOo) | kg | 533.3 |
| Formic acid | kg | 54.86 |
| Hydrogen peroxide | kg | 202.7 |
| Sodium chloride | kg | 42.0 |
| Sodium carbonate | kg | 5.33 |
| Water use for epoxidation process | kg | 3761.7 |
| Waste water from epoxidation process | kg | 4054.3 |
| Diol | kg | 51.18 |
| Catalyst | kg | 2.13 |
| Water use for alcoholysis process | kg | 2809.3 |
| Waste water from alcoholysis process | kg | 2837.7 |
| Transportation of refined palm olein to polyol plant | tkm | 25.17 |
| Transportation of chemicals to polyol plant | tkm | 19.58 |
| Transportation of catalyst to polyol plant | tkm | 0.09 |
| Dried polyol | kg | 448.6 |
| Electricity | kWh | 690.0 |

Others chemical calculations will be based on the feedstock input using 95% yield. So inventory data for the aggregated amount are shown in Table 4.3. However, for spent acid it was accumulated into the waste water amount during LCA analysis since it was diluted into water until close to pH neutral before released as waste water. This situation explains why the input on waste water from epoxidation process is slightly higher than input for water use for epoxidation process. This is due to the similarity of the solubility and characteristics for spent acid and waste water. Moreover, the spent acid amount is very minimal compared to waste water produced during the production.

Meanwhile, amounts of sodium chloride and sodium carbonate were depended on the pH value of the epoxidized palm oil (EPO) during washing process. The amount of both sodium chloride and sodium carbonate will increase if the washing cycles increase, because the washing process will continue until the EPO compound achieves pH around 6.5 to 7.5.

**Table 4.3: Life cycle inventory for 1 tonne POP Pioneer.**

| Parameter | Unit | Amount |
|---|---|---|
| Refined palm olein | t | 1.25 |
| Formic acid | t | 0.12 |
| Hydrogen peroxide | t | 0.45 |
| Sodium chloride | t | 0.09 |
| Sodium carbonate | kg | 11.88 |
| Water use for epoxidation process | t | 8.28 |
| Waste water from epoxidation process | t | 8.98 |
| Diol | t | 0.11 |
| Catalyst | kg | 4.75 |
| Water use for alcoholysis process | t | 6.18 |
| Waste water from alcoholysis process | t | 6.24 |
| Transportation of refined palm olein to polyol plant | tkm | 51.92 |
| Transportation of chemicals to polyol plant | tkm | 42.90 |
| Transportation of catalyst to polyol plant | tkm | 0.20 |
| Dried polyol | t | 1.00 |
| Electricity | kWh | 1380.0 |

The equipments that used electricity were the stirrer inside the reactors, pump, cooling tower motor, and electrical boiler as mentioned before in Chapter 3 under Clause 3.3. All these equipments run about 3 hours for each batch of palm polyol production with maximum capacity of 600 kg feedstock. Table 4.4 shows the electricity consumption per batch of polyol production.

**Table 4.4: Electricity usage for one batch of palm polyol production.**

| Electricity equipment | Energy |
|---|---|
| Electrical boiler | 210 kW |
| Stirrer, pump, cooling tower motor | 20 kW |
| Total running time | 3 hours per batch |
| Total energy used per batch | 230 kW x 3 h = 690 kWh |

If the maximum capacity of feedstock is 600 kg, the capacity of electricity usage also will be doubled up to cover the requirement of 1100 kg of feedstock (which needs two batch production). However, the transportation is the same since the chemicals, feedstock and catalyst requires only one delivery route for several batches of production. Table 4.5 shows the calculation on transportation for feedstocks and chemicals that were used in the POP Pioneer process.

**Table 4.5: Calculation for transportation of POP Pioneer.**

| Manufacturer | Parameter | Amount (t) | Distance (km) | Transportation (tkm) |
|---|---|---|---|---|
| Southern Edible Oil Industries (M) Sdn. Bhd. | Refined palm olein | 1.10 | 47.2 | 51.92 |
| Merck (HICOM) Shah Alam | Catalyst | 0.005 | 40.7 | 0.20 |
| Kong Long Huat (Klang) | Formic acid<br>Diol<br>Hydrogen peroxide<br>Sodium chloride<br>Sodium carbonate | 0.13<br>0.10<br>0.46<br>0.08<br>0.01 | 55.0 | 42.9 |

### 4.2.2 LCI for POP Primer Production

For POP Primer study, the inventory data collected was based on the pilot plant production. In this case, the production was run at small scale than the normal operation in order to have the competitive environmental impacts by using different production scale. However, the LCIA analysis will be aggregated to 1 tonne of POP Primer production. For soy bean oil, the background profile was modified to be as similar as oil palm scenario study. It was assumed there is no land use change during the soy bean cultivation. Even the land use change was excluded from the soy bean profile; other impacts such as emissions and wastes produced from the production are still taken into the analysis. Table 4.6 shows the average data for palm-based POP Primer produced using pilot plant polyol.

**Table 4.6: Inventory data of POP Primer from pilot study.**

| Parameter | Unit | Average amount |
|---|---|---|
| Refined palm olein | kg | 360.00 |
| Soy bean oil | kg | 40.0 |
| Formic acid | kg | 46.2 |
| Hydrogen peroxide | kg | 170.7 |
| Sodium chloride | kg | 60.0 |
| Sodium carbonate | kg | 10.0 |
| Water use for epoxidation process | kg | 1685.0 |
| Waste water from epoxidation process | kg | 1930.0 |
| Diol | kg | 51.0 |
| Catalyst | kg | 1.82 |
| Water use for alcoholysis process | kg | 2970.0 |
| Waste water from alcoholysis process | kg | 3230.0 |
| Transportation of refined palm olein to polyol plant | tkm | 16.99 |
| Transportation of soy bean oil to polyol plant | tkm | 1.24 |
| Transportation of chemicals to polyol plant | tkm | 18.58 |
| Transportation of catalyst to polyol plant | tkm | 0.07 |
| Dried polyol | kg | 356.5 |
| Electricity | kWh | 690.0 |

As previous assumption in POP Pioneer study, spent acid was accumulated into the waste water amount during the LCA analysis since it was diluted into water before released as waste water. The electricity consumption value was assumed to be the full capacity operation of the pilot plant polyol. The LCIA was based on one tonne of palm-based polyol production using the average amount as shown in Table 4.7.

**Table 4.7: Life cycle inventory for 1 tonne POP Primer.**

| Parameter | Unit | Amount |
|---|---|---|
| Refined palm olein | t | 1.06 |
| Soy bean oil | t | 0.12 |
| Formic acid | t | 0.13 |
| Hydrogen peroxide | t | 0.48 |
| Sodium chloride | t | 0.17 |
| Sodium carbonate | kg | 28.1 |
| Water use for epoxidation process | t | 4.72 |
| Waste water from epoxidation process | t | 5.40 |
| Diol | t | 0.14 |
| Catalyst | kg | 5.61 |
| Water use for alcoholysis process | t | 8.33 |
| Waste water from alcoholysis process | t | 9.04 |
| Transportation of refined palm olein to polyol plant | tkm | 50.03 |
| Transportation of soy bean oil to polyol plant | tkm | 3.76 |
| Transportation of chemicals to polyol plant | tkm | 52.14 |
| Transportation of catalyst to polyol plant | tkm | 0.21 |
| Dried polyol | t | 1.0 |
| Electricity | kWh | 1380.0 |

In this case, soy bean oil was purchased from Chuan Yee Marketing (M) Sdn. Bhd. from Cheras which is of distance about 31.3 km from the palm polyol plant. Other feedstock and chemicals remains the same as in POP Pioneer study. In this case, electricity was calculated based on the maximum capacity of plant during the POP Primer production. Table 4.8 shows the calculation on transportation for feedstocks and chemicals that were used in the POP Primer process.

**Table 4.8: Calculation for transportation of POP Primer.**

| Manufacturer | Parameter | Amount (t) | Distance (km) | Transportation (tkm) |
|---|---|---|---|---|
| Southern Edible Oil Industries (M) Sdn. Bhd. | Refined palm olein | 1.06 | 47.2 | 50.03 |
| Chuan Yee Marketing (M) Sdn Bhd | Soy bean oil | 0.12 | 31.3 | 3.76 |
| Merck (HICOM) Shah Alam | Catalyst | 0.0051 | 40.7 | 0.21 |
| Kong Long Huat (Klang) | Formic acid<br>Diol<br>Hydrogen peroxide<br>Sodium chloride<br>Sodium carbonate | 0.13<br>0.14<br>0.48<br>0.17<br>0.028 | 55.0 | 52.14 |

### 4.2.3 LCI for POP Premier Production

For the POP Premier study, the inventory data collected was based on the pilot plant production. Since the small scale production can give the similar impact as 1 tonne of palm polyol production, so the production was carried out at small scale too. However, it will be aggregated to 1 tonne of impact for LCIA. Table 4.9 shows the average LCI data for palm-based POP Premier produced using pilot plant polyol. An assumption for the LCIA of POP Premier is the same as POP Pioneer and POP Primer study. For POP Primer, soy bean oil was also purchased from Chuan Yee Marketing (M) Sdn. Bhd. from Cheras where the distance is about 31.3 km from the palm polyol plant. While, refined palm kernel olein was obtained from Southern Edible Oil Industries (M) Sdn. Bhd. which was the same manufacturer for refined palm olein. Other feedstock and chemicals remains the same as in POP Pioneer and POP Primer study.

**Table 4.9: Inventory data of POP Premier from pilot study.**

| Parameter | Unit | Average amount |
|---|---|---|
| Refined palm kernel olein | kg | 292.5 |
| Soy bean oil | kg | 37.5 |
| Formic acid | kg | 21.5 |
| Hydrogen peroxide | kg | 79.6 |
| Sodium chloride | kg | 48.0 |
| Sodium carbonate | kg | 4.5 |
| Water use for epoxidation process | kg | 1594.8 |
| Waste water from epoxidation process | kg | 1744.5 |
| Diol | kg | 20.2 |
| Catalyst | kg | 1.5 |
| Water use for alcoholysis process | kg | 1743.3 |
| Waste water from alcoholysis process | kg | 2580.0 |
| Transportation of refined palm kernel olein to polyol plant | tkm | 13.81 |
| Transportation of soy bean oil to polyol plant | tkm | 1.17 |
| Transportation of chemicals to polyol plant | tkm | 9.56 |
| Transportation of catalyst to polyol plant | tkm | 0.06 |
| Dried polyol | kg | 335.3 |
| Electricity | kWh | 690.0 |

LCI data for 1 tonne of POP Premier is shown in Table 4.10. In POP Primer study, data used for refined palm kernel olein was primary data and were obtained from the refineries in Peninsular Malaysia. For soy bean oil, the scenario used as in POP Primer study to make it as compatible with the palm oil scenario.

**Table 4.10: Life cycle inventory for 1 tonne POP Premier.**

| Parameter | Unit | Amount |
|---|---|---|
| Refined palm kernel olein | t | 0.92 |
| Soy bean oil | t | 0.12 |
| Formic acid | kg | 64.1 |
| Hydrogen peroxide | t | 0.24 |
| Sodium chloride | t | 0.14 |
| Sodium carbonate | kg | 13.42 |
| Water use for epoxidation process | t | 4.75 |
| Waste water from epoxidation process | t | 5.20 |
| Diol | kg | 60.2 |
| Catalyst | kg | 4.47 |
| Water use for alcoholysis process | t | 5.20 |
| Waste water from alcoholysis process | t | 7.69 |
| Transportation of refined palm kernel olein to polyol plant | tkm | 43.42 |
| Transportation of soy bean oil to polyol plant | tkm | 3.76 |
| Transportation of chemicals to polyol plant | tkm | 28.44 |
| Transportation of catalyst to polyol plant | tkm | 0.18 |
| Dried polyol | t | 1.0 |
| Electricity | kWh | 1380.0 |

Table 4.11 shows the calculation on transportation for feedstocks and chemicals that were used in the POP Pioneer process.

**Table 4.11: Calculation for transportation of POP Premier.**

| Manufacturer | Parameter | Amount (t) | Distance (km) | Transportation (tkm) |
|---|---|---|---|---|
| Southern Edible Oil Industries (M) Sdn. Bhd. | Refined palm kernel olein | 0.92 | 47.2 | 43.42 |
| Chuan Yee Marketing (M) Sdn Bhd | Soy bean oil | 0.12 | 31.3 | 3.76 |
| Merck (HICOM) Shah Alam | Catalyst | 0.0045 | 40.7 | 0.18 |
| Kong Long Huat (Klang) | Formic acid<br>Diol<br>Hydrogen peroxide<br>Sodium chloride<br>Sodium carbonate | 0.064<br>0.06<br>0.24<br>0.14<br>0.013 | 55.0 | 28.44 |

## 4.3 Life Cycle Impact Assessment (LCIA)

The LCIA study was conducted using the SimaPro software version 8.0.2 with Eco-indicator 99 methodology. This study used the midpoint approach where the results are more meaningful from a scientific perspective since this approach is problem-oriented approach that translates the impacts into environmental themes such as climate change, fossil fuels, land use etc. The characterization and weighting for the system boundary starts from the oil palm seed germination till the production of palm-based polyol at the pilot plant polyol. The LCIA will cover for the 'cradle-to-gate' study. The different scenario studies were described as in Chapter 3 Table 3.3.

## 4.4 LCIA of POP Pioneer Production – Scenario 1

LCIA was conducted for one batch of POP Pioneer produced at the polyol pilot plant. The system boundary includes oil palm germinated seed production until refined palm olein production (upstream palm oil production) till palm-based polyol production. As mentioned in Table 3.3, Scenario 1 involved production of palm-based polyol using continued land use (oil palm to oil palm) with biogas capture. This scenario be a base case study for palm-based polyol since it is the normal practice for upstream in the Malaysian oil palm industry. This scenario was carried out for each case study conducted.

### 4.4.1 Characterization for LCIA of 1 tonne POP Pioneer Production

The characterization results revealed the most significant impact in the life cycle stage in the production of palm-based polyol as shown in Table 4.12 and Figure 4.1 respectively. Impact characterization uses science-based conversion factors, called characterization factors, to convert and combine the LCI results into representative indicators of impacts to human and ecological health.

The contribution of raw materials, energy consumption and waste generated from the palm polyol production are outlined as in Figure 4.1 Electricity shows greater environmental impacts to four out of 11 categories (carcinogens, respiratory inorganics, climate change and fossil fuels), and it is responsible for almost 28% of the total life cycle impact. Hydrogen peroxide also showed the greater impacts toward the four categories which are respiratory inorganics, radiation, ecotoxicity and minerals. This is due to the production of hydrogen peroxide itself.

**Table 4.12: Characterization for LCIA of 1 tonne POP Pioneer (Scenario 1).**

| Impact Category | Unit | Total | RPOo | Catalyst | Formic acid | Hydrogen peroxide | Sodium chloride | Soda (Sodium carbonate) | Diol | Tap water | Transport of RPOo | Transport of catalyst | Transport of chemicals | Electricity Malaysia |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Carcinogens | DALY | 0.000219 | 4.9E-05 | 1.97E-06 | 1.09E-05 | 3.36E-05 | 2.71E-06 | 7.1E-07 | 7.28E-06 | 8.48E-07 | 1.32E-05 | 4.82E-08 | 1.09E-05 | 8.74E-05 |
| Respiratory organics | DALY | 3.1E-06 | 1.39E-06 | 8.54E-09 | 3.74E-07 | 6.41E-07 | 7.38E-09 | 1.86E-09 | 2.37E-07 | 1.52E-09 | 4.53E-08 | 1.66E-10 | 3.75E-08 | 3.57E-07 |
| Respiratory inorganics | DALY | 0.001308 | 0.000405 | 4.4E-05 | 8.73E-05 | 0.000202 | 1.03E-05 | 4.57E-06 | 0.000111 | 1.49E-06 | 2.01E-05 | 7.34E-08 | 1.66E-05 | 0.000406 |
| Climate change | DALY | 0.000573 | 0.000141 | 2.1E-06 | 4.05E-05 | 0.000106 | 3.16E-06 | 1.07E-06 | 3.31E-05 | 4.46E-07 | 3.49E-06 | 1.28E-08 | 2.89E-06 | 0.00024 |
| Radiation | DALY | 7.28E-06 | 9.4E-07 | 7.18E-08 | 1.61E-06 | 3.21E-06 | 1.99E-07 | 2.05E-08 | 1.08E-06 | 8.3E-08 | 3.31E-08 | 1.21E-10 | 2.74E-08 | 0 |
| Ozone layer | DALY | 3.5E-07 | 2.1E-07 | 9.79E-10 | 3.47E-08 | 4.91E-08 | 9.13E-10 | 1.18E-10 | 2.9E-09 | 1.36E-10 | 2.75E-09 | 1.01E-11 | 2.28E-09 | 4.57E-08 |
| Ecotoxicity | PAF*m2yr | 578.9843 | 117.977 | 9.227664 | 36.3515 | 204.0696 | 12.36744 | 1.593159 | 27.35436 | 0.69721 | 6.629743 | 0.024261 | 5.490735 | 157.2017 |
| Acidification/ Eutrophication | PDF*m2yr | 46.74668 | 16.92162 | 0.906605 | 2.408558 | 5.291569 | 0.241895 | 0.221118 | 3.694945 | 0.033609 | 0.777924 | 0.002847 | 0.644274 | 15.60172 |
| Land use | PDF*m2yr | 16.30363 | 4.950793 | 0.444822 | 3.45098 | 4.657204 | 0.579305 | 0.116214 | 1.421881 | 0.177951 | 0.275395 | 0.001008 | 0.228081 | 0 |
| Minerals | MJ surplus | 74.41836 | 23.76155 | 2.198507 | 7.298749 | 28.71262 | 3.037843 | 0.340617 | 6.818025 | 0.144373 | 1.149695 | 0.004207 | 0.952175 | 0 |
| Fossil fuels | MJ surplus | 4409.733 | 799.2895 | 14.9308 | 693.9516 | 961.0784 | 13.91821 | 2.155069 | 624.8087 | 1.513077 | 33.23594 | 0.121626 | 27.52592 | 1237.204 |

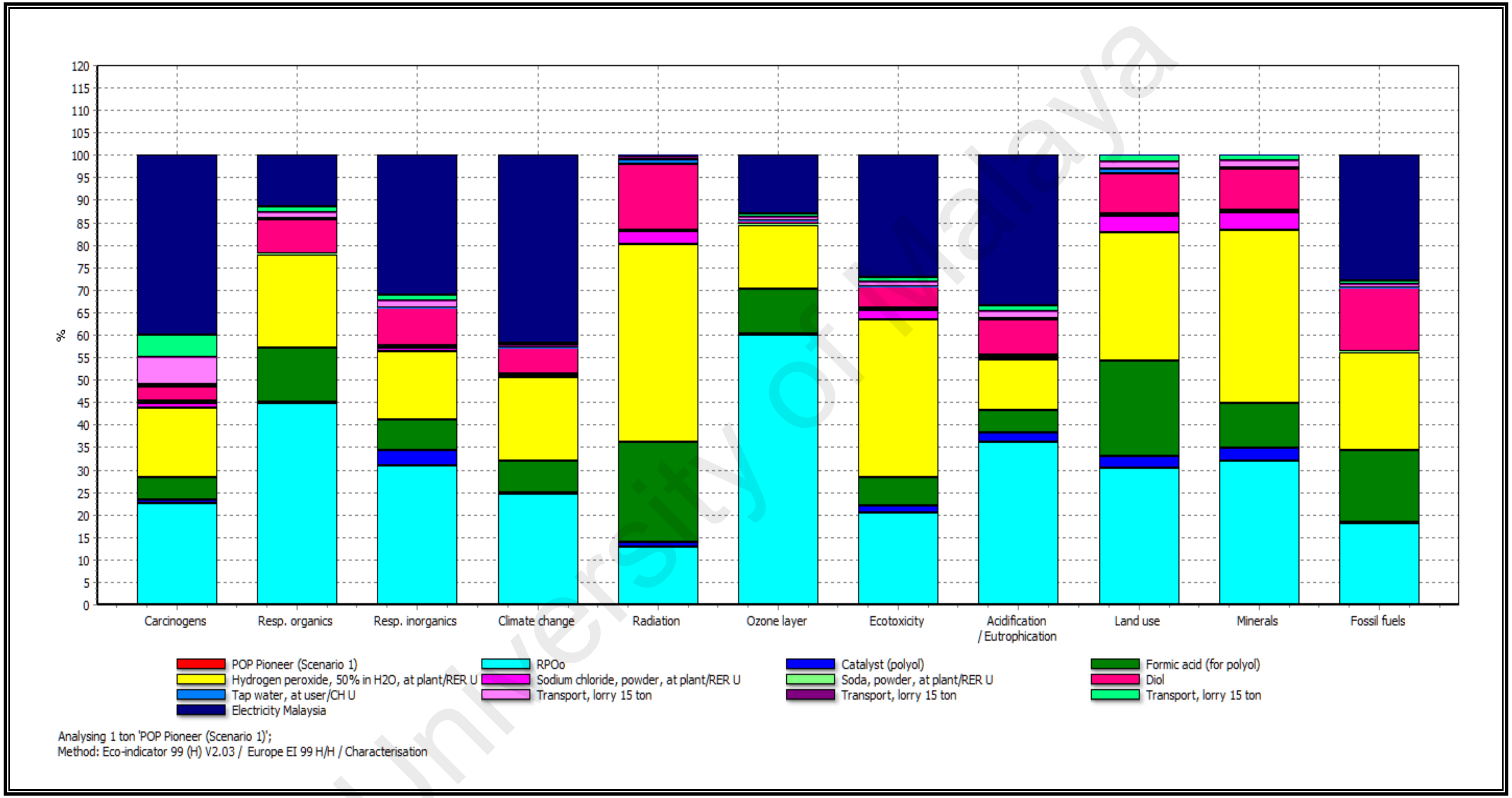


**Figure 4.1: Characterization for life cycle impact assessment (LCIA) of 1 tonne POP Pioneer – Scenario 1.**

### 4.4.2 Damage Assessment for LCIA of 1 tonne POP Pioneer Production

The damage assessment for the production of 1 tonne POP Pioneer for both scenarios are as shown in Table 4.13 and Figure 4.2 respectively. As mentioned in Chapter 2, there are three damage assessments which are human health, ecosystem quality and resources that are used to assess or classified the impact from the production to their respective damage assessment categories. All the impacts from the production will contribute into these three damage categories. Tables 4.13 clearly showed that the worst damage in the resources category was from the electricity. The highest value in resources indicated the highest chance of fossil depletion would occur. Thus, this is the main reason why nowadays people are looking towards renewable resources as a substitution or replacement of certain feedstock or materials in their production.

**Table 4.13: Damage assessment for LCIA of 1 tonne POP Pioneer (Scenario 1).**

| Impact Category | Unit | Total | RPOo | Catalyst | Formic acid | Hydrogen peroxide | Sodium chloride | Soda (Sodium carbonate) | Diol | Tap water | Transport of RPOo | Transport of catalyst | Transport of chemicals | Electricity Malaysia (adopted) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Human Health | DALY | 0.002111 | 0.000598 | 4.82E-05 | 0.000141 | 0.000345 | 1.64E-05 | 6.38E-06 | 0.000152 | 2.87E-06 | 3.68E-05 | 1.35E-07 | 3.05E-05 | 0.000734 |
| Ecosystem Quality | PDF*m2yr | 120.9488 | 33.67011 | 2.274193 | 9.494689 | 30.35573 | 2.057944 | 0.496648 | 7.852262 | 0.281281 | 1.716293 | 0.006281 | 1.421429 | 31.32189 |
| Resources | MJ surplus | 4484.152 | 823.0511 | 17.1293 | 701.2503 | 989.791 | 16.95605 | 2.495686 | 631.6268 | 1.65745 | 34.38564 | 0.125833 | 28.47809 | 1237.204 |

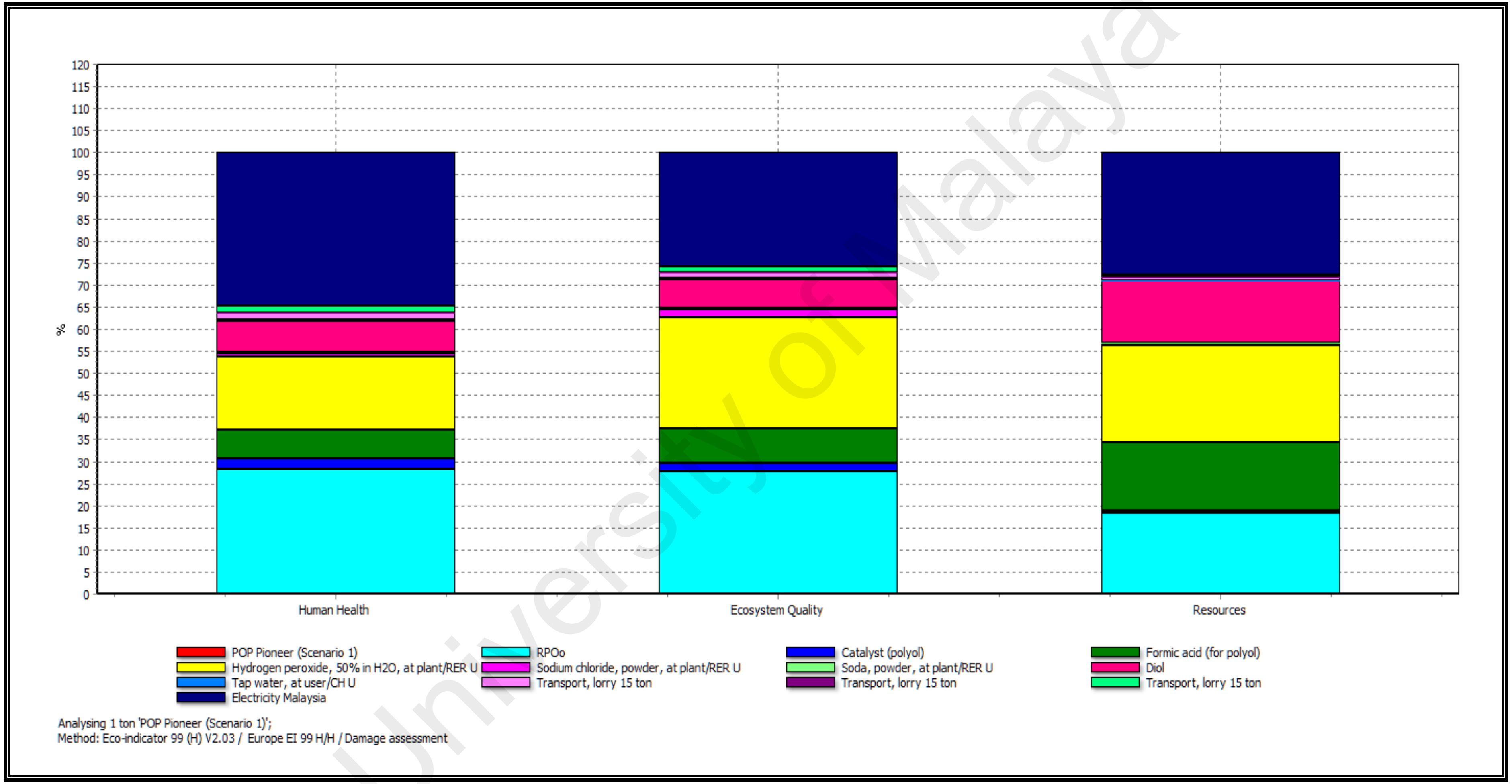


**Figure 4.2: Damage assessment for life cycle impact assessment (LCIA) of 1 tonne POP Pioneer – Scenario 1.**

### 4.4.3 Normalization for LCIA of 1 tonne POP Pioneer Production

Normalization was carried out for the production of 1 tonne POP Pioneer, as shown in Table 4.14 and Figure 4.3 respectively. The value for normalization is express unit of person-equivalents, i.e. fractions of the contribution to the impact deriving from the average person. This gives the normalization references the unit "impact potential per person per year" for each individual impact category. For normalization, all potential impacts and resources consumptions thus assume the same unit, and it is possible to compare their magnitudes. At the same time, the normalized potential impacts of the product are expressed in a comprehensive unit as they can be viewed relative to one's own average contribution to the impact.

As shown in Table 4.14, when normalization is conducted, the impact caused by the electricity during the production to the fossil fuels impact category is about 0.1472 PE. The other potential impact in Scenario 1 that was caused by electricity are respiratory inorganics and climate change categories with a value of 0.0265 PE and 0.0156 PE, respectively. Other than electricity, hydrogen peroxide also contributed toward the impacts of fossil fuels category about 0.1144 PE. This was caused by the production of hydrogen peroxide itself. According to Franklin Associates (2007), atmospheric emissions that can cause respiratory inorganics are directly from the sequence of processes that are used to extract, transform, fabricate or otherwise affect changes on a material or product during its life cycle, while fuel-related emissions are associated with the combustion of fuels used for process energy and transportation energy.

## Table 4.14: Normalization for LCIA of 1 tonne POP Pioneer (Scenario 1).

| Impact Category | Total | RPOo | Catalyst | Formic acid | Hydrogen peroxide | Sodium chloride | Soda (Sodium carbonate) | Diol | Tap water | Transport of RPOo | Transport of catalyst | Transport of chemicals | Electricity Malaysia (adopted) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Carcinogens | 0.014228 | 0.003189 | 0.000128 | 0.000709 | 0.002186 | 0.000176 | 4.63E-05 | 0.000474 | 5.52E-05 | 0.000858 | 3.14E-06 | 0.000711 | 0.005691 |
| Respiratory organics | 0.000202 | 9.06E-05 | 5.56E-07 | 2.44E-05 | 4.17E-05 | 4.81E-07 | 1.21E-07 | 1.54E-05 | 9.88E-08 | 2.95E-06 | 1.08E-08 | 2.44E-06 | 2.33E-05 |
| Respiratory inorganics | 0.08517 | 0.026387 | 0.002865 | 0.005683 | 0.013123 | 0.00067 | 0.000298 | 0.007195 | 9.68E-05 | 0.001306 | 4.78E-06 | 0.001082 | 0.02646 |
| Climate change | 0.037306 | 0.009192 | 0.000136 | 0.002636 | 0.006871 | 0.000206 | 6.99E-05 | 0.002153 | 2.9E-05 | 0.000227 | 8.31E-07 | 0.000188 | 0.015597 |
| Radiation | 0.000474 | 6.12E-05 | 4.68E-06 | 0.000105 | 0.000209 | 1.29E-05 | 1.33E-06 | 7.01E-05 | 5.4E-06 | 2.15E-06 | 7.87E-09 | 1.78E-06 | 0 |
| Ozone layer | 2.28E-05 | 1.37E-05 | 6.38E-08 | 2.26E-06 | 3.2E-06 | 5.95E-08 | 7.7E-09 | 1.89E-07 | 8.83E-09 | 1.79E-07 | 6.55E-10 | 1.48E-07 | 2.98E-06 |
| Ecotoxicity | 0.01129 | 0.002301 | 0.00018 | 0.000709 | 0.003979 | 0.000241 | 3.11E-05 | 0.000533 | 1.36E-05 | 0.000129 | 4.73E-07 | 0.000107 | 0.003065 |
| Acidification/ Eutrophication | 0.009116 | 0.0033 | 0.000177 | 0.00047 | 0.001032 | 4.72E-05 | 4.31E-05 | 0.000721 | 6.55E-06 | 0.000152 | 5.55E-07 | 0.000126 | 0.003042 |
| Land use | 0.003179 | 0.000965 | 8.67E-05 | 0.000673 | 0.000908 | 0.000113 | 2.27E-05 | 0.000277 | 3.47E-05 | 5.37E-05 | 1.97E-07 | 4.45E-05 | 0 |
| Minerals | 0.008856 | 0.002828 | 0.000262 | 0.000869 | 0.003417 | 0.000362 | 4.05E-05 | 0.000811 | 1.72E-05 | 0.000137 | 5.01E-07 | 0.000113 | 0 |
| Fossil fuels | 0.524758 | 0.095115 | 0.001777 | 0.08258 | 0.114368 | 0.001656 | 0.000256 | 0.074352 | 0.00018 | 0.003955 | 1.45E-05 | 0.003276 | 0.147227 |

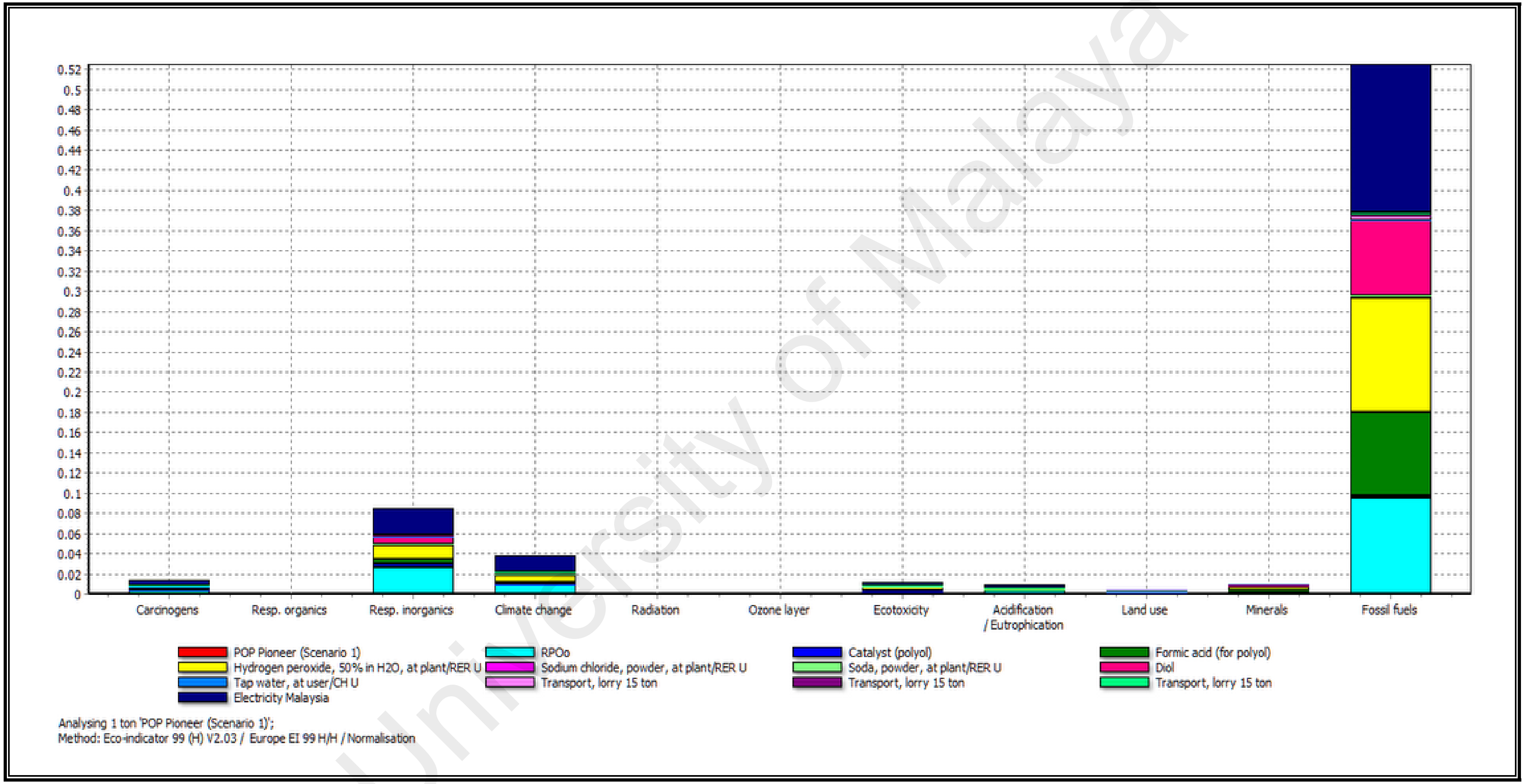


**Figure 4.3: Normalization for life cycle impact assessment (LCIA) of 1 tonne POP Pioneer – Scenario 1.**

## Table 4.15: Weighting for LCIA of 1 tonne POP Pioneer (Scenario 1).

| Impact Category | Unit | Total | RPOo | Catalyst | Formic acid | Hydrogen peroxide | Sodium chloride | Soda (Sodium carbonate) | Diol | Tap water | Transport of RPOo | Transport of catalyst | Transport of chemicals | Electricity Malaysia (adopted) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Carcinogens | Pt | 4.268365 | 0.956704 | 0.038488 | 0.212664 | 0.655925 | 0.052843 | 0.013875 | 0.14227 | 0.016556 | 0.257445 | 0.000942 | 0.213216 | 1.707437 |
| Respiratory organics | Pt | 0.060621 | 0.027193 | 0.000167 | 0.007312 | 0.012514 | 0.000144 | 3.63E-05 | 0.004627 | 2.96E-05 | 0.000885 | 3.24E-06 | 0.000733 | 0.006976 |
| Respiratory inorganics | Pt | 25.55111 | 7.915985 | 0.859547 | 1.70496 | 3.936869 | 0.201105 | 0.089329 | 2.158369 | 0.029048 | 0.39193 | 0.001434 | 0.324596 | 7.937938 |
| Climate change | Pt | 11.19194 | 2.757636 | 0.040944 | 0.790834 | 2.061417 | 0.061683 | 0.020973 | 0.645925 | 0.008715 | 0.068097 | 0.000249 | 0.056398 | 4.679071 |
| Radiation | Pt | 0.142114 | 0.018356 | 0.001403 | 0.031541 | 0.062713 | 0.003883 | 0.0004 | 0.021016 | 0.001621 | 0.000645 | 2.36E-06 | 0.000535 | 0 |
| Ozone layer | Pt | 0.006827 | 0.004102 | 1.91E-05 | 0.000677 | 0.000959 | 1.78E-05 | 2.31E-06 | 5.66E-05 | 2.65E-06 | 5.37E-05 | 1.97E-07 | 4.45E-05 | 0.000893 |
| Ecotoxicity | Pt | 4.516078 | 0.92022 | 0.071976 | 0.283542 | 1.591743 | 0.096466 | 0.012427 | 0.213364 | 0.005438 | 0.051712 | 0.000189 | 0.042828 | 1.226173 |
| Acidification/ Eutrophication | Pt | 3.646241 | 1.319886 | 0.070715 | 0.187868 | 0.412742 | 0.018868 | 0.017247 | 0.288206 | 0.002621 | 0.060678 | 0.000222 | 0.050253 | 1.216935 |
| Land use | Pt | 1.271683 | 0.386162 | 0.034696 | 0.269176 | 0.363262 | 0.045186 | 0.009065 | 0.110907 | 0.01388 | 0.021481 | 7.86E-05 | 0.01779 | 0 |
| Minerals | Pt | 2.656736 | 0.848287 | 0.078487 | 0.260565 | 1.025041 | 0.108451 | 0.01216 | 0.243403 | 0.005154 | 0.041044 | 0.00015 | 0.033993 | 0 |
| Fossil fuels | Pt | 157.4275 | 28.53464 | 0.533029 | 24.77407 | 34.3105 | 0.49688 | 0.076936 | 22.30567 | 0.054017 | 1.186523 | 0.004342 | 0.982675 | 44.1682 |

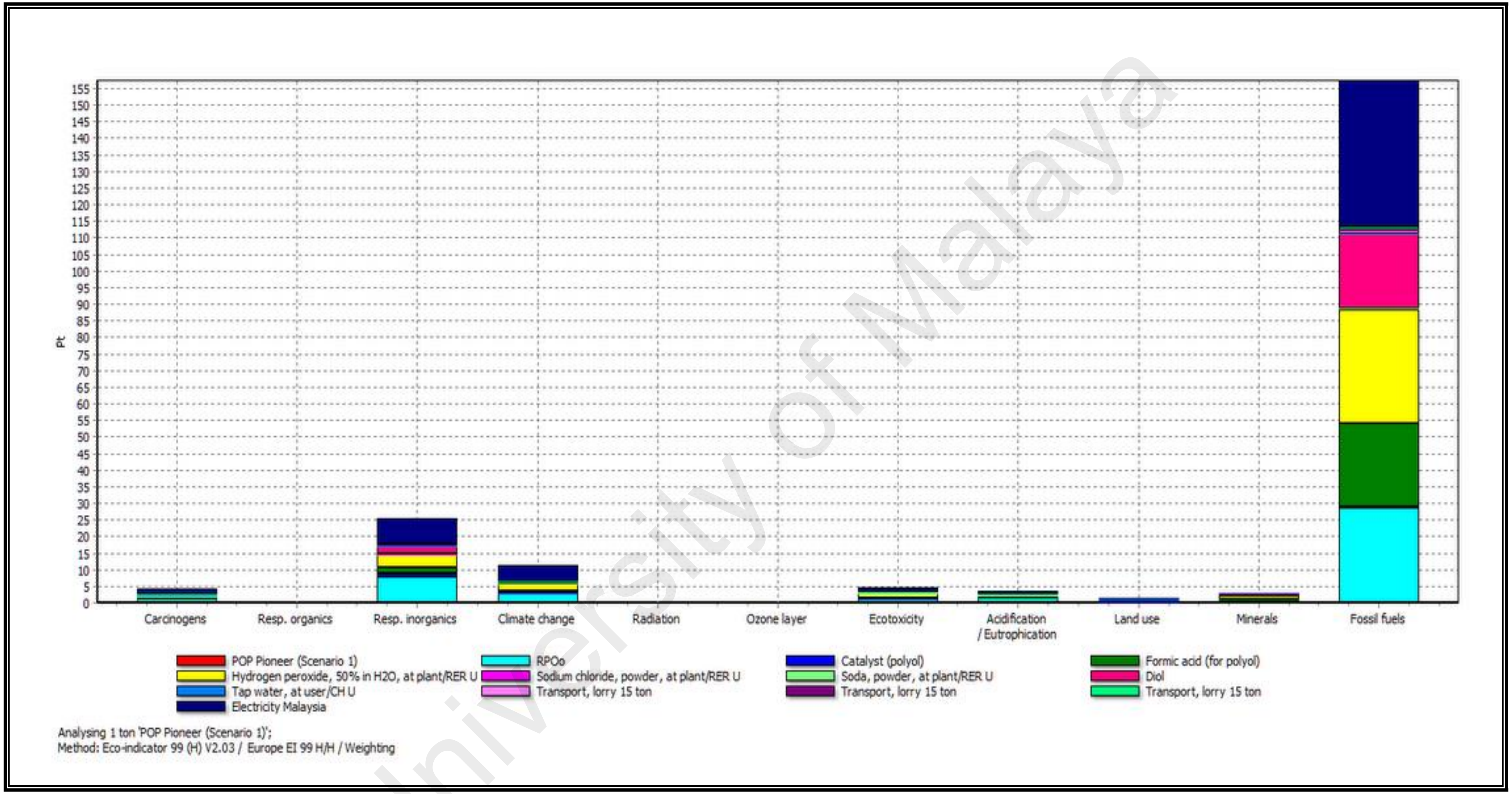


**Figure 4.4: Weighting for life cycle impact assessment (LCIA) of 1 tonne POP Pioneer – Scenario 1.**

### 4.4.4 Weighting for LCIA of 1 tonne POP Pioneer Production

Weighting was carried out for the production of 1 tonne POP Pioneer for both scenarios as is shown in Table 4.15 and Figure 4.4 respectively. The weighting results show that the most significant impact category was fossil fuels followed by respiratory inorganics and climate change. The main contributors toward the impact of fossil fuels were from electricity consumption at the polyol plant, followed by the production of hydrogen peroxide and production of refined palm olein. The impact on fossil fuels was highest among other categories due to the use of non-renewable resources for electricity production, plus the contribution from the production stage of the hydrogen peroxide and refined palm olein that was used as a chemical reagent and feedstock, respectively during the epoxidation process to produce epoxidized palm oil (EPO). Meanwhile, impact on respiratory inorganics is associated with the emissions to the atmosphere during the production of refined palm olein at upstream (Tan et. al, 2009).

## 4.5 LCIA of POP Primer Production – Scenario 1

### 4.5.1 Characterization for LCIA of 1 tonne POP Primer Production

For POP Primer, the analyses of impact which are characterization, damage, normalization and weighting were carried out using the Eco-indicator 99 methodology. For Scenario 1, the characterization for POP Primer is as shown in Figure 4.5 and Table 4.16. Table 4.16 showed that fossil fuels contributed about the highest impact with total about 4784.8 MJ surplus that accumulate the impact from the electricity usage (1237.2 MJ surplus) and also production of hydrogen peroxide and diol, which are used as a chemical reagent in the polyol production with 1025.2 and 795.2 MJ surplus, respectively.

**Table 4.16: Characterization for LCIA of 1 tonne POP Primer (Scenario 1).**

| Impact category | Unit | Total | RPOo | Catalyst | Formic acid | Hydrogen peroxide | Sodium chloride | Soda (sodium carbonate) | Diol | Tap water | Transport of RPOo | Transport of catalyst | Transport of chemical | Transport of soy bean oil | Soy beans oil | Electricity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Carcinogens | DALY | 0.000241 | 4.5E-05 | 2.12E-06 | 1.18E-05 | 3.58E-05 | 5.11E-06 | 1.79E-06 | 9.27E-06 | 6.01E-07 | 1.21E-05 | 5.33E-08 | 1.33E-05 | 8.73E-07 | 1.55E-05 | 8.74E-05 |
| Resp. organics | DALY | 3.35E-06 | 1.28E-06 | 9.17E-09 | 4.06E-07 | 6.83E-07 | 1.39E-08 | 4.69E-09 | 3.02E-07 | 1.07E-09 | 4.16E-08 | 1.83E-10 | 4.56E-08 | 3E-09 | 2.09E-07 | 3.57E-07 |
| Resp. inorganics | DALY | 0.001439 | 0.000372 | 4.73E-05 | 9.46E-05 | 0.000215 | 1.95E-05 | 1.16E-05 | 0.000141 | 1.05E-06 | 1.84E-05 | 8.12E-08 | 2.02E-05 | 1.33E-06 | 9.08E-05 | 0.000406 |
| Climate change | DALY | 0.000614 | 0.00013 | 2.25E-06 | 4.39E-05 | 0.000113 | 5.97E-06 | 2.71E-06 | 4.21E-05 | 3.16E-07 | 3.2E-06 | 1.41E-08 | 3.51E-06 | 2.31E-07 | 2.76E-05 | 0.00024 |
| Radiation | DALY | 8.26E-06 | 8.63E-07 | 7.71E-08 | 1.75E-06 | 3.43E-06 | 3.76E-07 | 5.17E-08 | 1.37E-06 | 5.88E-08 | 3.04E-08 | 1.34E-10 | 3.33E-08 | 2.19E-09 | 2.21E-07 | 0 |
| Ozone layer | DALY | 3.58E-07 | 1.93E-07 | 1.05E-09 | 3.76E-08 | 5.24E-08 | 1.73E-09 | 2.99E-10 | 3.69E-09 | 9.61E-11 | 2.53E-09 | 1.11E-11 | 2.77E-09 | 1.82E-10 | 1.68E-08 | 4.57E-08 |
| Ecotoxicity | PAF*m2yr | 633.4328 | 108.3243 | 9.907597 | 39.3808 | 217.6742 | 23.36073 | 4.023129 | 34.81464 | 0.49399 | 6.088331 | 0.026815 | 6.671881 | 0.439259 | 25.02542 | 157.2017 |
| Acidification/ Eutrophication | PDF*m2yr | 51.15796 | 15.53712 | 0.973408 | 2.609271 | 5.64434 | 0.456913 | 0.558378 | 4.702657 | 0.023813 | 0.714395 | 0.003146 | 0.782868 | 0.051542 | 3.498383 | 15.60172 |
| Land use | PDF*m2yr | 18.71533 | 4.545729 | 0.477598 | 3.738565 | 4.967684 | 1.094243 | 0.29347 | 1.809667 | 0.126083 | 0.252905 | 0.001114 | 0.277145 | 0.018246 | 1.112881 | 0 |
| Minerals | MJ surplus | 83.0321 | 21.81743 | 2.360503 | 7.906978 | 30.62679 | 5.738149 | 0.860144 | 8.677486 | 0.102292 | 1.055807 | 0.00465 | 1.157003 | 0.076174 | 2.648695 | 0 |
| Fossil fuels | MJ surplus | 4784.839 | 733.8931 | 16.03096 | 751.7809 | 1025.15 | 26.28995 | 5.442094 | 795.2111 | 1.072051 | 30.52176 | 0.134429 | 33.44719 | 2.202073 | 126.4586 | 1237.204 |

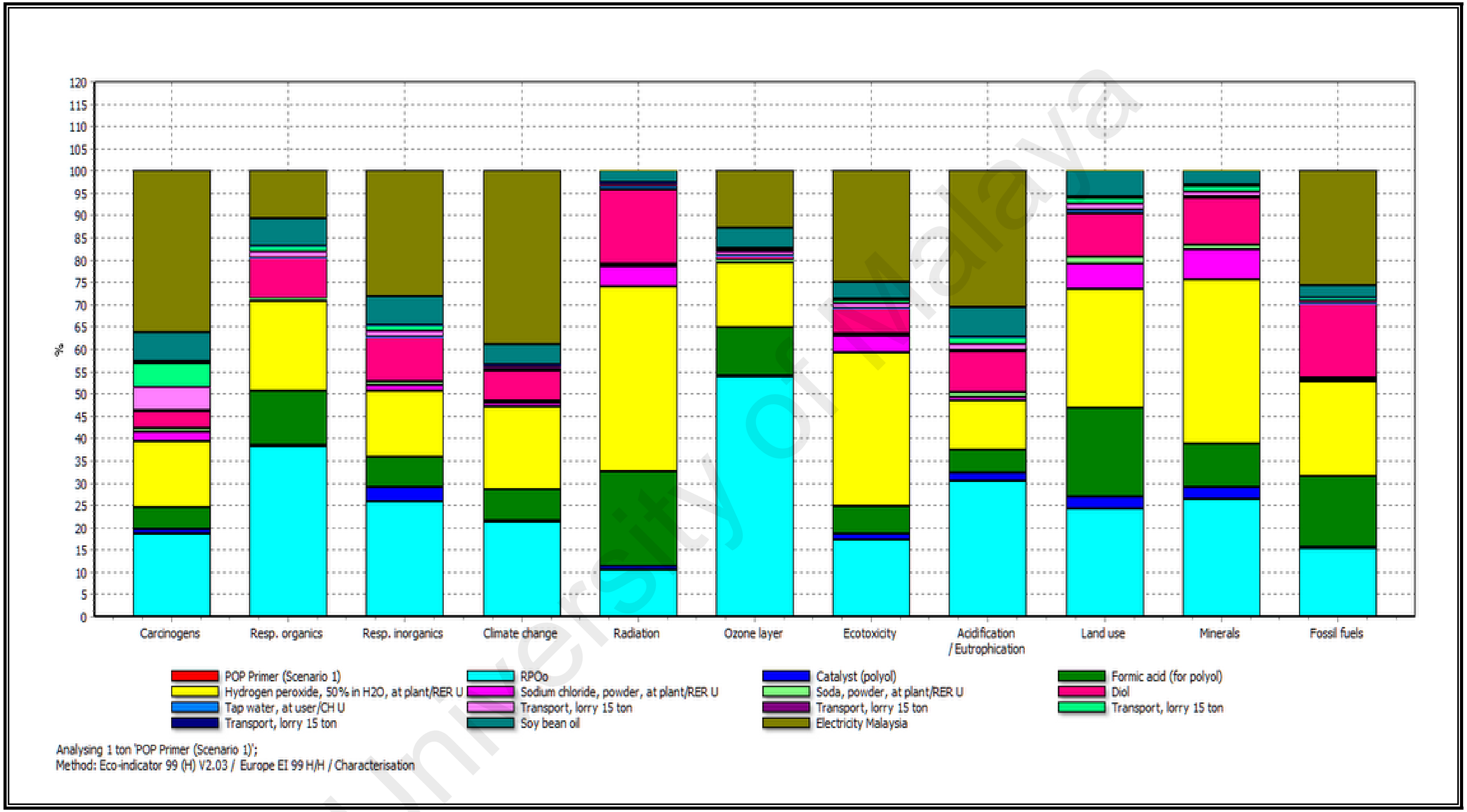


**Figure 4.5: Characterization for life cycle impact assessment (LCIA) of 1 tonne POP Primer – Scenario 1.**

### 4.5.2 Damage Assessment for LCIA of 1 tonne POP Primer Production

Similar to characterization, the damage assessment result for Scenario 1 is as shown in Table 4.17 and Figure 4.6. It showed that the electricity consumption caused the damage to the human health category followed by resources and ecosystem quality. Since the electricity was identified as a main contributor towards the production, it caused the highest damage to resources that are mainly used to produce electricity.

### 4.5.3 Normalization for LCIA of 1 tonne POP Primer Production

As for normalization, the result showed that the biggest impact is mainly contributed by the electricity consumption at palm polyol pilot plant as shown by Figure 4.7. The magnitude of the impact contributed to the fossil fuels category is about 0.6167 PE. Similar to the study on POP Pioneer, other potential main contributors in POP Primer were hydrogen peroxide and diol with a value of 0.1217 PE and 0.0967 PE, respectively (Table 4.18). This hydrogen peroxide was used in the epoxidation production. As mentioned by Niklas and André (2014), the largest contributor to total GHG emissions is from the production of epoxides.

**Table 4.17: Damage assessment for LCIA of 1 tonne POP Primer (Scenario 1).**

| Impact category | Unit | Total | RPOo | Catalyst | Formic acid | Hydrogen peroxide | Sodium chloride | Soda (sodium carbonate) | Diol | Tap water | Transport of RPOo | Transport of catalyst | Transport of chemical | Transport of soy bean oil | Soy beans oil | Electricity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Human Health | DALY | 0.002305 | 0.000549 | 5.17E-05 | 0.000152 | 0.000368 | 3.09E-05 | 1.61E-05 | 0.000194 | 2.03E-06 | 3.38E-05 | 1.49E-07 | 3.71E-05 | 2.44E-06 | 0.000134 | 0.000734 |
| Ecosystem Quality | PDF*m2yr | 133.2166 | 30.91528 | 2.441765 | 10.28592 | 32.37945 | 3.887228 | 1.254162 | 9.993788 | 0.199294 | 1.576133 | 0.006942 | 1.727201 | 0.113714 | 7.113807 | 31.32189 |
| Resources | MJ surplus | 4867.871 | 755.7105 | 18.39146 | 759.6879 | 1055.777 | 32.0281 | 6.302238 | 803.8886 | 1.174343 | 31.57757 | 0.139079 | 34.60419 | 2.278247 | 129.1073 | 1237.204 |

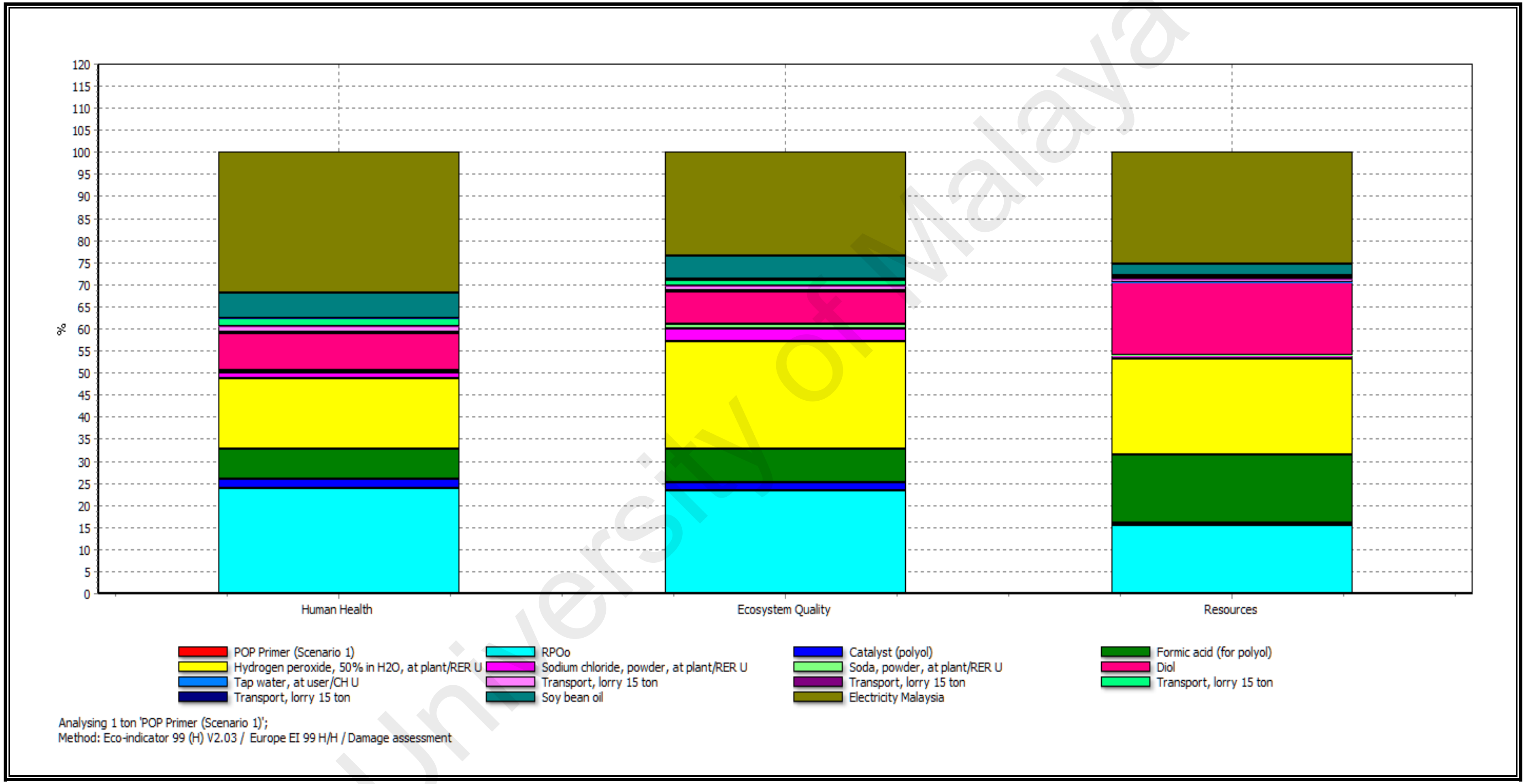


**Figure 4.6: Damage assessment for life cycle impact assessment (LCIA) of 1 tonne POP Primer – Scenario 1.**

## Table 4.18: Normalization for LCIA of 1 tonne POP Primer (Scenario 1).

| Impact category | Total | RPOo | Catalyst | Formic acid | Hydrogen peroxide | Sodium chloride | Soda (sodium carbonate) | Diol | Tap water | Transport of RPOo | Transport of catalyst | Transport of chemical | Transport of soy bean oil | Soy beans oil | Electricity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Carcinogens | 0.015673 | 0.002928 | 0.000138 | 0.000768 | 0.002332 | 0.000333 | 0.000117 | 0.000604 | 3.91E-05 | 0.000788 | 3.47E-06 | 0.000864 | 5.69E-05 | 0.001011 | 0.005691 |
| Resp. organics | 0.000218 | 8.32E-05 | 5.97E-07 | 2.64E-05 | 4.45E-05 | 9.08E-07 | 3.05E-07 | 1.96E-05 | 7E-08 | 2.71E-06 | 1.19E-08 | 2.97E-06 | 1.96E-07 | 1.36E-05 | 2.33E-05 |
| Resp. inorganics | 0.093677 | 0.024228 | 0.003076 | 0.006157 | 0.013998 | 0.001266 | 0.000752 | 0.009157 | 6.86E-05 | 0.0012 | 5.28E-06 | 0.001315 | 8.66E-05 | 0.005908 | 0.02646 |
| Climate change | 0.039944 | 0.00844 | 0.000147 | 0.002856 | 0.007329 | 0.000388 | 0.000177 | 0.00274 | 2.06E-05 | 0.000208 | 9.18E-07 | 0.000228 | 1.5E-05 | 0.001797 | 0.015597 |
| Radiation | 0.000538 | 5.62E-05 | 5.02E-06 | 0.000114 | 0.000223 | 2.44E-05 | 3.37E-06 | 8.92E-05 | 3.83E-06 | 1.98E-06 | 8.7E-09 | 2.17E-06 | 1.43E-07 | 1.44E-05 | 0 |
| Ozone layer | 2.33E-05 | 1.26E-05 | 6.84E-08 | 2.45E-06 | 3.41E-06 | 1.12E-07 | 1.95E-08 | 2.4E-07 | 6.25E-09 | 1.64E-07 | 7.24E-10 | 1.8E-07 | 1.19E-08 | 1.1E-06 | 2.98E-06 |
| Ecotoxicity | 0.012352 | 0.002112 | 0.000193 | 0.000768 | 0.004245 | 0.000456 | 7.85E-05 | 0.000679 | 9.63E-06 | 0.000119 | 5.23E-07 | 0.00013 | 8.57E-06 | 0.000488 | 0.003065 |
| Acidification/ Eutrophication | 0.009976 | 0.00303 | 0.00019 | 0.000509 | 0.001101 | 8.91E-05 | 0.000109 | 0.000917 | 4.64E-06 | 0.000139 | 6.14E-07 | 0.000153 | 1.01E-05 | 0.000682 | 0.003042 |
| Land use | 0.003649 | 0.000886 | 9.31E-05 | 0.000729 | 0.000969 | 0.000213 | 5.72E-05 | 0.000353 | 2.46E-05 | 4.93E-05 | 2.17E-07 | 5.4E-05 | 3.56E-06 | 0.000217 | 0 |
| Minerals | 0.009881 | 0.002596 | 0.000281 | 0.000941 | 0.003645 | 0.000683 | 0.000102 | 0.001033 | 1.22E-05 | 0.000126 | 5.53E-07 | 0.000138 | 9.06E-06 | 0.000315 | 0 |
| Fossil fuels | 0.569396 | 0.087333 | 0.001908 | 0.089462 | 0.121993 | 0.003129 | 0.000648 | 0.09463 | 0.000128 | 0.003632 | 1.6E-05 | 0.00398 | 0.000262 | 0.015049 | 0.147227 |

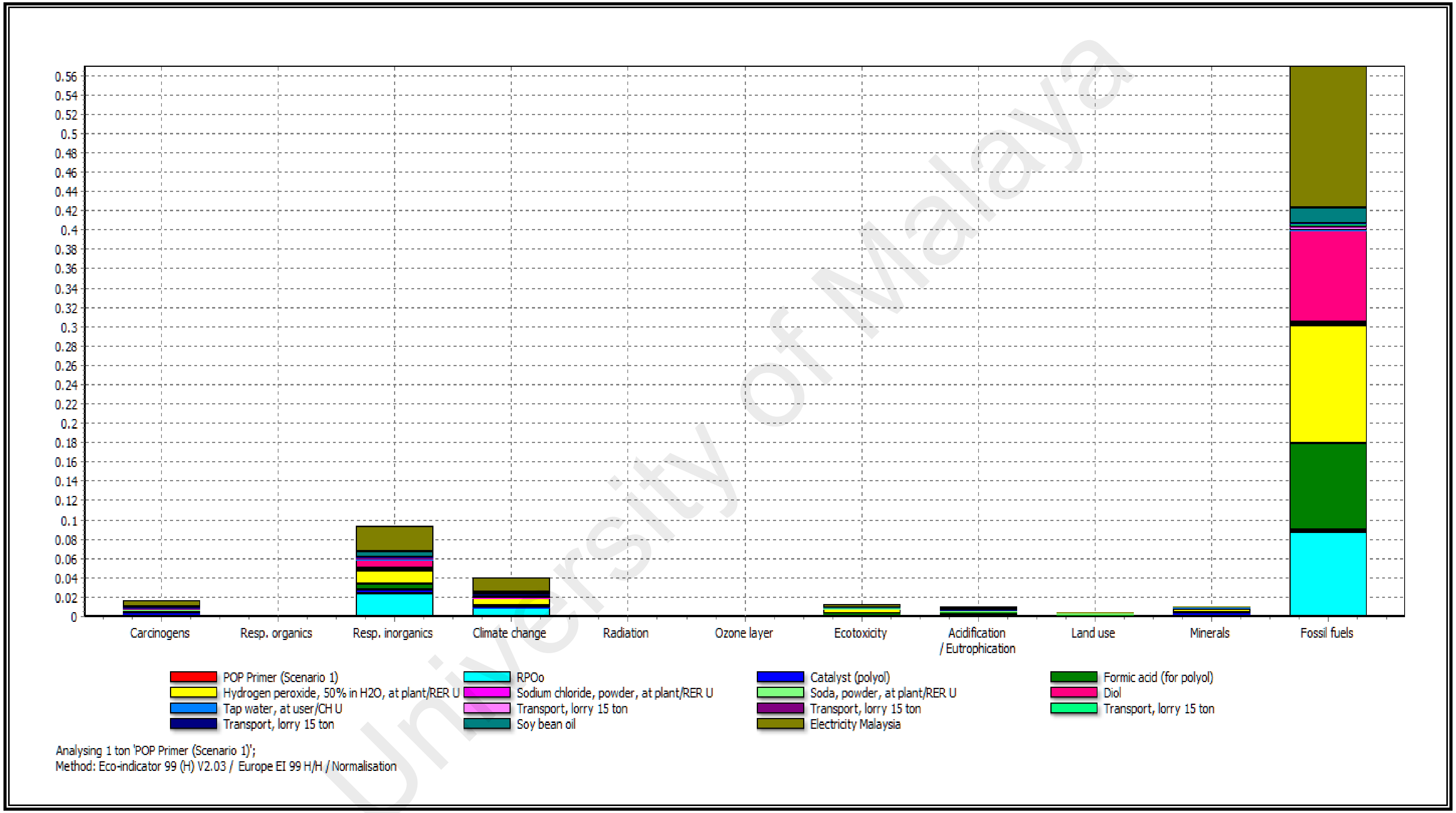


**Figure 4.7: Normalization for life cycle impact assessment (LCIA) of 1 tonne POP Primer – Scenario 1.**

## Table 4.19: Weighting for LCIA of 1 tonne POP Primer (Scenario 1).

| Impact category | Unit | Total | RPOo | Catalyst | Formic acid | Hydrogen peroxide | Sodium chloride | Soda (sodium carbonate) | Diol | Tap water | Transport of RPOo | Transport of catalyst | Transport of chemical | Transport soy bean oi | Soy beans oil | Electricity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Carcinogens | Pt | 4.701926 | 0.878429 | 0.041324 | 0.230386 | 0.699654 | 0.099814 | 0.035038 | 0.18107 | 0.01173 | 0.236421 | 0.001041 | 0.259082 | 0.017057 | 0.303442 | 1.707437 |
| Resp. organics | Pt | 0.065511 | 0.024968 | 0.000179 | 0.007921 | 0.013348 | 0.000272 | 9.16E-05 | 0.005889 | 2.1E-05 | 0.000813 | 3.58E-06 | 0.000891 | 5.87E-05 | 0.004078 | 0.006976 |
| Resp. inorganics | Pt | 28.10297 | 7.268313 | 0.922882 | 1.84704 | 4.199327 | 0.379864 | 0.225577 | 2.747015 | 0.020581 | 0.359924 | 0.001585 | 0.394422 | 0.025968 | 1.772536 | 7.937938 |
| Climate change | Pt | 11.98327 | 2.532012 | 0.043961 | 0.856737 | 2.198844 | 0.116513 | 0.052962 | 0.822087 | 0.006175 | 0.062536 | 0.000275 | 0.06853 | 0.004512 | 0.539058 | 4.679071 |
| Radiation | Pt | 0.161263 | 0.016854 | 0.001506 | 0.034169 | 0.066894 | 0.007334 | 0.001011 | 0.026748 | 0.001148 | 0.000593 | 2.61E-06 | 0.00065 | 4.28E-05 | 0.004312 | 0 |
| Ozone layer | Pt | 0.006985 | 0.003766 | 2.05E-05 | 0.000734 | 0.001023 | 3.37E-05 | 5.84E-06 | 7.2E-05 | 1.88E-06 | 4.93E-05 | 2.17E-07 | 5.4E-05 | 3.56E-06 | 0.000329 | 0.000893 |
| Ecotoxicity | Pt | 4.940776 | 0.84493 | 0.077279 | 0.30717 | 1.697859 | 0.182214 | 0.03138 | 0.271554 | 0.003853 | 0.047489 | 0.000209 | 0.052041 | 0.003426 | 0.195198 | 1.226173 |
| Acidification/ Eutrophication | Pt | 3.990321 | 1.211895 | 0.075926 | 0.203523 | 0.440259 | 0.035639 | 0.043554 | 0.366807 | 0.001857 | 0.055723 | 0.000245 | 0.061064 | 0.00402 | 0.272874 | 1.216935 |
| Land use | Pt | 1.459796 | 0.354567 | 0.037253 | 0.291608 | 0.387479 | 0.085351 | 0.022891 | 0.141154 | 0.009834 | 0.019727 | 8.69E-05 | 0.021617 | 0.001423 | 0.086805 | 0 |
| Minerals | Pt | 2.964246 | 0.778882 | 0.08427 | 0.282279 | 1.093377 | 0.204852 | 0.030707 | 0.309786 | 0.003652 | 0.037692 | 0.000166 | 0.041305 | 0.002719 | 0.094558 | 0 |
| Fossil fuels | Pt | 170.8188 | 26.19998 | 0.572305 | 26.83858 | 36.59787 | 0.938551 | 0.194283 | 28.38904 | 0.038272 | 1.089627 | 0.004799 | 1.194065 | 0.078614 | 4.514574 | 44.1682 |

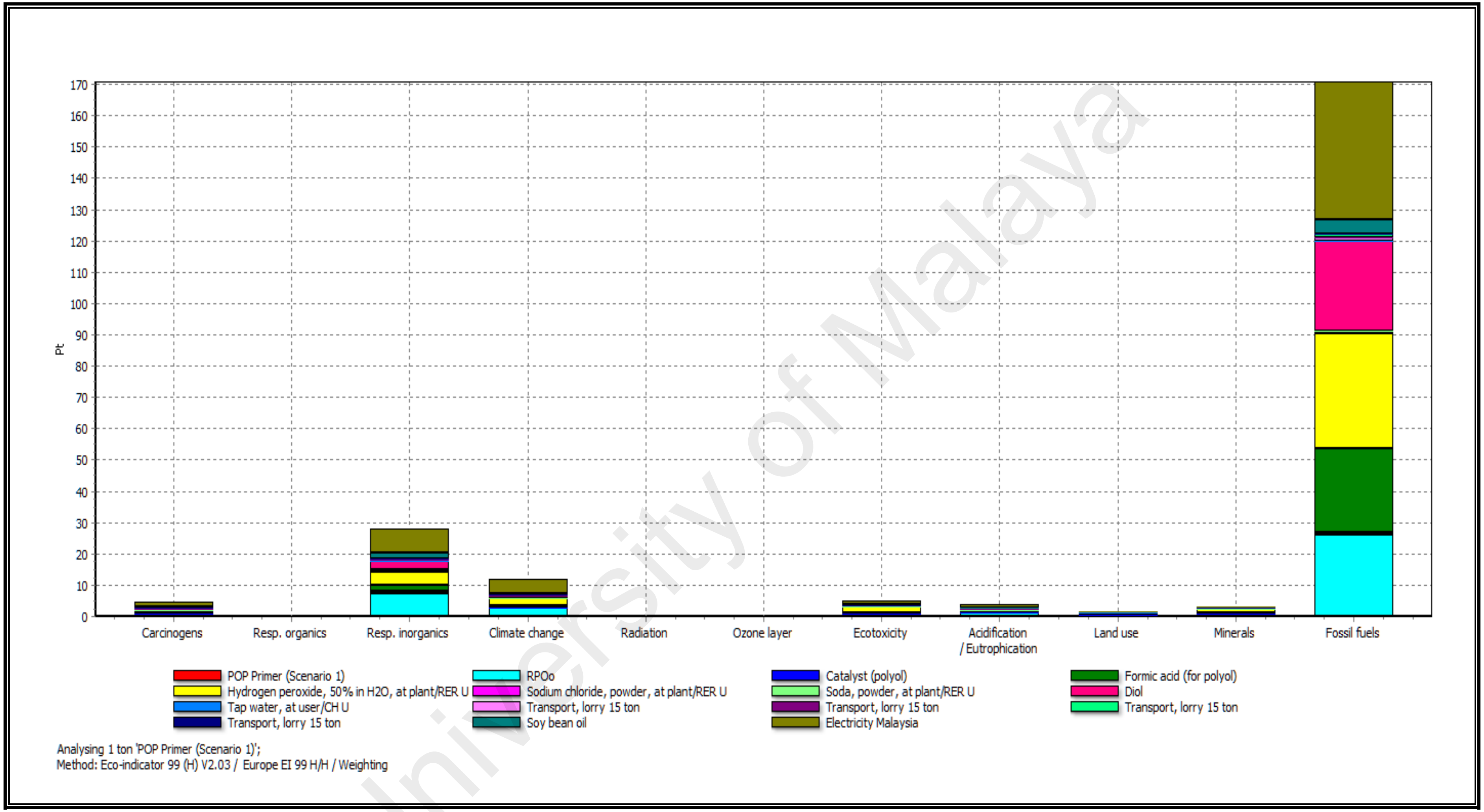


**Figure 4.8: Weighting for life cycle impact assessment (LCIA) of 1 tonne POP Primer – Scenario 1.**

### 4.5.4 Weighting for LCIA of 1 tonne POP Primer Production

The weighting results for the production of POP Primer is similar as in the production of POP Pioneer (Table 4.19). The main impacts and in the same order of significance are again in the categories of fossil fuels, respiratory inorganics and then followed by climate change (Figure 4.8). The impact caused by the electricity for fossil fuels impact category is higher compared to the impact for respiratory inorganics and climate change impact categories. The significant impacts were also similar as had been found by Pollack (2004) in his study on soy-based polyol versus conventional petro-based polyol where the fossil fuels is one of the impact that have been observed in the study findings.

## 4.6 LCIA of POP Premier Production – Scenario 1

### 4.6.1 Characterization for LCIA of 1 tonne POP Premier Production

The data production from the inventory were processes to obtain a higher level of aggregation by characterizing the data (Table 4.20) under the 11 impact categories as outlined in Chapter 3. Figure 4.9 shows the characterized results with the relative contribution from the POP Premier production. The significant impact will be observed for all 11 impact categories for the study.

**Table 4.20: Characterization for LCIA of 1 tonne POP Premier (Scenario 1).**

| Impact category | Unit | Total | RPKOo | Catalyst | Formic acid | Hydrogen peroxide | Sodium chloride | Soda (sodium carbonate) | Diol | Tap water | Transport of RPKOo | Transport of catalyst | Transport of chemical | Transport of soy bean oil | Soy beans oil | Electricity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Carcinogens | DALY | 0.000196 | 3.98E-05 | 1.87E-06 | 5.82E-06 | 1.79E-05 | 4.21E-06 | 8.03E-07 | 3.99E-06 | 6.46E-10 | 1.04E-05 | 4.57E-08 | 7.24E-06 | 8.63E-07 | 1.55E-05 | 8.74E-05 |
| Resp. organics | DALY | 3.88E-06 | 2.56E-06 | 8.1E-09 | 2E-07 | 3.42E-07 | 1.15E-08 | 2.1E-09 | 1.3E-07 | 1.16E-12 | 3.59E-08 | 1.57E-10 | 2.49E-08 | 2.97E-09 | 2.09E-07 | 3.57E-07 |
| Resp. inorganics | DALY | 0.001182 | 0.000379 | 4.17E-05 | 4.66E-05 | 0.000108 | 1.6E-05 | 5.17E-06 | 6.05E-05 | 1.13E-09 | 1.59E-05 | 6.96E-08 | 1.1E-05 | 1.31E-06 | 9.08E-05 | 0.000406 |
| Climate change | DALY | 0.000513 | 0.000137 | 1.99E-06 | 2.16E-05 | 5.63E-05 | 4.91E-06 | 1.21E-06 | 1.81E-05 | 3.4E-10 | 2.76E-06 | 1.21E-08 | 1.91E-06 | 2.28E-07 | 2.76E-05 | 0.00024 |
| Radiation | DALY | 5.29E-06 | 1.46E-06 | 6.8E-08 | 8.63E-07 | 1.71E-06 | 3.09E-07 | 2.31E-08 | 5.89E-07 | 6.32E-11 | 2.62E-08 | 1.15E-10 | 1.81E-08 | 2.16E-09 | 2.21E-07 | 0 |
| Ozone layer | DALY | 1.16E-06 | 1.04E-06 | 9.28E-10 | 1.85E-08 | 2.62E-08 | 1.42E-09 | 1.34E-10 | 1.59E-09 | 1.03E-13 | 2.18E-09 | 9.53E-12 | 1.51E-09 | 1.8E-10 | 1.68E-08 | 4.57E-08 |
| Ecotoxicity | PAF*m2yr | 495.8014 | 131.2242 | 8.741997 | 19.41776 | 108.8371 | 19.23824 | 1.79968 | 14.9703 | 0.000531 | 5.248121 | 0.022984 | 3.639208 | 0.434151 | 25.02542 | 157.2017 |
| Acidification/ Eutrophication | PDF*m2yr | 47.77368 | 19.96125 | 0.858889 | 1.286571 | 2.82217 | 0.376281 | 0.249781 | 2.022142 | 2.56E-05 | 0.615806 | 0.002697 | 0.427019 | 0.050943 | 3.498383 | 15.60172 |
| Land use | PDF*m2yr | 13.85076 | 5.790351 | 0.42141 | 1.8434 | 2.483842 | 0.901141 | 0.131279 | 0.778157 | 0.000136 | 0.218003 | 0.000955 | 0.15117 | 0.018034 | 1.112881 | 0 |
| Minerals | MJ surplus | 50.14062 | 15.73478 | 2.082797 | 3.898748 | 15.3134 | 4.725534 | 0.384771 | 3.731319 | 0.00011 | 0.910102 | 0.003986 | 0.631092 | 0.075288 | 2.648695 | 0 |
| Fossil fuels | MJ surplus | 4498.478 | 1824.537 | 14.14497 | 370.6858 | 512.5752 | 21.65055 | 2.43443 | 341.9408 | 0.001153 | 26.30965 | 0.115225 | 18.24392 | 2.176468 | 126.4586 | 1237.204 |

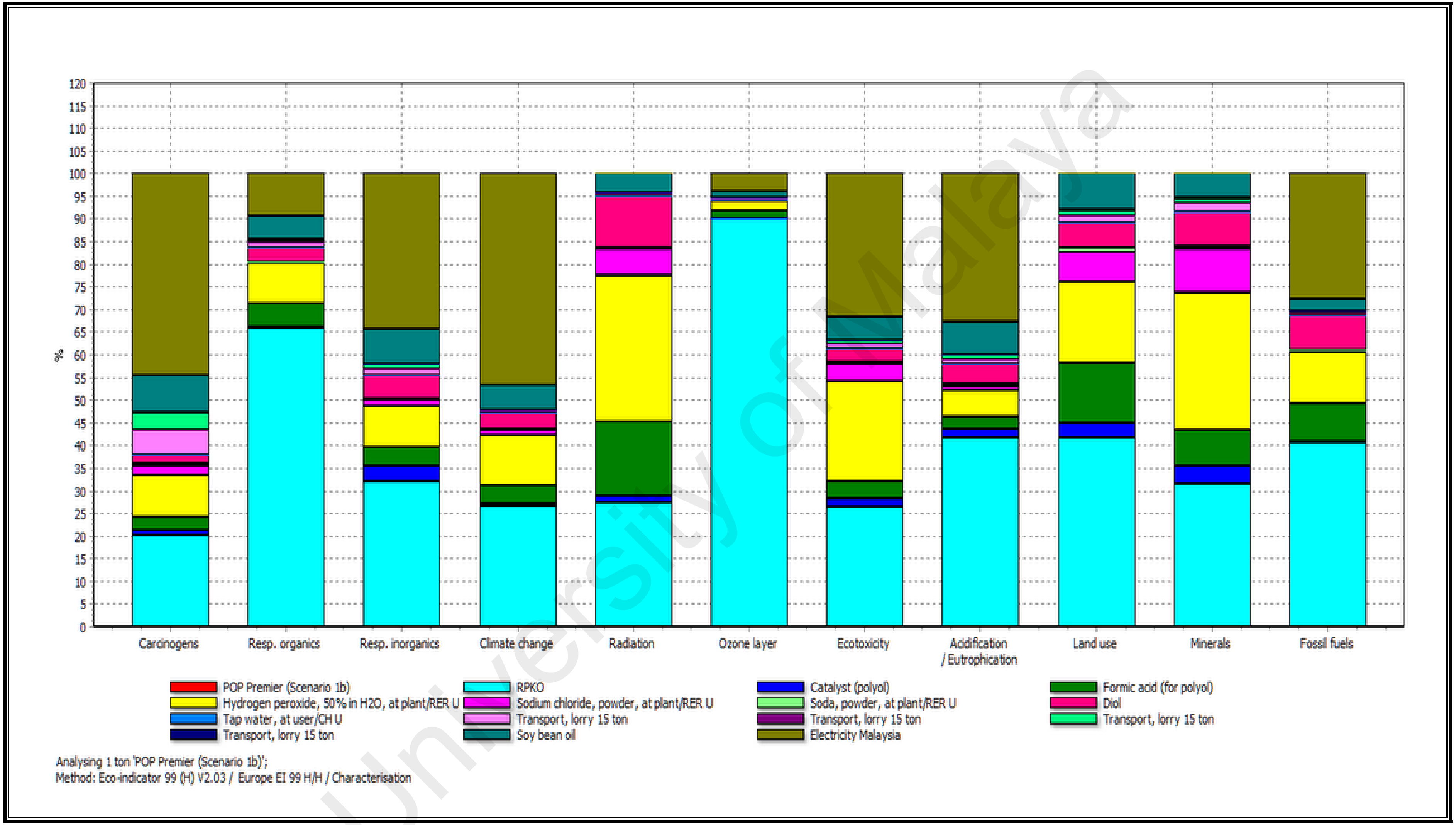


**Figure 4.9: Characterization for life cycle impact assessment (LCIA) of 1 tonne POP Premier – Scenario 1.**

### 4.6.2 Damage Assessment for LCIA of 1 tonne POP Premier Production

In POP Premier production, refined palm kernel olein production contributes the highest impact to all three damage assessment categories followed by the use of electricity. In this case, the data used for refined palm kernel olein is a default data and does not represent Malaysian scenario. There is a reason why the refined palm kernel olein give the highest impact to the production. Based on Table 4.21, it contributed about 40% total damage on resources, 35% total damage on ecosystem and 29% total damage on human health. In this case, the damage on human health was from the emissions of refined palm kernel olein production as shown in Figure 4.10.

### 4.6.3 Normalization for LCIA of 1 tonne POP Premier Production

The magnitude of the impact contributed to the fossil fuels category is about 0.4492 PE (Table 4.22). Same as studies conducted on POP Pioneer and POP Primer, the impact was from electricity followed by the production of hydrogen peroxide with a value of 0.2204 PE and 0.0655 PE, respectively. Other impact categories are not too significant for this scenario.

### 4.6.4 Weighting for LCIA of 1 tonne POP Premier Production

The characterised results were weighted using the weighting factor in Eco-indicator 99 methodology. Weighting is used to compare impact categories among themselves. Figure 4.12 shows the results for POP Premier production for Scenario 1. The most significant impact category is the same as POP Pioneer and POP Primer which are fossil fuels, respiratory inorganics followed by climate change impact categories. Even though the feedstock for each types of polyol is not same; the impact categories affected by each palm polyol production is still same as mentioned above. This shows that the feedstock does not contribute much to the impact associated with the palm-based polyol production as compared to the palm-based polyol process itself where the impacts are from the energy and chemical usage during the epoxidation and alcoholysis to produce palm-based polyol.

**Table 4.21: Damage assessment for LCIA of 1 tonne POP Premier (Scenario 1).**

| Impact category | Unit | Total | RPKOo | Catalyst | Formic acid | Hydrogen peroxide | Sodium chloride | Soda (sodium carbonate) | Diol | Tap water | Transport of RPKOo | Transport of catalyst | Transport of chemical | Transport of soy bean oil | Soy beans oil | Electricity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Human Health | DALY | 0.001901 | 0.00056 | 4.56E-05 | 7.52E-05 | 0.000184 | 2.55E-05 | 7.21E-06 | 8.33E-05 | 2.18E-09 | 2.91E-05 | 1.28E-07 | 2.02E-05 | 2.41E-06 | 0.000134 | 0.000734 |
| Ecosystem Quality | PDF*m2yr | 111.2046 | 38.87402 | 2.154499 | 5.071747 | 16.18972 | 3.201246 | 0.561028 | 4.297329 | 0.000214 | 1.358622 | 0.00595 | 0.94211 | 0.112392 | 7.113807 | 31.32189 |
| Resources | MJ surplus | 4548.619 | 1840.272 | 16.22776 | 374.5846 | 527.8886 | 26.37608 | 2.819201 | 345.6721 | 0.001263 | 27.21976 | 0.119211 | 18.87501 | 2.251756 | 129.1073 | 1237.204 |

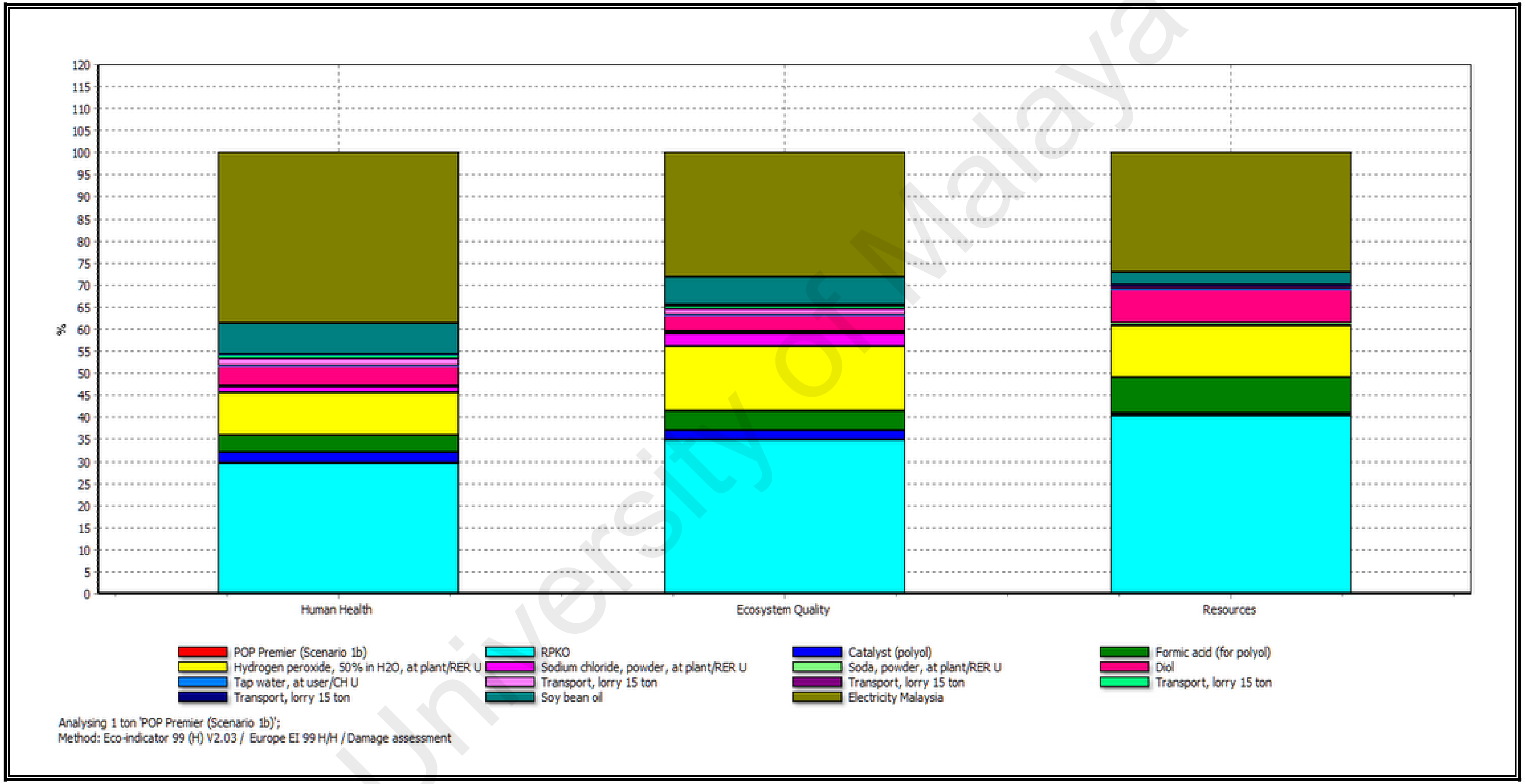


**Figure 4.10: Damage assessment for life cycle impact assessment (LCIA) of 1 tonne POP Premier – Scenario 1.**

## Table 4.22: Normalization for LCIA of 1 tonne POP Premier (Scenario 1).

| Impact category | Total | RPKOo | Catalyst | Formic acid | Hydrogen peroxide | Sodium chloride | Soda (sodium carbonate) | Diol | Tap water | Transport of RPKOo | Transport of catalyst | Transport of chemical | Transport of soy bean oil | Soy beans oil | Electricity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Carcinogens | 0.012754 | 0.002589 | 0.000122 | 0.000379 | 0.001166 | 0.000274 | 5.22E-05 | 0.00026 | 4.2E-08 | 0.000679 | 2.98E-06 | 0.000471 | 5.62E-05 | 0.001011 | 0.005691 |
| Resp. organics | 0.000253 | 0.000167 | 5.27E-07 | 1.3E-05 | 2.22E-05 | 7.48E-07 | 1.37E-07 | 8.44E-06 | 7.52E-11 | 2.34E-06 | 1.02E-08 | 1.62E-06 | 1.93E-07 | 1.36E-05 | 2.33E-05 |
| Resp. inorganics | 0.076922 | 0.024647 | 0.002714 | 0.003036 | 0.006999 | 0.001043 | 0.000336 | 0.003937 | 7.38E-08 | 0.001034 | 4.53E-06 | 0.000717 | 8.56E-05 | 0.005908 | 0.02646 |
| Climate change | 0.033414 | 0.008921 | 0.000129 | 0.001408 | 0.003665 | 0.00032 | 7.9E-05 | 0.001178 | 2.21E-08 | 0.00018 | 7.87E-07 | 0.000125 | 1.49E-05 | 0.001797 | 0.015597 |
| Radiation | 0.000344 | 9.49E-05 | 4.43E-06 | 5.62E-05 | 0.000111 | 2.01E-05 | 1.51E-06 | 3.83E-05 | 4.12E-09 | 1.7E-06 | 7.46E-09 | 1.18E-06 | 1.41E-07 | 1.44E-05 | 0 |
| Ozone layer | 7.53E-05 | 6.78E-05 | 6.04E-08 | 1.21E-06 | 1.7E-06 | 9.25E-08 | 8.7E-09 | 1.03E-07 | 6.72E-12 | 1.42E-07 | 6.21E-10 | 9.83E-08 | 1.17E-08 | 1.1E-06 | 2.98E-06 |
| Ecotoxicity | 0.009668 | 0.002559 | 0.00017 | 0.000379 | 0.002122 | 0.000375 | 3.51E-05 | 0.000292 | 1.04E-08 | 0.000102 | 4.48E-07 | 7.1E-05 | 8.47E-06 | 0.000488 | 0.003065 |
| Acidification/ Eutrophication | 0.009316 | 0.003892 | 0.000167 | 0.000251 | 0.00055 | 7.34E-05 | 4.87E-05 | 0.000394 | 4.99E-09 | 0.00012 | 5.26E-07 | 8.33E-05 | 9.93E-06 | 0.000682 | 0.003042 |
| Land use | 0.002701 | 0.001129 | 8.22E-05 | 0.000359 | 0.000484 | 0.000176 | 2.56E-05 | 0.000152 | 2.64E-08 | 4.25E-05 | 1.86E-07 | 2.95E-05 | 3.52E-06 | 0.000217 | 0 |
| Minerals | 0.005967 | 0.001872 | 0.000248 | 0.000464 | 0.001822 | 0.000562 | 4.58E-05 | 0.000444 | 1.31E-08 | 0.000108 | 4.74E-07 | 7.51E-05 | 8.96E-06 | 0.000315 | 0 |
| Fossil fuels | 0.535319 | 0.21712 | 0.001683 | 0.044112 | 0.060996 | 0.002576 | 0.00029 | 0.040691 | 1.37E-07 | 0.003131 | 1.37E-05 | 0.002171 | 0.000259 | 0.015049 | 0.147227 |

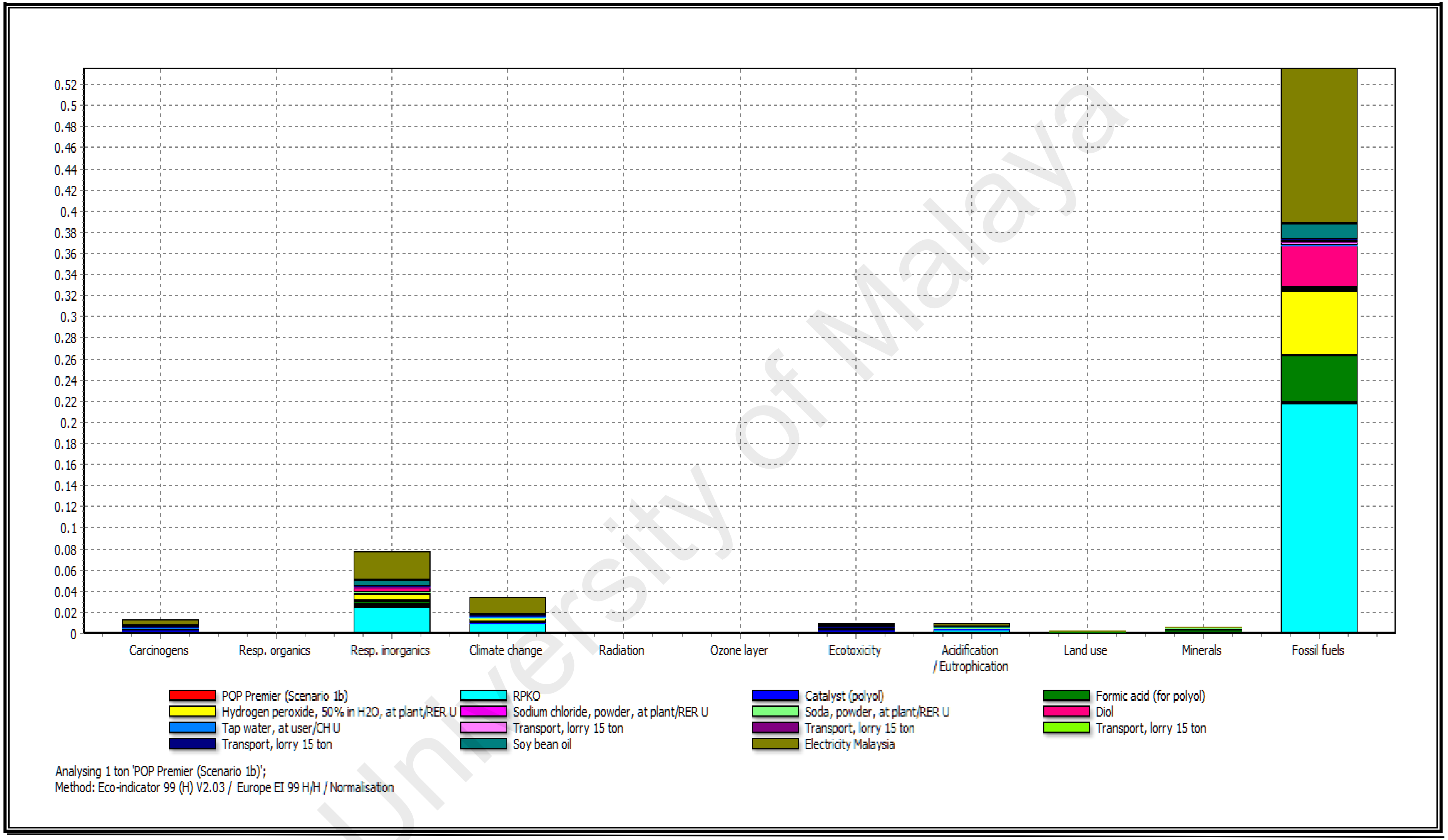


**Figure 4.11: Normalization for life cycle impact assessment (LCIA) of 1 tonne POP Premier – Scenario 1.**

**Table 4.23: Weighting for LCIA of 1 tonne POP Premier (Scenario 1).**

| Impact category | Unit | Total | RPKOo | Catalyst | Formic acid | Hydrogen peroxide | Sodium chloride | Soda (sodium carbonate) | Diol | Tap water | Transport of RPKOo | Transport of catalyst | Transport of chemical | Transport soy bean oi | Soy beans oil | Electricity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Carcinogens | Pt | 3.826195 | 0.776819 | 0.036463 | 0.113598 | 0.349827 | 0.0822 | 0.015674 | 0.07786 | 1.26E-05 | 0.203794 | 0.000893 | 0.141317 | 0.016859 | 0.303442 | 1.707437 |
| Resp. organics | Pt | 0.075862 | 0.050024 | 0.000158 | 0.003906 | 0.006674 | 0.000224 | 4.1E-05 | 0.002532 | 2.26E-08 | 0.000701 | 3.07E-06 | 0.000486 | 5.8E-05 | 0.004078 | 0.006976 |
| Resp. inorganics | Pt | 23.07661 | 7.394039 | 0.814308 | 0.910733 | 2.099664 | 0.312829 | 0.100908 | 1.181216 | 2.21E-05 | 0.310253 | 0.001359 | 0.215139 | 0.025666 | 1.772536 | 7.937938 |
| Climate change | Pt | 10.02407 | 2.676167 | 0.038789 | 0.422437 | 1.099422 | 0.095952 | 0.023692 | 0.353497 | 6.64E-06 | 0.053906 | 0.000236 | 0.03738 | 0.004459 | 0.539058 | 4.679071 |
| Radiation | Pt | 0.103298 | 0.028458 | 0.001329 | 0.016848 | 0.033447 | 0.00604 | 0.000452 | 0.011502 | 1.23E-06 | 0.000511 | 2.24E-06 | 0.000354 | 4.23E-05 | 0.004312 | 0 |
| Ozone layer | Pt | 0.022579 | 0.020329 | 1.81E-05 | 0.000362 | 0.000511 | 2.77E-05 | 2.61E-06 | 3.1E-05 | 2.02E-09 | 4.25E-05 | 1.86E-07 | 2.95E-05 | 3.52E-06 | 0.000329 | 0.000893 |
| Ecotoxicity | Pt | 3.867251 | 1.023549 | 0.068188 | 0.151459 | 0.848929 | 0.150058 | 0.014038 | 0.116768 | 4.14E-06 | 0.040935 | 0.000179 | 0.028386 | 0.003386 | 0.195198 | 1.226173 |
| Acidification/ Eutrophication | Pt | 3.726347 | 1.556977 | 0.066993 | 0.100353 | 0.220129 | 0.02935 | 0.019483 | 0.157727 | 2E-06 | 0.048033 | 0.00021 | 0.033307 | 0.003974 | 0.272874 | 1.216935 |
| Land use | Pt | 1.080359 | 0.451647 | 0.03287 | 0.143785 | 0.19374 | 0.070289 | 0.01024 | 0.060696 | 1.06E-05 | 0.017004 | 7.45E-05 | 0.011791 | 0.001407 | 0.086805 | 0 |
| Minerals | Pt | 1.79002 | 0.561732 | 0.074356 | 0.139185 | 0.546688 | 0.168702 | 0.013736 | 0.133208 | 3.93E-06 | 0.032491 | 0.000142 | 0.02253 | 0.002688 | 0.094558 | 0 |
| Fossil fuels | Pt | 160.5957 | 65.13598 | 0.504975 | 13.23348 | 18.29893 | 0.772924 | 0.086909 | 12.20729 | 4.11E-05 | 0.939255 | 0.004114 | 0.651308 | 0.0777 | 4.514574 | 44.1682 |

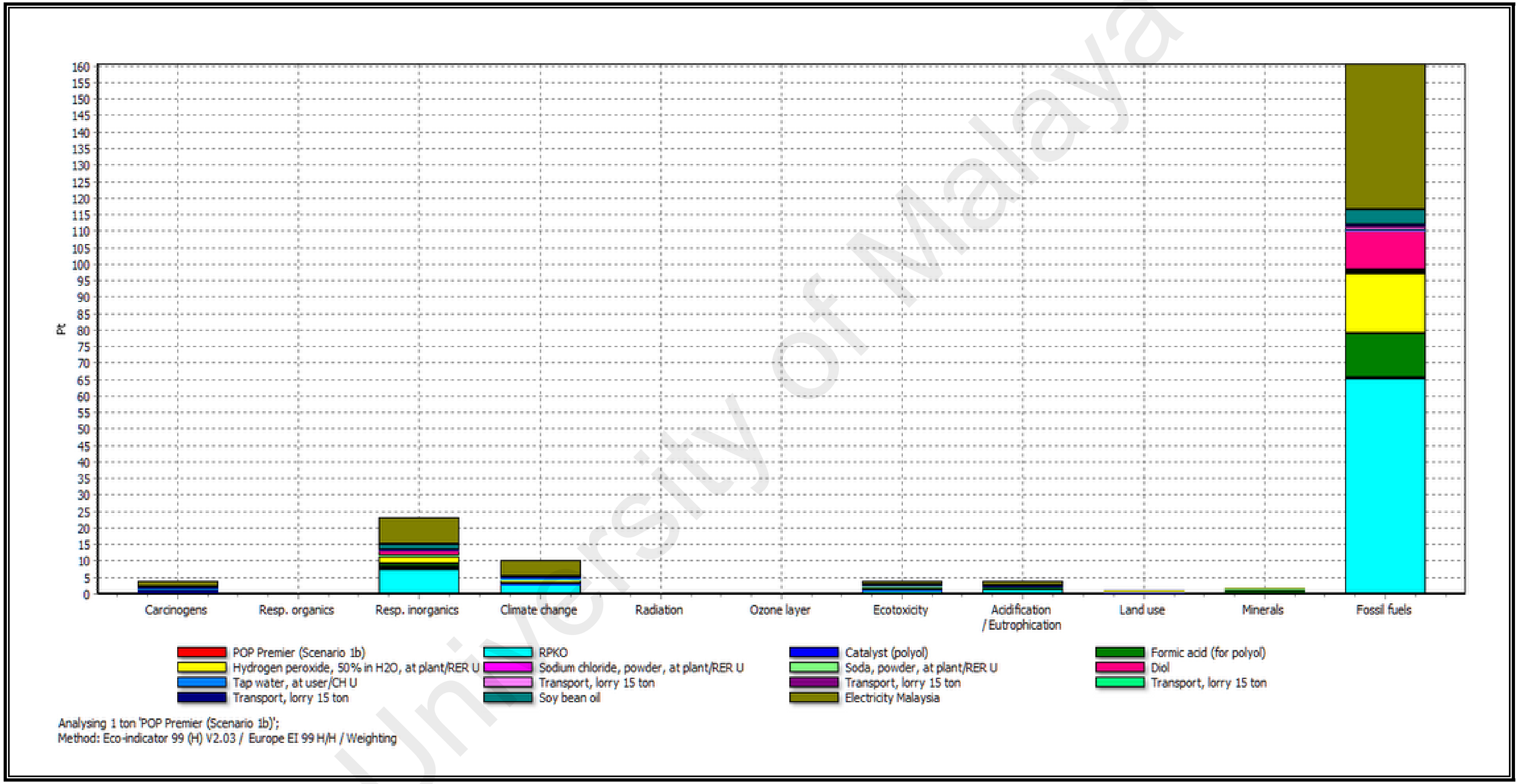


**Figure 4.12: Weighting for life cycle impact assessment (LCIA) of 1 tonne POP Premier – Scenario 1.**

## 4.7 Alternative Scenarios

Alternative scenarios were carried out in order to gauge the impacts when possible improvements are made to the system. For this palm-based polyol production, several inputs were highlighted to be substituted in order to create the lowest impacts for the production i. e. electricity and diols. These inputs were chosen because of their contribution to the impact categories where electricity as a main contributors to fossil fuels category, while glycerol were chosen to substitute diol due to the abundant supply of glycerol obtained from the transesterification of triglycerides and also by-product from biodiesel production. As observed in the LCIA results, it showed the impact on fossil fuels was highest among other categories due to the use of non-renewable resources for electricity production, plus the contribution from the production stage of diols that were used in palm-based polyol process. Two scenarios study will be discussed under alternatives scenario as mentioned in Chapter 3 Table 3.3.

### 4.7.1 Production of Palm-based Polyol using Continued Land Use with Biogas Capture and Substitution of Electricity with Oil Palm Biomass as an Energy Source – Scenario 2

The electricity generated from national grid was substituted with the oil palm biomass, which are shell and mesocarp fibre. These oil palm biomass are actually wastes from the fresh fruit bunch (FFB) and then were recycled as boiler fuel. In the palm oil mill, shell and mesocarp fibre are considered as valuable by-products and were directly burnt as fuel for boiler in order to produce heat to convert water into steam. This steam is then used to run a turbine which generates electricity for the milling process and the whole mill compound (Vijaya, 2009). As in Scenario 1, the total non-renewable primary energy demand for palm-based polyol is 4.97 MJ $kg^{-1}$.

Appendices 1 to 12 show the characterization and weighting results of three types of palm-based polyol by replacing the national grid electricity with the electricity generated at the palm oil mill using oil palm biomass. By using shell and mesocarp fibre as fuels for the production of palm-based polyol, the impact from climate change category was reduced about 39-47% as compared to using electricity from the national grid. Impact from fossil fuels category also decreased about 26-28% which was caused by the use of electricity from biomass as in Scenario 2. The impact from respiratory inorganics were also reduced to about 28-34% compared to Scenario 1. The results are summarised in Table 4.24. Again, these results confirmed that the largest contributor to the impacts for the whole cycle of palm-based polyol production is from the use of electricity. Thus, approach would help to reduce the use of electricity from fossil fuels and also can reduce the GHG emissions from fossil fuels and also the entire process for palm-based polyol production.



**Table 4.24: Percent of difference between Scenario 1 and Scenario 2 on impact categories: climate change, fossil fuels and respiratory inorganics.**

| Parameter | | POP Pioneer | POP Primer | POP Premier |
|---|---|---|---|---|
| Climate change | Scenario 1 | 11.192 | 11.983 | 10.024 |
| | Scenario 2 | 6.513 | 7.304 | 5.345 |
| | % difference | 41.8 | 39.0 | 46.7 |
| Fossil fuels | Scenario 1 | 157.428 | 170.819 | 160.596 |
| | Scenario 2 | 113.259 | 126.651 | 116.428 |
| | % difference | 28.1 | 25.9 | 27.5 |
| Respiratory inorganics | Scenario 1 | 25.551 | 28.103 | 23.077 |
| | Scenario 2 | 17.613 | 20.165 | 15.139 |
| | % difference | 31.3 | 28.2 | 34.4 |

### 4.7.2 Production of Palm-based Polyol using Continued Land Use with Biogas Capture and Substitution of Diol with Glycerol – Scenario 3

As mentioned by Abu Hassan et. al (2011), during the alcoholysis, the epoxide ring of the epoxidized oil will be opened due to nucleophilic addition of the polyhydric alcohol used under the influence of catalyst. The amount of polyhydric alcohol used relies upon the amount and type of epoxidized oil, preferably not less than the mole of oxirane oxygen retained in the epoxidized oil. Polyhydric alcohol in excess amount can be used to prevent polymerization during the alcoholysis reaction. In the base case study, ethylene glycol (diols) was choosen and there are other polyhdric alcohol can be used such as pentaerythritol, propylene glycol, sorbitol, xylitol, trimethylolpropane and glycerol. However for the Scenario 3, the substitution of the material is only applicable as a one of factor to be used in the scenario study. It to focuses on the impact contribution from the materials itself.

For that purpose, glycerol was choosen to replace the diols in alcoholysis reaction. The glycerol used is from the fatty acids production which is considered as a by-product from the production. The reason glycerol was chosen from the fatty acids production is to utilise the by-product from the oleochemical industry for the benefit of other oleochemical production. This replacement is more on screening purpose to find out other suitable diols with the lowest impact generated towards green product and improved environmental performance. Moreover, Dow was recently announced to produce propylene glycol, which is also polyhydric alcohol from glycerol. Huntsman Corp. are also exploring the similar options while Cargill-Ashland and Archer Daniels Midland are planning to produce propylene glycol from glycerol (Michael et. al, 2007). This renewable approach can provide a straightforward contribution to a sustainable development in polyol manufacturing. From the weighting results for the three case studies, i. e. POP Pioneer, POP Primer and POP Premier, it was found that there is no impact generated from the usage of glycerol instead of diol in the palm-based polyol production as shown in Figures 4.13, 4.14 and 4.15, respectively. This is because glycerol is a by-product thus giving a saving to the fatty acids production by using it as a material for other process/production, which is in this case is polyol production. At the same time, it can help to reduce the abundant supply of glycerol in oleochemical industry wisely. Other figures and values for each impact categories are shown in Appendices 13 to 21, respectively.

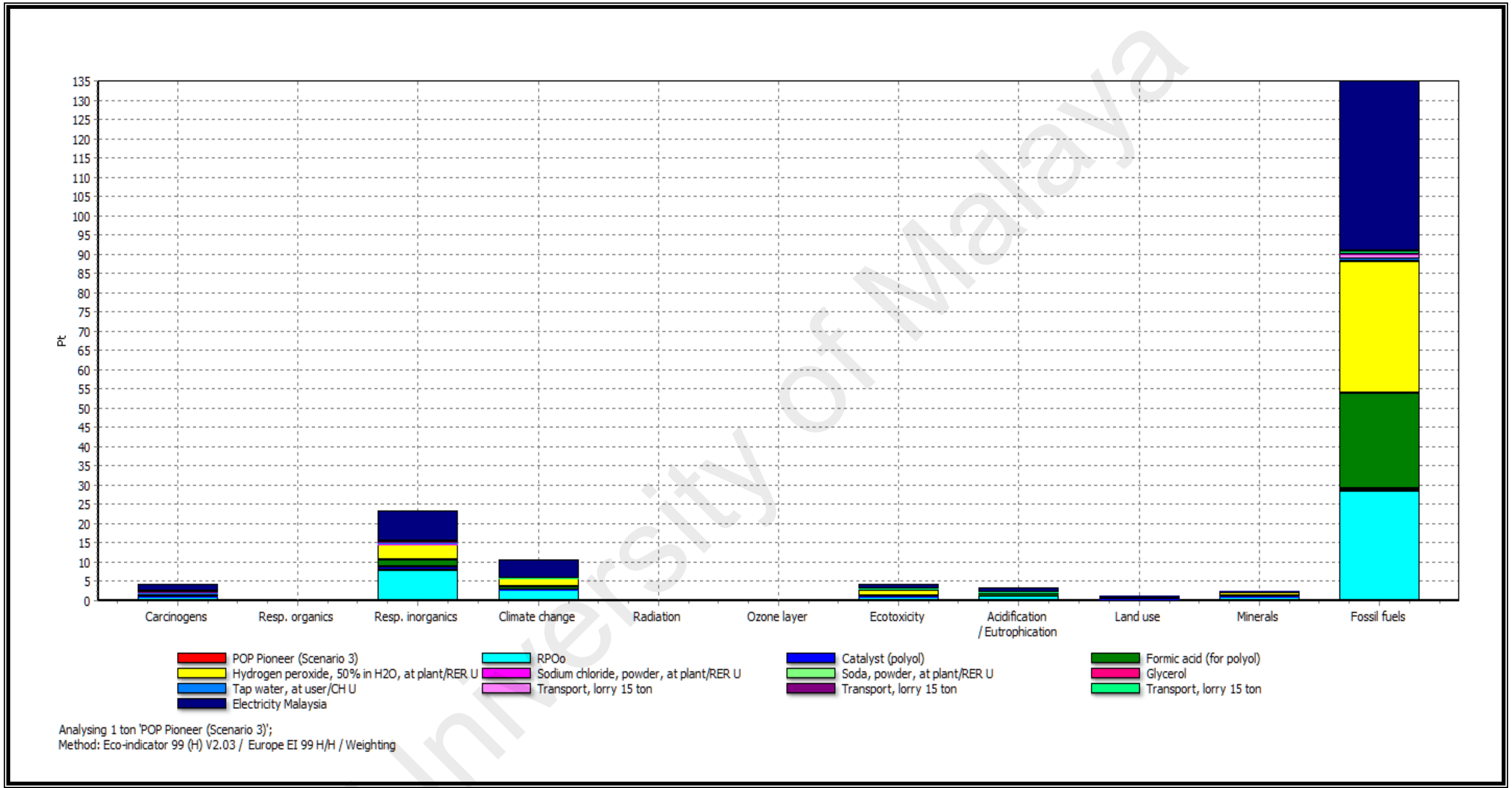


**Figure 4.13: Weighting for life cycle impact assessment (LCIA) of 1 tonne POP Pioneer – Scenario 3.**

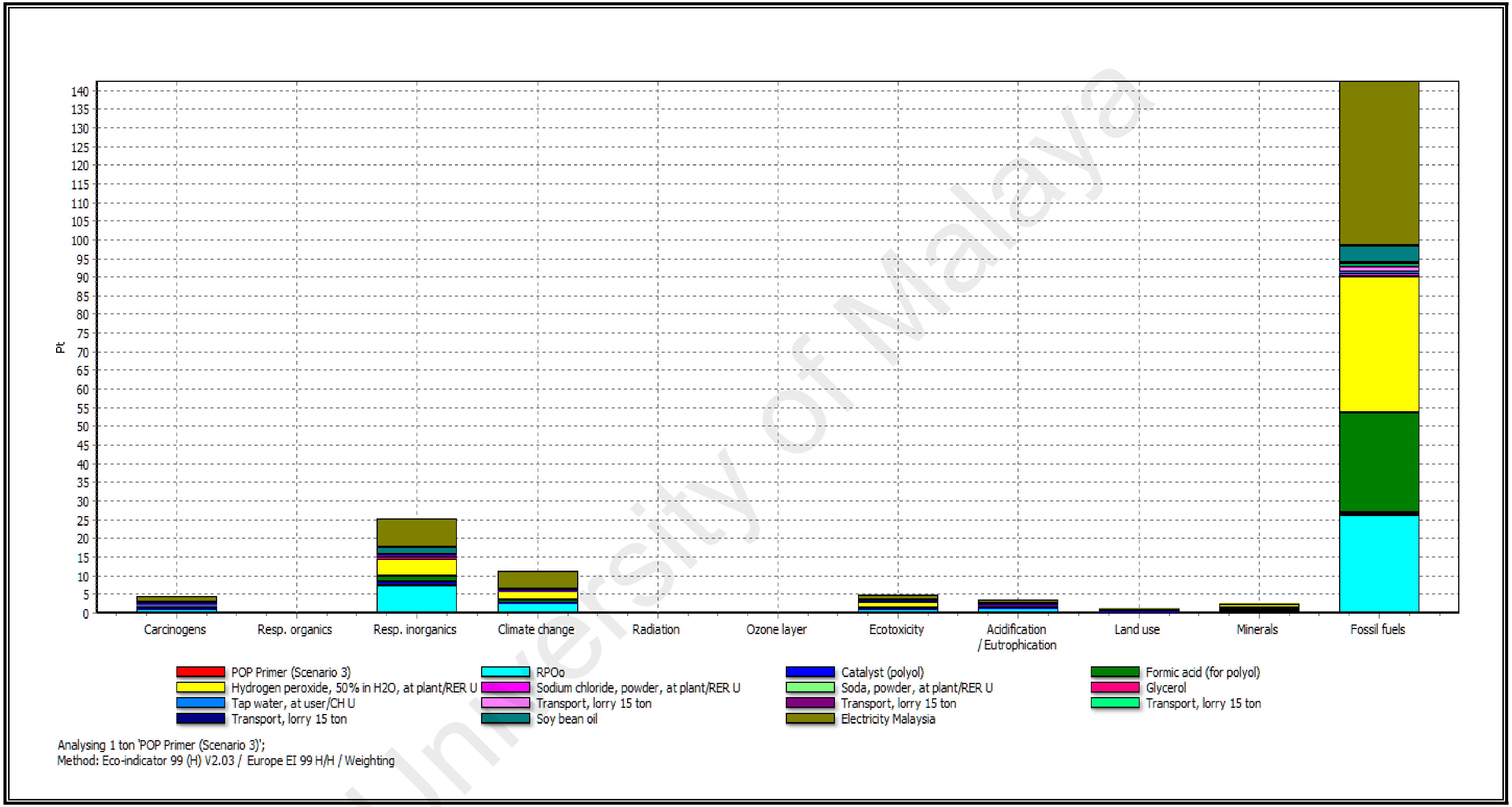


**Figure 4.14: Weighting for life cycle impact assessment (LCIA) of 1 tonne POP Primer – Scenario 3.**

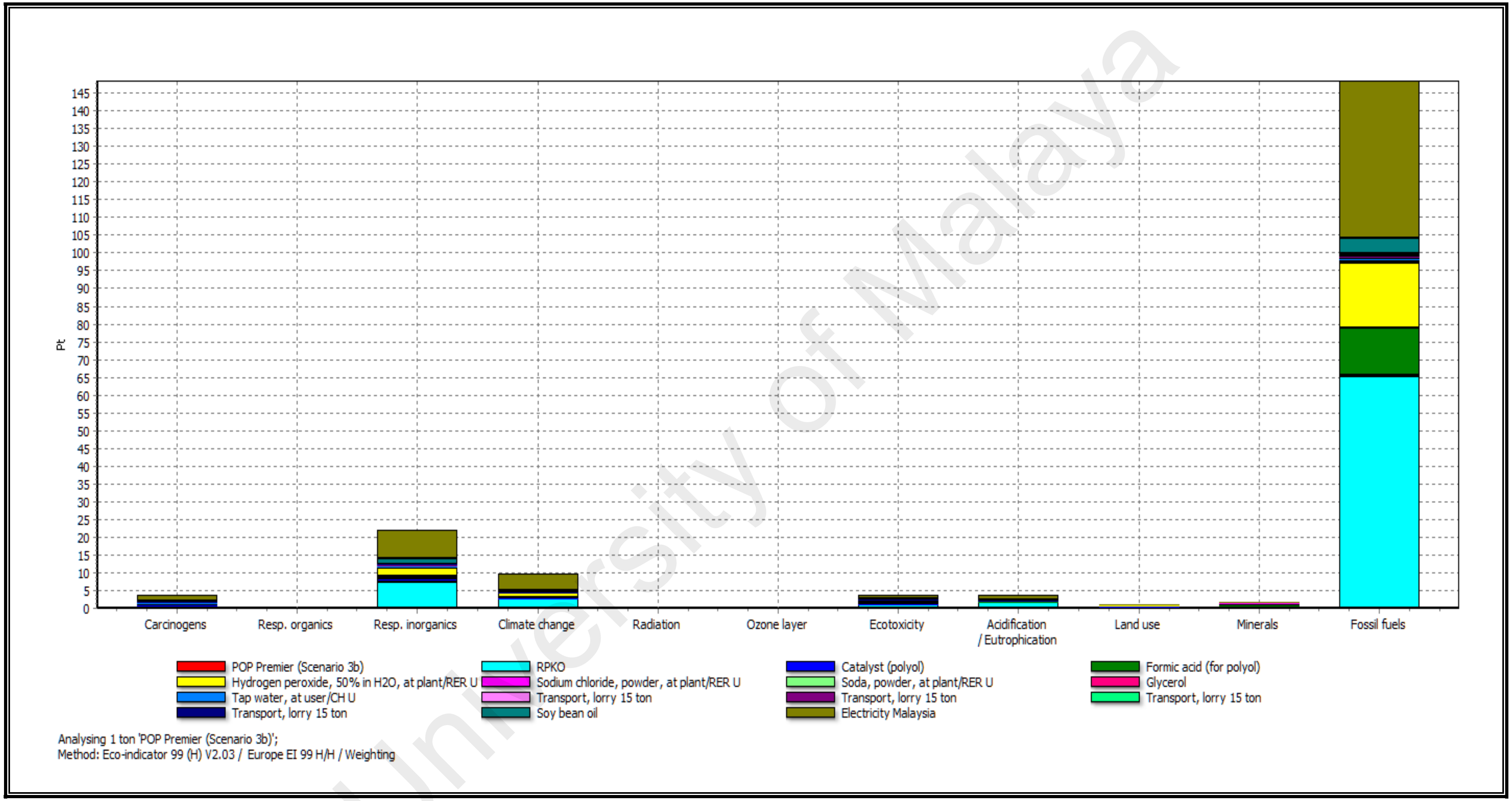


**Figure 4.15: Weighting for life cycle impact assessment (LCIA) of 1 tonne POP Premier – Scenario 3.**

### 4.8 Sensitivity Analysis – Scenario 4

The sensitivity analysis in the LCA study is carried out in order to investigate any changes in calculation the total result of the LCA by assigning any different values of the key figure in study, while all other assumptions are unchanged. The variation in the key figures is chosen on the basis of the uncertainty with which they are burdened. According to the ISO 14044:2006 (E), sensitivity analysis is a procedure to determine how changes in data affect the results of the LCIA (ISO, 2006).

This LCA study does not only focus on the design, process or finish product but also in the life cycle stage of feedstock was used to produce the product. Scenario 1 for the palm-based polyol study is based on the best case scenario which is using continued land use in the plantation with the biogas capture at the palm oil mill. It is well known that in Malaysia all the plantations are from continued land use, since there are old estates and there are no more logged over forest being converted to oil palm plantation. However, in Malaysia as of March 2015, only 73 palm oil mill has implemented biogas capture facility/system. The main reason for this limited number are mainly due to the lack of infrastructure to channel the excess energy either to the national grid or for use in other facilities. Thus under the 8$^{th}$ Malaysia plan, Malaysian energy policy has broadened the four fuel diversification policy to include renewable energy as a fifth fuel in the new five fuel strategy (Vijaya et. al, 2010). Thus, this sensitivity analysis was carried out to consider if the feedstock used in the palm-based polyol production which are refined palm olein or refined palm kernel olein was obtained from the palm oil mill that are not implementing biogas capture system in their system production. This kind of production will cause biogas emissions during the production at the palm oil mill itself.

The sensitivity analysis can determine how the final results are affected by changing the feedstock production. By considering this issue, the scenario for sensitivity analysis was carried out as follows:

- Production of palm-based polyol using continued land use (oil palm to oil palm) with biogas emissions at the palm oil mill

The sensitivity analysis scenario will be compared with the best case study scenario of palm-based polyol (Scenario 1). The characterization and weighting results for three types of palm-based polyol are shown in Tables 4.25 to 4.30 and Figures 4.16 to 4.21, respectively.

**Table 4.25: Characterization for LCIA of 1 tonne POP Pioneer (Sensitivity analysis).**

| Impact category | Unit | Total | RPOo | Catalyst | Formic acid | Hydrogen peroxide, | Sodium chloride | Soda (Sodium carbonate) | Diol | Tap water | Transport of RPOo | Transport of catalyst | Transport of chemicals | **Electricity Malaysia** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Carcinogens | DALY | 0.000216 | 4.65E-05 | 1.97E-06 | 1.09E-05 | 3.36E-05 | 2.71E-06 | 7.1E-07 | 7.28E-06 | 8.48E-07 | 1.32E-05 | 4.82E-08 | 1.09E-05 | 8.74E-05 |
| Resp. organics | DALY | 2.98E-06 | 1.26E-06 | 8.54E-09 | 3.74E-07 | 6.41E-07 | 7.38E-09 | 1.86E-09 | 2.37E-07 | 1.52E-09 | 4.53E-08 | 1.66E-10 | 3.75E-08 | 3.57E-07 |
| Resp. inorganics | DALY | 0.001303 | 0.0004 | 4.4E-05 | 8.73E-05 | 0.000202 | 1.03E-05 | 4.57E-06 | 0.000111 | 1.49E-06 | 2.01E-05 | 7.34E-08 | 1.66E-05 | 0.000406 |
| Climate change | DALY | 0.000781 | 0.000349 | 2.1E-06 | 4.05E-05 | 0.000106 | 3.16E-06 | 1.07E-06 | 3.31E-05 | 4.46E-07 | 3.49E-06 | 1.28E-08 | 2.89E-06 | 0.00024 |
| Radiation | DALY | 8.15E-06 | 1.81E-06 | 7.18E-08 | 1.61E-06 | 3.21E-06 | 1.99E-07 | 2.05E-08 | 1.08E-06 | 8.3E-08 | 3.31E-08 | 1.21E-10 | 2.74E-08 | 0 |
| Ozone layer | DALY | 2.48E-07 | 1.09E-07 | 9.79E-10 | 3.47E-08 | 4.91E-08 | 9.13E-10 | 1.18E-10 | 2.9E-09 | 1.36E-10 | 2.75E-09 | 1.01E-11 | 2.28E-09 | 4.57E-08 |
| Ecotoxicity | PAF*m2yr | 608.6115 | 147.6041 | 9.227664 | 36.35151 | 204.0696 | 12.36744 | 1.593159 | 27.35436 | 0.69721 | 6.629743 | 0.024261 | 5.490735 | 157.2017 |
| Acidification/ Eutrophication | PDF*m2yr | 52.80575 | 22.98068 | 0.906605 | 2.408558 | 5.291569 | 0.241895 | 0.221118 | 3.694945 | 0.033609 | 0.777924 | 0.002847 | 0.644274 | 15.60172 |
| Land use | PDF*m2yr | 17.41609 | 6.063248 | 0.444822 | 3.450982 | 4.657203 | 0.579305 | 0.116214 | 1.421881 | 0.177951 | 0.275395 | 0.001008 | 0.228081 | 0 |
| Minerals | MJ surplus | 74.70331 | 24.0465 | 2.198507 | 7.298749 | 28.71262 | 3.037843 | 0.340617 | 6.818025 | 0.144373 | 1.149695 | 0.004207 | 0.952175 | 0 |
| Fossil fuels | MJ surplus | 4511.739 | 901.2953 | 14.9308 | 693.9516 | 961.0784 | 13.91821 | 2.155069 | 624.8087 | 1.513077 | 33.23594 | 0.121626 | 27.52592 | 1237.204 |

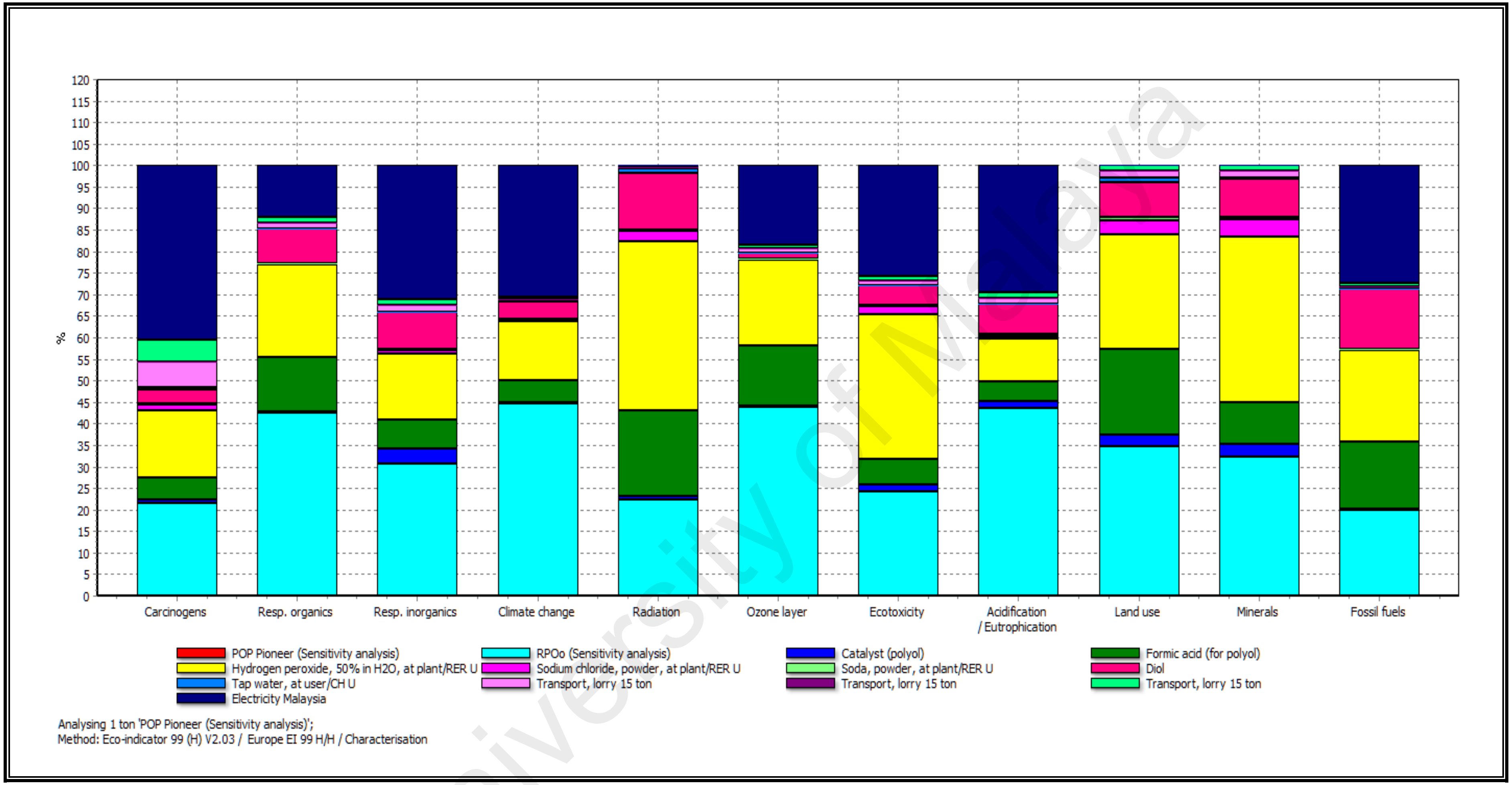


**Figure 4.16: Characterization for life cycle impact assessment (LCIA) of 1 tonne POP Pioneer – Sensitivity analysis.**

## Table 4.26: Weighting for LCIA of 1 tonne POP Pioneer (Sensitivity analysis).

| Impact Category | Unit | Total | RPOo | Catalyst | Formic acid | Hydrogen peroxide | Sodium chloride | Soda (Sodium carbonate) | Diol | Tap water | Transport of RPOo | Transport of catalyst | Transport of chemicals | Electricity Malaysia |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Carcinogens | Pt | 4.219223 | 0.907563 | 0.038488 | 0.212664 | 0.655925 | 0.052843 | 0.013875 | 0.14227 | 0.016556 | 0.257445 | 0.000942 | 0.213216 | 1.707437 |
| Respiratory organics | Pt | 0.058125 | 0.024698 | 0.000167 | 0.007312 | 0.012514 | 0.000144 | 3.63E-05 | 0.004627 | 2.96E-05 | 0.000885 | 3.24E-06 | 0.000733 | 0.006976 |
| Respiratory inorganics | Pt | 25.45321 | 7.818089 | 0.859547 | 1.70496 | 3.936869 | 0.201105 | 0.089329 | 2.158369 | 0.029048 | 0.39193 | 0.001434 | 0.324596 | 7.937938 |
| Climate change | Pt | 15.25387 | 6.819568 | 0.040944 | 0.790834 | 2.061417 | 0.061683 | 0.020973 | 0.645925 | 0.008715 | 0.068097 | 0.000249 | 0.056398 | 4.679071 |
| Radiation | Pt | 0.159128 | 0.03537 | 0.001403 | 0.031541 | 0.062713 | 0.003883 | 0.0004 | 0.021016 | 0.001621 | 0.000645 | 2.36E-06 | 0.000535 | 0 |
| Ozone layer | Pt | 0.004849 | 0.002124 | 1.91E-05 | 0.000677 | 0.000959 | 1.78E-05 | 2.31E-06 | 5.66E-05 | 2.65E-06 | 5.37E-05 | 1.97E-07 | 4.45E-05 | 0.000893 |
| Ecotoxicity | Pt | 4.747169 | 1.151312 | 0.071976 | 0.283542 | 1.591743 | 0.096466 | 0.012427 | 0.213364 | 0.005438 | 0.051712 | 0.000189 | 0.042828 | 1.226173 |
| Acidification/ Eutrophication | Pt | 4.118848 | 1.792493 | 0.070715 | 0.187868 | 0.412742 | 0.018868 | 0.017247 | 0.288206 | 0.002621 | 0.060678 | 0.000222 | 0.050253 | 1.216935 |
| Land use | Pt | 1.358455 | 0.472933 | 0.034696 | 0.269177 | 0.363262 | 0.045186 | 0.009065 | 0.110907 | 0.01388 | 0.021481 | 7.86E-05 | 0.01779 | 0 |
| Minerals | Pt | 2.666908 | 0.85846 | 0.078487 | 0.260565 | 1.025041 | 0.108451 | 0.01216 | 0.243403 | 0.005154 | 0.041044 | 0.00015 | 0.033993 | 0 |
| Fossil fuels | Pt | 161.0691 | 32.17624 | 0.533029 | 24.77407 | 34.3105 | 0.49688 | 0.076936 | 22.30567 | 0.054017 | 1.186523 | 0.004342 | 0.982675 | 44.1682 |

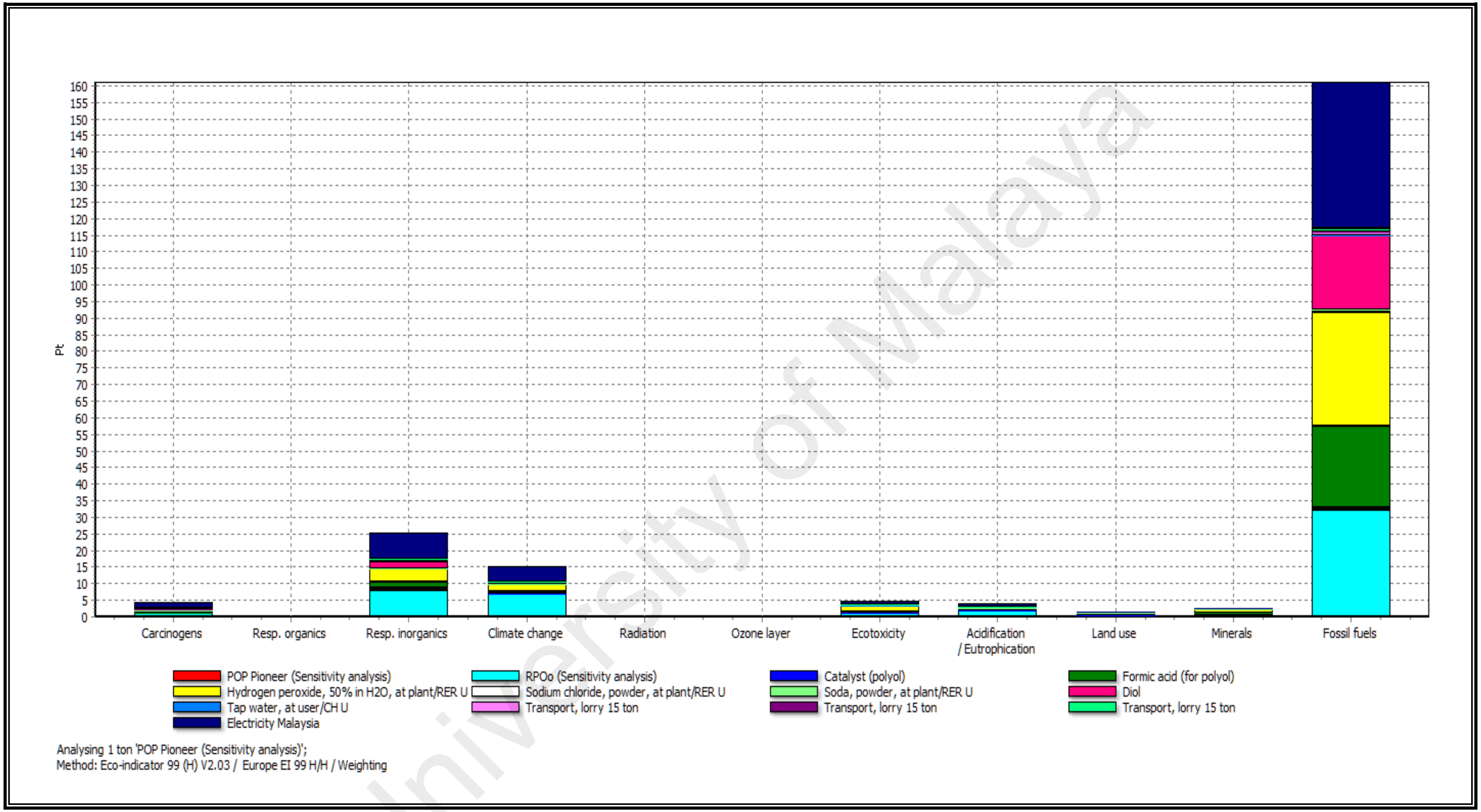


**Figure 4.17: Weighting for life cycle impact assessment (LCIA) of 1 tonne POP Pioneer – Sensitivity analysis.**

## Table 4.27: Characterization for LCIA of 1 tonne POP Primer (Sensitivity analysis).

| Impact category | Unit | Total | RPOo | Catalyst | Formic acid | Hydrogen peroxide | Sodium chloride | Soda (sodium carbonate) | Diol | Tap water | Transport of RPOo | Transport of catalyst | Transport of chemical | Transport of soy bean oil | Soy beans oil | Electricity Malaysia |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Carcinogens | DALY | 0.000238 | 4.27E-05 | 2.12E-06 | 1.18E-05 | 3.58E-05 | 5.11E-06 | 1.79E-06 | 9.27E-06 | 6.01E-07 | 1.21E-05 | 5.33E-08 | 1.33E-05 | 8.73E-07 | 1.55E-05 | 8.74E-05 |
| Resp. organics | DALY | 3.24E-06 | 1.16E-06 | 9.17E-09 | 4.06E-07 | 6.83E-07 | 1.39E-08 | 4.69E-09 | 3.02E-07 | 1.07E-09 | 4.16E-08 | 1.83E-10 | 4.56E-08 | 3E-09 | 2.09E-07 | 3.57E-07 |
| Resp. inorganics | DALY | 0.001434 | 0.000368 | 4.73E-05 | 9.46E-05 | 0.000215 | 1.95E-05 | 1.16E-05 | 0.000141 | 1.05E-06 | 1.84E-05 | 8.12E-08 | 2.02E-05 | 1.33E-06 | 9.08E-05 | 0.000406 |
| Climate change | DALY | 0.000805 | 0.000321 | 2.25E-06 | 4.39E-05 | 0.000113 | 5.97E-06 | 2.71E-06 | 4.21E-05 | 3.16E-07 | 3.2E-06 | 1.41E-08 | 3.51E-06 | 2.31E-07 | 2.76E-05 | 0.00024 |
| Radiation | DALY | 9.06E-06 | 1.66E-06 | 7.71E-08 | 1.75E-06 | 3.43E-06 | 3.76E-07 | 5.17E-08 | 1.37E-06 | 5.88E-08 | 3.04E-08 | 1.34E-10 | 3.33E-08 | 2.19E-09 | 2.21E-07 | 0 |
| Ozone layer | DALY | 2.65E-07 | 9.98E-08 | 1.05E-09 | 3.76E-08 | 5.24E-08 | 1.73E-09 | 2.99E-10 | 3.69E-09 | 9.61E-11 | 2.53E-09 | 1.11E-11 | 2.77E-09 | 1.82E-10 | 1.68E-08 | 4.57E-08 |
| Ecotoxicity | PAF*m2yr | 660.6359 | 135.5274 | 9.907597 | 39.3808 | 217.6742 | 23.36073 | 4.023129 | 34.81464 | 0.49399 | 6.088331 | 0.026815 | 6.671881 | 0.439259 | 25.02542 | 157.2017 |
| Acidification/ Eutrophication | PDF*m2yr | 56.72128 | 21.10044 | 0.973408 | 2.609271 | 5.64434 | 0.456913 | 0.558378 | 4.702657 | 0.023813 | 0.714395 | 0.003146 | 0.782868 | 0.051542 | 3.498383 | 15.60172 |
| Land use | PDF*m2yr | 19.73676 | 5.567164 | 0.477598 | 3.738563 | 4.967683 | 1.094243 | 0.29347 | 1.809667 | 0.126083 | 0.252905 | 0.001114 | 0.277145 | 0.018246 | 1.112881 | 0 |
| Minerals | MJ surplus | 83.29373 | 22.07906 | 2.360503 | 7.906978 | 30.62679 | 5.738149 | 0.860144 | 8.677486 | 0.102292 | 1.055807 | 0.00465 | 1.157003 | 0.076174 | 2.648695 | 0 |
| Fossil fuels | MJ surplus | 4878.499 | 827.553 | 16.03096 | 751.7809 | 1025.15 | 26.28995 | 5.442093 | 795.2111 | 1.072051 | 30.52176 | 0.134429 | 33.44719 | 2.202073 | 126.4586 | 1237.204 |

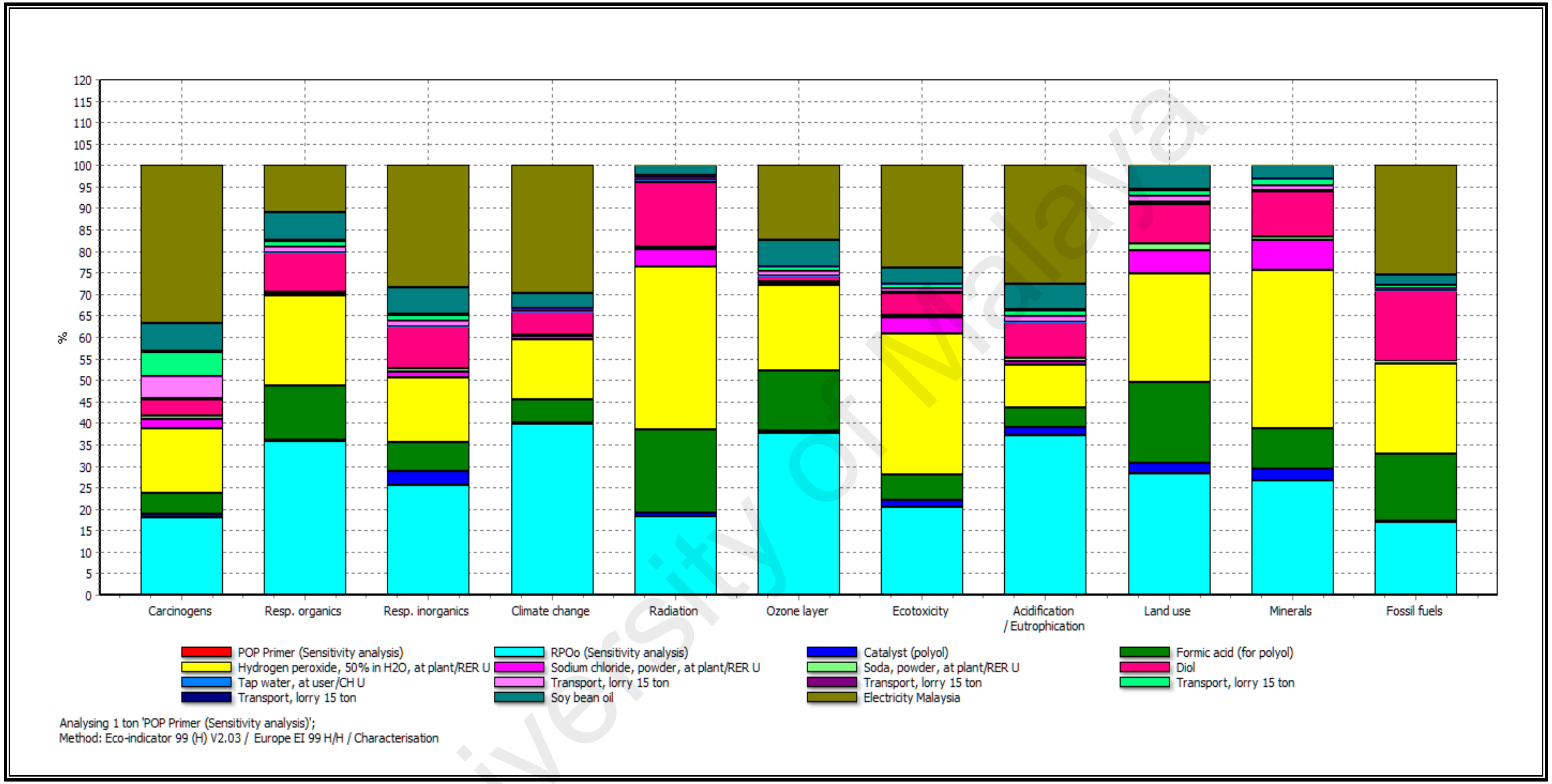


**Figure 4.18: Characterization for life cycle impact assessment (LCIA) of 1 tonne POP Primer – Sensitivity analysis.**

## Table 4.28: Weighting for LCIA of 1 tonne POP Primer (Sensitivity analysis).

| Impact category | Unit | Total | RPOo | Catalyst | Formic acid | Hydrogen peroxide | Sodium chloride | Soda (sodium carbonate) | Diol | Tap water | Transport of RPOo | Transport of catalyst | Transport of chemical | Transport soy bean oi | Soy beans oil | Electricity Malaysia |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Carcinogens | Pt | 4.656805 | 0.833308 | 0.041324 | 0.230386 | 0.699654 | 0.099814 | 0.035038 | 0.18107 | 0.01173 | 0.236421 | 0.001041 | 0.259082 | 0.017057 | 0.303442 | 1.707437 |
| Resp. organics | Pt | 0.06322 | 0.022677 | 0.000179 | 0.007921 | 0.013348 | 0.000272 | 9.16E-05 | 0.005889 | 2.1E-05 | 0.000813 | 3.58E-06 | 0.000891 | 5.87E-05 | 0.004078 | 0.006976 |
| Resp. inorganics | Pt | 28.01309 | 7.178427 | 0.922882 | 1.84704 | 4.199327 | 0.379864 | 0.225577 | 2.747015 | 0.020581 | 0.359924 | 0.001585 | 0.394422 | 0.025968 | 1.772536 | 7.937938 |
| Climate change | Pt | 15.71286 | 6.261604 | 0.043961 | 0.856737 | 2.198844 | 0.116513 | 0.052962 | 0.822087 | 0.006175 | 0.062536 | 0.000275 | 0.06853 | 0.004512 | 0.539058 | 4.679071 |
| Radiation | Pt | 0.176885 | 0.032476 | 0.001506 | 0.034169 | 0.066894 | 0.007334 | 0.001011 | 0.026748 | 0.001148 | 0.000593 | 2.61E-06 | 0.00065 | 4.28E-05 | 0.004312 | 0 |
| Ozone layer | Pt | 0.005168 | 0.00195 | 2.05E-05 | 0.000734 | 0.001023 | 3.37E-05 | 5.84E-06 | 7.2E-05 | 1.88E-06 | 4.93E-05 | 2.17E-07 | 5.4E-05 | 3.56E-06 | 0.000329 | 0.000893 |
| Ecotoxicity | Pt | 5.15296 | 1.057114 | 0.077279 | 0.30717 | 1.697859 | 0.182214 | 0.03138 | 0.271554 | 0.003853 | 0.047489 | 0.000209 | 0.052041 | 0.003426 | 0.195198 | 1.226173 |
| Acidification/ Eutrophication | Pt | 4.42426 | 1.645835 | 0.075926 | 0.203523 | 0.440259 | 0.035639 | 0.043554 | 0.366807 | 0.001857 | 0.055723 | 0.000245 | 0.061064 | 0.00402 | 0.272874 | 1.216935 |
| Land use | Pt | 1.539468 | 0.434239 | 0.037253 | 0.291608 | 0.387479 | 0.085351 | 0.022891 | 0.141154 | 0.009834 | 0.019727 | 8.69E-05 | 0.021617 | 0.001423 | 0.086805 | 0 |
| Minerals | Pt | 2.973586 | 0.788222 | 0.08427 | 0.282279 | 1.093377 | 0.204852 | 0.030707 | 0.309786 | 0.003652 | 0.037692 | 0.000166 | 0.041305 | 0.002719 | 0.094558 | 0 |
| Fossil fuels | Pt | 174.1624 | 29.54364 | 0.572305 | 26.83858 | 36.59787 | 0.938551 | 0.194283 | 28.38904 | 0.038272 | 1.089627 | 0.004799 | 1.194065 | 0.078614 | 4.514574 | 44.1682 |

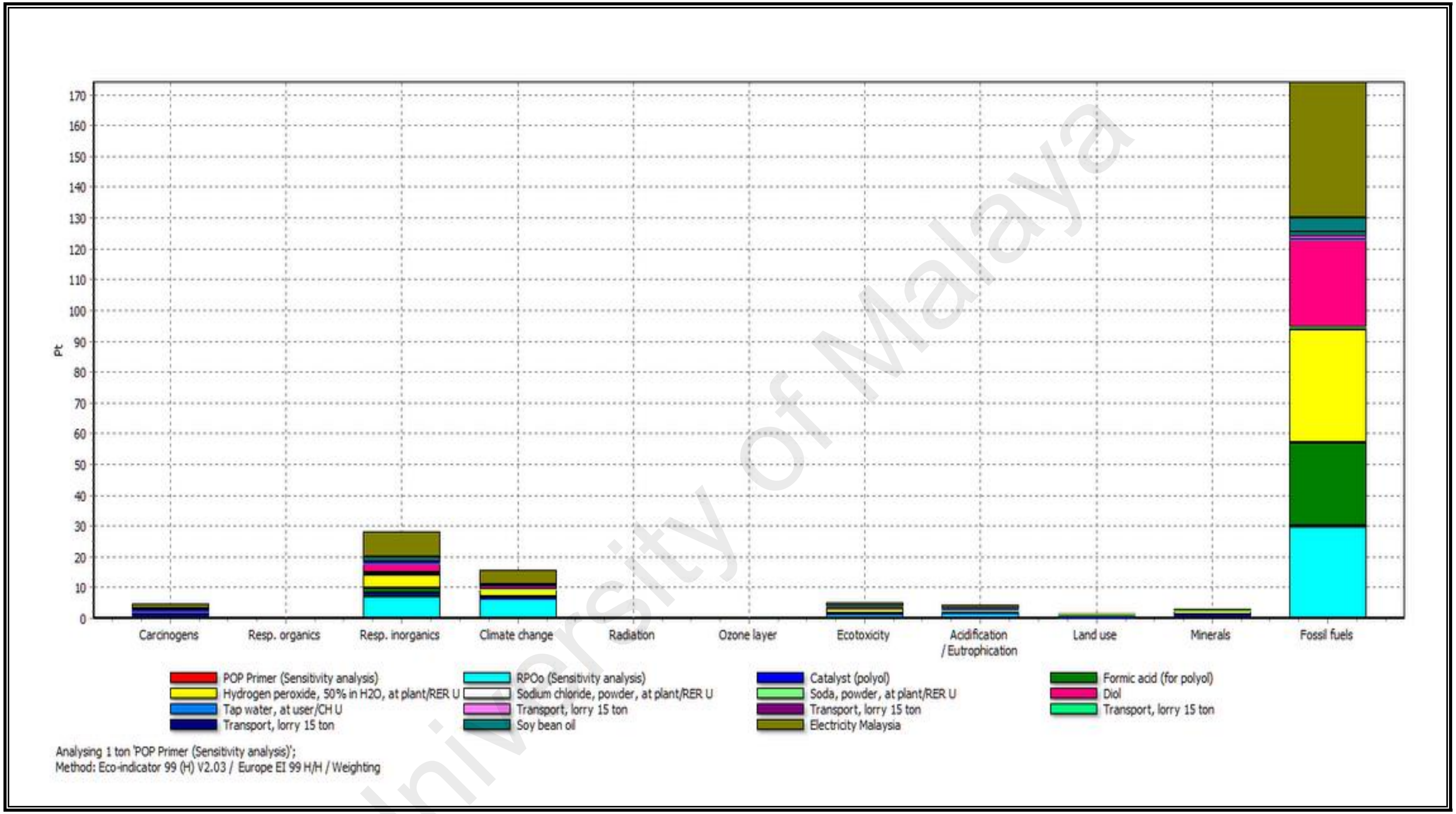


**Figure 4.19: Weighting for life cycle impact assessment (LCIA) of 1 tonne POP Primer – Sensitivity analysis.**

## Table 4.29: Characterization for LCIA of 1 tonne POP Premier (Sensitivity analysis).

| Impact category | Unit | Total | RPKOo | Catalyst | Formic acid | Hydrogen peroxide | Sodium chloride | Soda (sodium carbonate) | Diol | Tap water | Transport of RPKOo | Transport of catalyst | Transport of chemical | Transport of soy bean oil | Soy beans oil | Electricity Malaysia |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Carcinogens | DALY | 0.000196 | 3.98E-05 | 1.87E-06 | 5.82E-06 | 1.79E-05 | 4.21E-06 | 8.03E-07 | 3.99E-06 | 6.46E-10 | 1.04E-05 | 4.57E-08 | 7.24E-06 | 8.63E-07 | 1.55E-05 | 8.74E-05 |
| Resp. organics | DALY | 4.19E-06 | 2.87E-06 | 8.1E-09 | 2E-07 | 3.42E-07 | 1.15E-08 | 2.1E-09 | 1.3E-07 | 1.16E-12 | 3.59E-08 | 1.57E-10 | 2.49E-08 | 2.97E-09 | 2.09E-07 | 3.57E-07 |
| Resp. inorganics | DALY | 0.001182 | 0.000379 | 4.17E-05 | 4.66E-05 | 0.000108 | 1.6E-05 | 5.17E-06 | 6.05E-05 | 1.13E-09 | 1.59E-05 | 6.96E-08 | 1.1E-05 | 1.31E-06 | 9.08E-05 | 0.000406 |
| Climate change | DALY | 0.000626 | 0.00025 | 1.99E-06 | 2.16E-05 | 5.63E-05 | 4.91E-06 | 1.21E-06 | 1.81E-05 | 3.4E-10 | 2.76E-06 | 1.21E-08 | 1.91E-06 | 2.28E-07 | 2.76E-05 | 0.00024 |
| Radiation | DALY | 5.29E-06 | 1.46E-06 | 6.8E-08 | 8.63E-07 | 1.71E-06 | 3.09E-07 | 2.31E-08 | 5.89E-07 | 6.32E-11 | 2.62E-08 | 1.15E-10 | 1.81E-08 | 2.16E-09 | 2.21E-07 | 0 |
| Ozone layer | DALY | 1.16E-06 | 1.04E-06 | 9.28E-10 | 1.85E-08 | 2.62E-08 | 1.42E-09 | 1.34E-10 | 1.59E-09 | 1.03E-13 | 2.18E-09 | 9.53E-12 | 1.51E-09 | 1.8E-10 | 1.68E-08 | 4.57E-08 |
| Ecotoxicity | PAF*m2yr | 495.8014 | 131.2242 | 8.741997 | 19.41776 | 108.8371 | 19.23824 | 1.79968 | 14.9703 | 0.000531 | 5.248121 | 0.022984 | 3.639208 | 0.434151 | 25.02542 | 157.2017 |
| Acidification/ Eutrophication | PDF*m2yr | 47.77368 | 19.96125 | 0.858889 | 1.286571 | 2.82217 | 0.376281 | 0.249781 | 2.022142 | 2.56E-05 | 0.615806 | 0.002697 | 0.427019 | 0.050943 | 3.498383 | 15.60172 |
| Land use | PDF*m2yr | 13.85076 | 5.790351 | 0.42141 | 1.843399 | 2.483842 | 0.901141 | 0.131279 | 0.778157 | 0.000136 | 0.218003 | 0.000955 | 0.15117 | 0.018034 | 1.112881 | 0 |
| Minerals | MJ surplus | 50.14062 | 15.73478 | 2.082797 | 3.898748 | 15.3134 | 4.725534 | 0.384771 | 3.731319 | 0.00011 | 0.910102 | 0.003986 | 0.631092 | 0.075288 | 2.648695 | 0 |
| Fossil fuels | MJ surplus | 4498.478 | 1824.537 | 14.14497 | 370.6858 | 512.5752 | 21.65055 | 2.43443 | 341.9408 | 0.001153 | 26.30965 | 0.115225 | 18.24392 | 2.176468 | 126.4586 | 1237.204 |

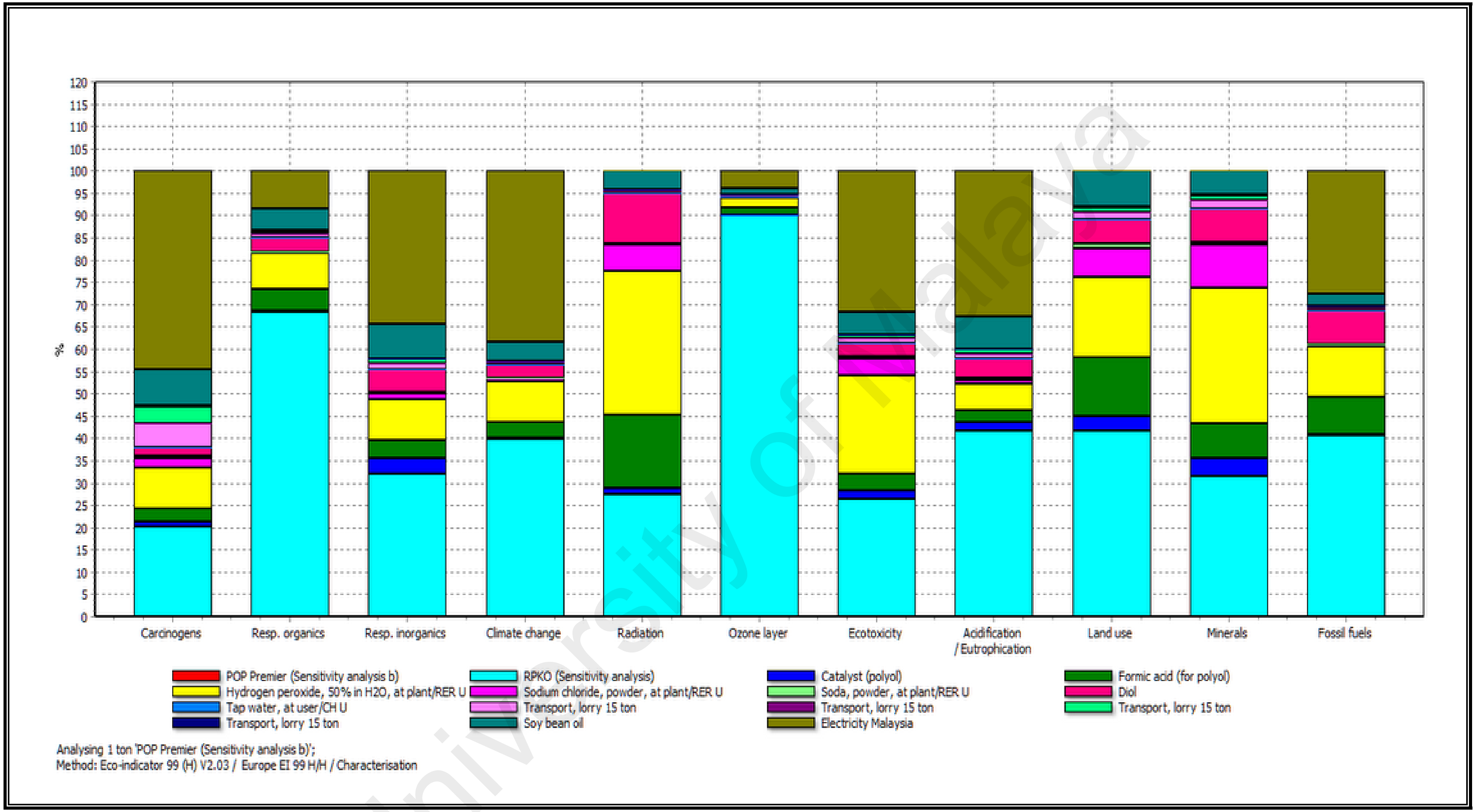


**Figure 4.20: Characterization for life cycle impact assessment (LCIA) of 1 tonne POP Premier - Sensitivity analysis.**

## Table 4.30: Weighting for LCIA of 1 tonne POP Premier (Sensitivity analysis).

| Impact category | Unit | Total | RPKOo | Catalyst | Formic acid | Hydrogen peroxide | Sodium chloride | Soda (sodium carbonate) | Diol | Tap water | Transport of RPKOo | Transport of catalyst | Transport of chemical | Transport of soy bean oil | Soy beans oil | Electricity Malaysia |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Carcinogens | Pt | 3.826195 | 0.776819 | 0.036463 | 0.113598 | 0.349827 | 0.0822 | 0.015674 | 0.07786 | 1.26E-05 | 0.203794 | 0.000893 | 0.141317 | 0.016859 | 0.303442 | 1.707437 |
| Resp. organics | Pt | 0.081911 | 0.056073 | 0.000158 | 0.003906 | 0.006674 | 0.000224 | 4.1E-05 | 0.002532 | 2.26E-08 | 0.000701 | 3.07E-06 | 0.000486 | 5.8E-05 | 0.004078 | 0.006976 |
| Resp. inorganics | Pt | 23.07661 | 7.394039 | 0.814308 | 0.910733 | 2.099664 | 0.312829 | 0.100908 | 1.181216 | 2.21E-05 | 0.310253 | 0.001359 | 0.215139 | 0.025666 | 1.772536 | 7.937938 |
| Climate change | Pt | 12.22078 | 4.872873 | 0.038789 | 0.422437 | 1.099422 | 0.095952 | 0.023692 | 0.353497 | 6.64E-06 | 0.053906 | 0.000236 | 0.03738 | 0.004459 | 0.539058 | 4.679071 |
| Radiation | Pt | 0.103298 | 0.028458 | 0.001329 | 0.016848 | 0.033447 | 0.00604 | 0.000452 | 0.011502 | 1.23E-06 | 0.000511 | 2.24E-06 | 0.000354 | 4.23E-05 | 0.004312 | 0 |
| Ozone layer | Pt | 0.022579 | 0.020329 | 1.81E-05 | 0.000362 | 0.000511 | 2.77E-05 | 2.61E-06 | 3.1E-05 | 2.02E-09 | 4.25E-05 | 1.86E-07 | 2.95E-05 | 3.52E-06 | 0.000329 | 0.000893 |
| Ecotoxicity | Pt | 3.867251 | 1.023549 | 0.068188 | 0.151459 | 0.848929 | 0.150058 | 0.014038 | 0.116768 | 4.14E-06 | 0.040935 | 0.000179 | 0.028386 | 0.003386 | 0.195198 | 1.226173 |
| Acidification/ Eutrophication | Pt | 3.726347 | 1.556977 | 0.066993 | 0.100353 | 0.220129 | 0.02935 | 0.019483 | 0.157727 | 2E-06 | 0.048033 | 0.00021 | 0.033307 | 0.003974 | 0.272874 | 1.216935 |
| Land use | Pt | 1.080359 | 0.451647 | 0.03287 | 0.143785 | 0.19374 | 0.070289 | 0.01024 | 0.060696 | 1.06E-05 | 0.017004 | 7.45E-05 | 0.011791 | 0.001407 | 0.086805 | 0 |
| Minerals | Pt | 1.79002 | 0.561732 | 0.074356 | 0.139185 | 0.546688 | 0.168702 | 0.013736 | 0.133208 | 3.93E-06 | 0.032491 | 0.000142 | 0.02253 | 0.002688 | 0.094558 | 0 |
| Fossil fuels | Pt | 160.5957 | 65.13598 | 0.504975 | 13.23348 | 18.29893 | 0.772924 | 0.086909 | 12.20729 | 4.11E-05 | 0.939255 | 0.004114 | 0.651308 | 0.0777 | 4.514574 | 44.1682 |

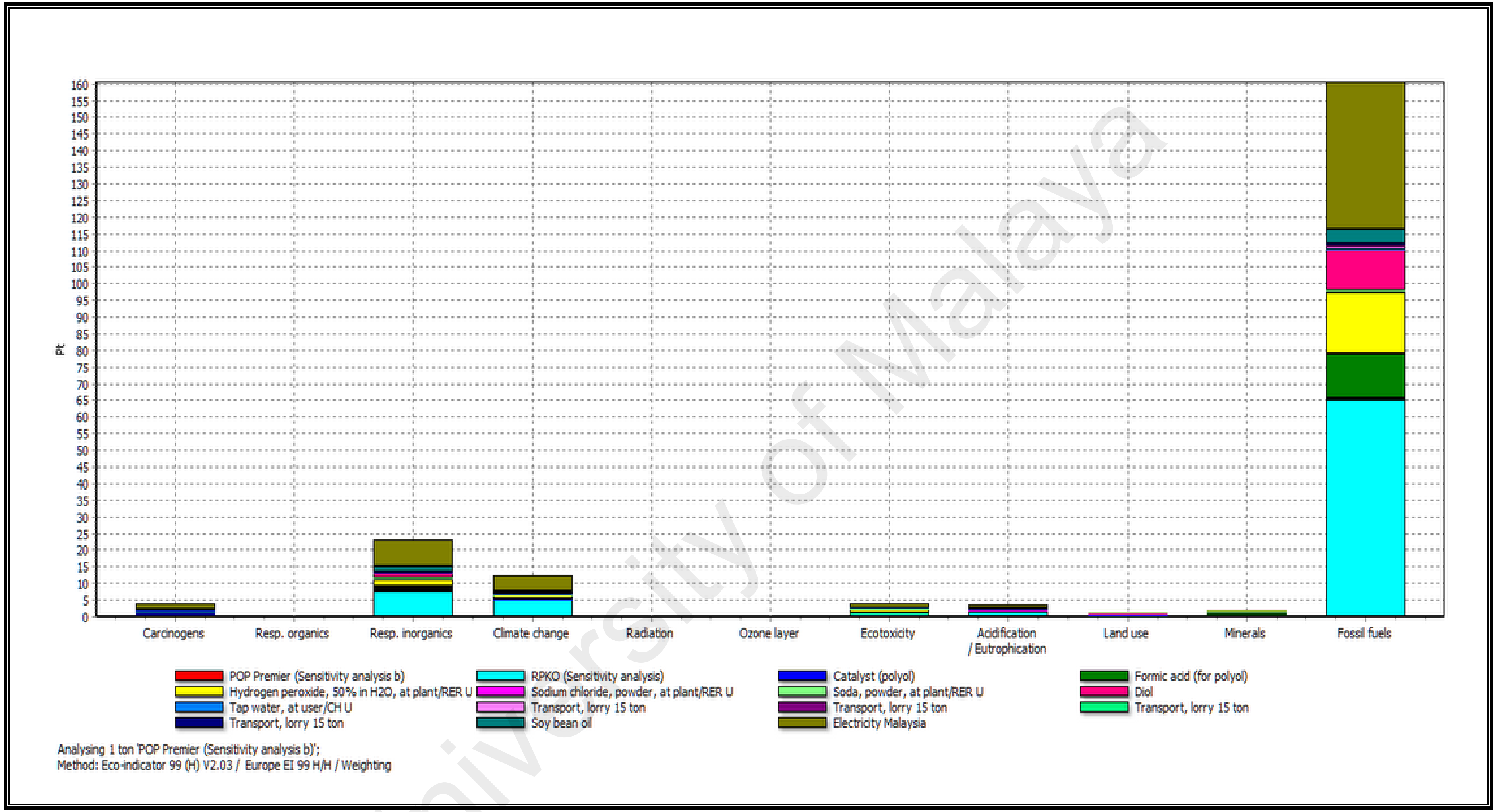


**Figure 4.21: Weighting for life cycle impact assessment (LCIA) of 1 tonne POP Premier – Sensitivity analysis.**

The biogas emissions from the palm oil mill production will influence the impact on climate change category. The climate change impact for three types of palm-based polyol are slightly higher comparing to impact from Scenario 1, which uses biogas capture facility. The percent of difference for each impact from three types of palm-based polyol production (POP Pioneer, POP Primer and POP Premier) is shown in Table 4.31.

**Table 4.31: Percent of difference for sensitivity analysis of three types of palm-based polyol.**

| Impact Category | POP Pioneer | | | POP Primer | | | POP Premier | | |
|---|---|---|---|---|---|---|---|---|---|
| | Scenario 1 | Sensitivity analysis | % Difference | Scenario 1 | Sensitivity analysis | % Difference | Scenario 1 | Sensitivity analysis | % Difference |
| Carcinogens | 4.268 | 4.219 | -1.16 | 4.702 | 4.657 | -0.97 | 3.826 | 3.826 | 0.00 |
| Respiratory organics | 0.061 | 0.058 | -4.29 | 0.066 | 0.063 | -3.62 | 0.076 | 0.082 | 7.38 |
| Respiratory inorganics | 25.551 | 25.453 | -0.38 | 28.103 | 28.013 | -0.32 | 23.077 | 23.077 | 0.00 |
| Climate change | 11.192 | 15.254 | 26.63 | 11.983 | 15.713 | 23.74 | 10.024 | 12.221 | 17.98 |
| Radiation | 0.142 | 0.159 | 10.69 | 0.161 | 0.177 | 8.83 | 0.103 | 0.103 | 0.00 |
| Ozone layer | 0.007 | 0.005 | -40.79 | 0.007 | 0.005 | -35.16 | 0.023 | 0.023 | 0.00 |
| Ecotoxicity | 4.516 | 4.747 | 4.87 | 4.941 | 5.153 | 4.12 | 3.867 | 3.867 | 0.00 |
| Acidification/ Eutrophication | 3.646 | 4.119 | 11.47 | 3.990 | 4.424 | 9.81 | 3.726 | 3.726 | 0.00 |
| Land use | 1.272 | 1.358 | 6.39 | 1.460 | 1.539 | 5.18 | 1.080 | 1.080 | 0.00 |
| Minerals | 2.657 | 2.667 | 0.38 | 2.964 | 2.974 | 0.31 | 1.790 | 1.790 | 0.00 |
| Fossil fuels | 157.428 | 161.069 | 2.26 | 170.819 | 174.162 | 1.92 | 160.596 | 160.596 | 0.00 |

About 27% of climate change impact figure can be reduced by using the biogas capture facility for POP Pioneer production, followed by 24% reduction in POP Primer and 17% difference in POP Premier production. But, there is not much difference for other impact categories other than climate change category. The results from the weighting (Figures 4.17, 4.19 and 4.21) showed that the palm-based polyol from the best case scenario study showed better results for most of the impact categories mainly in climate change, acidification, and radiation, ranging from 11% to 27%.

This proved that the climate change impact can be reduced by the installation and implementation of biogas capture facilities at palm oil mill as had been applied in Scenario 1, even the approach is not too significant for the main palm-based polyol production. This facility actually can help the palm oil mill to convert the methane gas into an electricity source after a series of treatment, so that the mills can use it for their own consumption. Meanwhile, for biogas plant which meets certain criteria will be able to feed the excess electricity into the national power grid (ETP, Annual Report, 2012). However, due to the expensive cost of installation for this facility, it has resulted in only small number of palm oil mills in Malaysia capable of having this facility. Probably, through incentives from the government, could perhaps help the palm oil millers to implement this good facility for a better environment.

## 4.9 Greenhouse Gas (GHG) Inventory

The GHG emissions for the 1 tonne of POP Pioneer, POP Primer and POP Premier are shown in Tables 4.32 to 4.34. The GHG emissions were calculated based on the GWP indexes and Emission Factor as mentioned in Chapter 3. All the figures with less than 0.05% in the airborne emissions profile from the SimaPro software was not taken into consideration for GHG calculation for the total GHG inventory.

The largest GHG contribution for palm-based polyol production comes from the consumption of electricity from the grid for the palm-based polyol plant process which emits 819.72 kg $CO_2$ eq/ tonne palm-based polyol (Scenario 1). When the electricity from national grid is replaced by the energy from biomass (Scenario 2), the GHG for the palm-based polyol process will be reduced to about 63-65% from the present GHG values. It is also similar to the study conducted by Helling and Russell (2009), where they found that seed oil-based polyol could generate very low greenhouse gas emissions from -13% up to 46% and also can reduce usage on fossil resources about 33% to 34%.

**Table 4.32: GHG inventory and total emissions for 1 tonne of POP Pioneer.**

| GHG from input and output | Scenario 1 (kg $CO_2$ eq) | Scenario 2 (kg $CO_2$ eq) | Scenario 3 (kg $CO_2$ eq) | Sensitivity analysis (kg $CO_2$ eq) |
|---|---|---|---|---|
| Refined palm olein | 438.26 | 438.26 | 438.26 | 1255.38 |
| Chemicals (as listed in Table 4.4) | 25.56 | 25.56 | 21.89 | 25.56 |
| Water | 0.74 | 0.74 | 0.74 | 0.74 |
| Transport of feedstock and chemicals | 23.59 | 23.59 | 23.59 | 23.59 |
| Electricity | 819.72 | NA (using biomass) | 819.72 | 819.72 |
| Total | 1307.87 | 488.15 | 1304.20 | 2124.99 |

Note: NA- Not applicable

**Table 4.33: GHG inventory and total emissions for 1 tonne of POP Primer.**

| GHG from input and output | Scenario 1 (kg $CO_2$ eq) | Scenario 2 (kg $CO_2$ eq) | Scenario 3 (kg $CO_2$ eq) | Sensitivity analysis (kg $CO_2$ eq) |
|---|---|---|---|---|
| Refined palm olein | 402.40 | 402.40 | 402.40 | 1152.67 |
| Soy bean oil | 29.98 | 29.98 | 29.98 | 29.98 |
| Chemicals (as listed in Table 4.4) | 29.38 | 29.38 | 24.71 | 29.38 |
| Water | 0.52 | 0.52 | 0.52 | 0.52 |
| Transport of feedstock and chemicals | 25.67 | 25.67 | 25.67 | 25.67 |
| Electricity | 819.72 | NA (using biomass) | 819.72 | 819.72 |
| Total | 1307.67 | 487.95 | 1303.00 | 2057.94 |

Note: NA- Not applicable

**Table 4.34: GHG inventory and total emissions for 1 tonne of POP Premier.**

| GHG from input and output | Scenario 1 (kg $CO_2$ eq) | Scenario 2 (kg $CO_2$ eq) | Scenario 3 (kg $CO_2$ eq) | Sensitivity analysis (kg $CO_2$ eq) |
|---|---|---|---|---|
| Refined palm kernel olein | 379.33 | 379.33 | 379.33 | 964.49 |
| Soy bean oil | 29.98 | 29.98 | 29.98 | 29.98 |
| Chemicals (as listed in Table 4.4) | 15.68 | 15.68 | 13.67 | 15.68 |
| Water | 0.001 | 0.001 | 0.001 | 0.001 |
| Transport of feedstock and chemicals | 18.13 | 18.13 | 18.13 | 18.13 |
| Electricity | 819.72 | NA (using biomass) | 819.72 | 819.72 |
| Total | 1262.841 | 443.121 | 1260.831 | 1848.001 |

Note: NA- Not applicable

For cradle-to-gate LCIA study, Table 4.35 shows the GHG emissions for each stage of palm-based polyol production. The GHG emissions for the palm-based polyol scenarios were calculated as per kg palm-based polyol products. Calculation for each stage was carried out in order to obtain GHG emissions per kg POP Pioneer[a], POP Primer[b] and POP Premier[c] as follow:

1) Nursery

= 0.05 x 0.34 (seedling factor) x 3.10 (plantation factor) x 1.05 (CPO factor) x $1.10^a$/ $1.01^b$/$0.87^c$ (RPO factor)

= $0.06^a$/ $0.06^b$/ $0.05^c$ kg $CO_2$ eq/kg polyol

2) Plantation

= [118.8 x 3.10 x 1.05 x $1.10^a$/ $1.01^b$/$0.87^c$] / 1000 kg/tonne= $0.43^a$/ $0.39^b$/ $0.34^c$ kg $CO_2$ eq/kg polyol

3) Palm oil mill

Scenario 1 = [505.76 x 1.05 x 1.10[a]/ 1.01[b]/0.87[c]] / 1000 = 0.58[a]/ 0.54[b]/ 0.46[c] kg $CO_2$ eq/kg polyol

Sensitivity analysis = [970.58 x 1.05 x 1.10[a]/ 1.01[b]/0.87[c]] / 1000 = 1.12[a]/ 1.03[b]/ 0.89[c] kg $CO_2$ eq/kg polyol

4) Refinery

Scenario 1 = [625.67 x 1.10[a]/ 1.01[b]/0.87[c]] / 1000 = 0.69[a]/ 0.63[b]/ 0.54[c] kg $CO_2$ eq/kg polyol

Sensitivity analysis = [1113.73 x 1.10[a]/ 1.01[b]/0.87[c]] / 1000 = 1.23[a]/ 1.12[b]/ 0.97[c] kg $CO_2$ eq/kg polyol

Note: [a, b, c] = *Factor use for POP Pioneer, POP Primer and POP Premier.*

**Table 4.35: GHG emissions for palm-based polyol production.**

| **Stage** | **GHG emissions (kg $CO_2$ eq/ unit product)** | **GHG emissions* (kg $CO_2$ eq/kg palm-based polyol)** |
|---|---|---|
| Nursery (per seedling) | 0.05 | 0.06 |
| Plantation (per 1 tonne FFB using continued land use) | 118.8 | 0.43 |
| Palm oil mill (per 1 tonne CPO) | | |
| i) With biogas capture | 505.76 | 0.58 |
| ii) With biogas emissions | 970.58 | 1.12 |
| Refinery (per 1 tonne CPO) | | |
| i) With biogas capture | 625.67 | 0.69 |
| ii) With biogas emissions | 1113.73 | 1.23 |
| POP Pioneer (per 1 tonne product) | | |
| i) Scenario 1 | 1307.87 | 1.31 |
| ii) Scenario 2 | 488.15 | 0.49 |
| iii) Scenario 3 | 1304.20 | 1.30 |
| iv) Sensitivity analysis | 2124.99 | 2.12 |

**Table 4.35, continued**

| Stage | GHG emissions (kg $CO_2$ eq/ unit product) | GHG emissions* (kg $CO_2$ eq/kg palm-based polyol) |
|---|---|---|
| POP Primer (per 1 tonne product) | | |
| i) Scenario 1 | 1307.67 | 1.31 |
| ii) Scenario 2 | 487.95 | 0.49 |
| iii) Scenario 3 | 1303.00 | 1.30 |
| iv) Sensitivity analysis | 2057.94 | 2.06 |
| POP Premier (per 1 tonne product) | | |
| i) Scenario 1 | 1262.841 | 1.26 |
| ii) Scenario 2 | 443.121 | 0.44 |
| iii) Scenario 3 | 1260.831 | 1.26 |
| iv) Sensitivity analysis | 1848.001 | 1.85 |

**GHG emissions are calculated based on factor for each stage.*

All the data for GHG calculations were obtained individually for each stage production in order to produce one kg of palm-based polyol referring to GHG value reported by Choo et. al. (2011). The GHG contributions from nursery only contributed minimal impact compared to others. In the plantation stage, continued land use was considered in replanting oil palms and the major portion of the GHG emissions was from N fertilizer. Thus, there are no land use changes from conversion of secondary or degraded forest or conversion of other tree crops to oil palm (Choo et. al., 2011). For the palm oil mill, with 85% biogas capture during CPO production helps to reduce about 48% GHG emissions. In order to reduce the burden to the environment, the wastes from oil palm biomass i.e. shell and mesocarp fibre were reused as fuel for boiler to generate the energy and reduce the usage of energy from the national grid.

The biogas captured from palm oil mill effluent (POME) is also used as a renewable energy to facilitate energy demand for the plant (Scenario 1). Thus, it can reduce the dependency on fossil fuels and move towards the use of renewable fuels. On the other hand, it has benefited the oil palm industry since the biomass is not considered as a wastes generated from the CPO production but rather seen as a by-product. The difference in GHG emissions values in Tables 4.32 to 4.34 are evidence of the significance of biogas capture facilities used in the palm oil mill. The GHG emission at the refinery stage was mainly from the fractionation of refined palm product process which is related to the consumption of electricity and water elements only.

The productions of POP Pioneer and POP Primer produced only 1.31 kg $CO_2$ eq per kg polyol using Scenario 1 while POP Premier produced about 1.26 kg $CO_2$ eq per kg polyol which is lower than POP Pioneer and POP Primer. However, the GHG emissions for each of palm-based polyol are much lower in Scenario 2 which is around 0.44 to 0.49 kg $CO_2$ eq per kg polyol. This value proved that by using biomass as energy source can help to reduce the GHG emissions figure for the whole palm-based polyol production. The worst GHG emissions value was found from the approach during the sensitivity analysis which is around 1.85 to 2.12 kg $CO_2$ eq per kg polyol.

As mentioned by Pollack (2004), the total fuel energy represent the fuel value of the materials extracted from the earth plus the energy needed to process them into final product. The value of carbon dioxide for palm-based polyol also covered for the 'cradle-to-gate' of the petro-based polyol production which was around 3500 gm/kg $CO_2$ eq. with fuel energy ranging between 61.54 MJ/kg to 93.16 MJ/kg. However, the palm-based polyol shows the lowest figures in carbon dioxide equivalents and also on fuel energy compared to the polyol produced from petro-based with a value 1308 gm/kg $CO_2$ eq and 4.97 MJ/kg respectively (Table 4.36).

**Table 4.36: Comparison carbon dioxide equivalents and fuel energy used during the polyol process based on polyol study using palm-based and petro-based as feedstocks.**

| Parameter | Palm Polyol[1] | Petro Polyol[2] | Petro Polyol[3] | Petro Polyol[4] |
|---|---|---|---|---|
| Carbon dioxide (100 years eq.) | 1308 gm/kg | 3590 gm/kg | 3500 gm/kg | 3500 gm/kg |
| Fuel energy | 4.97 MJ/kg | 61.54 MJ/kg | 87.9 MJ/kg | 93.16 MJ/kg |

[1]*LCI value based on the Scenario 1 figure since polyol is 100% using palm-based as feedstock.*
[2]*LCI value for petro polyol were reported by Pollack (2004) from ACS Annual Meeting Presentation.*
[3]*LCI value based on preliminary study by Cargill (2008).*
[4]*LCI value based on PlasticEurope study by Boustead (2005).*

## 4.10 Consistency check

As outlined in ISO 14044, Clause 4.5.3.4, the objective of the consistency check is to determine whether the assumptions, methods and data are consistent with the goal and scope. Inconsistency are including differences in i) data sources, ii) data accuracy, iii) technology coverage, iv) time-related coverage, v) data age and vi) geographical coverage. According to UNEP (2011), the methodological approach and viewpoints must be very clear so that independent data collection activities can yield similar data. Expanding upon the goal and scope of the unit process datasets, some inconsistency may be acceptable. Table 4.37 shows the examples of data inconsistency as developed by USEPA in 2006.

As mentioned and viewed in Table 4.37, all data quality in terms of representative of the scenarios studies in the pilot plant has been addressed well.

**Table 4.37: Examples of data inconsistency (USEPA, 2006).**

| Category | Example of inconsistency |
|---|---|
| Data source | Some unit process data can be based on literature or on measured data. |
| Data accuracy and integrity | Data can be developed using a detailed process flow diagram or using limited process information for a process that is not described or analysed in detail. Data accuracy and integrity are important if data consistency is to be assured. |
| Data age | Data can be 30 years old or one year old. |
| Technological representativeness | The unit process can be based on a bench-scale laboratory model or on a full-scale production plant operation. |
| Temporal representativeness | Data can be based on a recently developed technology or it can be based on a technology mix, including recently build and older plants. |
| Geographical representativeness | Data can be from technology employer under local, regional or international environmental standards. These alternatives can provide different data. |
| Goal, scope, models and assumptions | Unit process dataset modelling and assumptions will depend on the skill of the modeller in terms of rigor, scientific approach and methodology. |

# CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

The objectives of this study were to evaluate and identify the environmental performance for palm-based polyol production at pilot plant scale, to establish LCI of palm-based polyol production and to determine and give the best solutions to reduce the environmental impacts from the production using the LCA approach.

## 5.1 Conclusions

Rapid research and development of polyol and polyurethane (PU) in polymer industry had influenced many people and organizations to searching for other renewable materials as an alternative for the petroleum-based polyol/PU material. This shifting scenario is a good sign for the oil palm market to expanding their global market. Apart of that, it also accessible a faster growth of polymer industry due to expansion of their own market. Through this approach, the polymer industry can find other potential applications that can be used by consumers.

The oil palm industry has now become an important industry which contributes immensely towards the economy of Malaysia. In this study, the potential of palm oil as raw material for polyol manufacturing was highlighted. It was proven that the use of palm oil as a renewable raw material in polymer making can significantly contribute to a sustainable development. Biggest player in polymer industry, i. e. Dow, BASF, Cargill, and etc. have moved towards producing the renewable polyol material from palm oil feedstock. This industry need to worked continuously to improve their overall product performance by setting high standards in their productivity and also quality. Perhaps, by replacing petroleum-based using partially or fully renewable polyol materials, i. e. palm-based, soy-based, castor-based it helps to reduce the finished product's carbon footprint.

In summary, all the objectives of this study were successfully achieved. The findings of this study are calculated based on the Eco-indicator 99 methodology using the 'cradle-to-gate' system boundary of palm-based polyol at pilot plant scale. This study has four scenarios including scenario for sensitivity analysis. In the production of palm-based polyol, the impacts are mainly associated with fossil fuels, respiratory inorganics and climate change impact categories. The major contributor towards these impacts were mainly from electricity and hydrogen peroxide. However, palm-based products which were used as a raw materials, i. e. refined palm olein and refined palm kernel olein also contributed an impact specifically toward POP Pioneer and POP Premier productions, respectively.

The best scenario for the production of palm-based polyol with the least environmental impact is when the major impact contributor (electricity form the national grid) is replaced with renewable energy from oil palm biomass boiler (Scenario 2) which was proposed as an alternative scenario. This alternative scenario can help to reduce about 63-65% of the GHG emissions for the overall palm-based polyol production. However, the replacement of diol with the glycerol (Scenario 3) does not show much difference as compared to Scenario 1.

It is observed that sensitivity analysis results showed that without the biogas capture system/facility used at the palm oil mill, the GHG emissions will be higher by 1.85 to 2.12 kg $CO_2$ eq per kg polyol. Overall, the GHG for each kg palm-based polyol was about 1.31 kg $CO_2$ eq for POP Pioneer and POP Primer and 1.26 kg $CO_2$ eq for POP Premier.

It was proven that the best approach for the palm-based polyol production is by using the normal practice in oil palm activities in Malaysia, i. e. continued land use in oil palm plantation with biogas capture at the palm oil mill.

## 5.2 Recommendation/Suggestions

To improve the impacts generated from the palm-based polyol production, several recommendations are suggested as follow:

1. To eliminate washing of epoxidized palm oil (EPO) during epoxidation process before transferring to the next reactor for the following process. This can help reduce cost and consumption of utilities and raw materials which are electricity (was used as energy), chemicals such as sodium chloride and sodium carbonate, water and time during the epoxidation process. In the same time, the impacts towards the environment can be reduced.

2. Find ways to reduce or minimize the spent acids production during the epoxidation process by recycling it. In the commercial plant, the spent acids will be recycled during the production.

3. According to the pilot plant procedure, spent acids are neutralized with alkaline base chemicals such as soda ash to get neutral pH before it is discarded into the drain to avoid effects to human and environment especially the sewage system. A better way of disposal must be sought.

4. In order to have a better suction flow of the emissions of gas, a flexible hose with suitable material and specifications are attached to the reactor during the alcoholysis process which is then fixed to a water damn outside the plant. This is done to prevent the rise of pressure inside the reactor during the alcoholysis reaction which generates a lot of vapour. The gas emissions are not good for human health and also the environment.

5. In order to develop a system that keeps the reaction temperature constant (63-65°C) during the alcoholysis process, the correct amount of complex chemicals and water flow from the cooling system has to be added during the process. This will make the system secure and also reduces the power consumption during the production process.

6. To increase the supply of the product to obtain a more representative data. It will also be good if the scope of study be expanded to the commercial scale in order to have data from a commercial plant.

The results generated from this study are suitable for the pilot plant scale production. However, the results will be more interesting if future work can be carried out at a commercial plant at a larger scale. The inventory data from the commercial scale could be different from the pilot plant scale. However, the main impact generated from the analysis should be similar even if the assessment is carried out at a different production scale.

It is recommended that the most sustainable way to produce palm-based polyol is by integrating the polyol plant with the integrated palm oil plants including palm oil mill and palm oil refinery as shown in the sensitivity analysis scenario. The energy produced from the integrated palm oil plant can be consumed by the polyol plant for the process. This approach can reduce the GHG emissions and adds value to oil palm biomass. It also helps to reduce reliance on fossil-based energy and feedstock in the production of palm polyol.

By using this LCA results, perhaps it can help palm-based polyol to promote their products since it has similarity properties, performance even on sustainability with other types of polyol from other resources, i. e. petro-based or soy-based.

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