Journal of Oil Palm Research Vol. 27 (2) June 2015 p. 144-155

EVALUATION OF ENVIRONMENTAL IMPACTS AND GHG OF PALM POLYOL PRODUCTION USING LIFE CYCLE ASSESSMENT APPROACH

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ABSTRACT

Presently, very few life cycle assessment (LCA) studies have been conducted and reported on the production of palm polyol. Previously, most of the LCA studies on the polyol production are limited to petroleum, soya or castor polyol. In this study, a LCA of a palm polyol was performed. The objective of this study is to identify any potential environmental impacts that could be associated with the production of palm polyol. The cradle-to-gate system boundary for the production of palm polyol shows that the most significant impact from the palm polyol production comes from the energy use at the polyol plant. This impact is mainly contributed by electricity, and production of hydrogen peroxide and formic acid that were used during the epoxidation process. The largest greenhouse gasses (GHG) contribution was from consumption of electricity from the national grid that was mainly used for pilot plant polyol process. However, from this study, about 29% reduction in the GHG emissions generated by the production of palm polyol could be achieved by using the best approach normally used in oil palm industry which is using continued land use and biogas capture scenario.

Keywords: palm oil, life cycle impact assessment, bio-based polyol, LCA, greenhouse gasses.

Date received: 20 May 2014; **Sent for revision:** 23 May 2014; **Received in final form:** 30 September 2014; **Accepted:** 18 February 2015.

INTRODUCTION

Malaysia is one of the biggest exporters and second largest producer of palm oil in the world. Oil palm has become the most important commodity crop in Malaysia and palm oil has become the most traded oil in the world. According to the *Oil World Annual Report in* 2012, Malaysia contributed about 43.1% of the world's palm oil exports. In 2013, the total export of oil palm products (which consist of palm oil, palm kernel oil, palm kernel cake, oleochemicals, biodiesel and finished products) increased by 4.3% or 1.10 million tonnes to 25.66 million tonnes compared with 24.56 million tonnes in 2012 (MPOB, 2014). The oleochemicals are one of the most important oil palm products in the non-food industries. The industry has expanded significantly since the establishment of its first oleochemical plant in 1979 (Mohtar *et al.*, 2001). Oleochemical derivatives, such as polyols and polyurethanes, have their own roles in the oleochemical industry, and the demand for these kinds of products increases due to their market expansion and applications.

Currently, most of the commercial polyols available in the markets are from petroleum, soya or castor oil. With increasing global awareness

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about sustainable development, the search for raw materials from renewable resources has been actively pursued. Polyol is recognised as a major feedstock material used in the manufacture of polyurethanes. Generally, polyols from renewable resources can be used as an alternative to petroleum-based polyols and have good potential for future polyurethane markets. To date, the market for polyols is being driven by the rapid growth of the polyurethane market across the globe. The global polyol market itself was estimated at USD 14.4 billion in 2011 and is expected to reach USD 22.4 billion by 2017 (www.marketsandmarkets.com, 2012). Commercially, polyols can be used to produce various types of polyurethane products such as ceiling panel, flora foams, cushions and car seats. Apart from polyurethanes, polyols can also be used in CASE (coating, adhesive, sealants and elastomers) manufacturing. Some of the major global players in polyol production are BASF, Bayer Material Science, Cargill Inc, Dow Chemical Company, Huntsman Corporation, Perstorp AB, Shell Chemicals, and Stepan Company.

To date, many studies on LCA of polyols have been conducted and published. Pollack compared the environmental impacts of two soya polyol materials with a conventional petroleum-based polyol using LCA approach (Pollack, 2004). In the study, all stages in the life cycle of a product area were analysed, such as raw material acquisition, manufacturing, transportation, use and end of life. The results showed that the environmental impact scores for the two soya polyols are only about one-quarter of that of the petro polyol. The most significant environmental impacts noted were global warming, smog formation, eutrophication, ecological toxicity and fossil fuels depletion. For total fuel energy, soya polyols consumed about 11.58 MJ kg^{-1} while petroleum-based polyols consumed about 61.54 MJ kg^{-1}. Based on these values, the lower energy value (MJ kg^{-1}) favours the soya polyol materials. It shows that soya polyols are more environmental-friendly than petroleum-based polyols.

A preliminary life cycle analysis done by Cargill reported that the production of bio-based polyols (soya-based) had successfully reduced 36% of the global warming emissions, 61% less non-renewable energy use and 23% less total energy demand compared to the petroleum-based polyols. This situation will give credit to the bio-based polyol industry since the bio-based polyols are more competitive and much better than petroleum-based polyols in terms of environmental performance. In 2011, with the increasing awareness on energy consumption and to reduce dependency on the fossil fuels, Cargill has successfully manufactured soya-based polyol with 48% to 57% reduction in non-renewable energy compared to the traditional petroleum-based polyols (Biobased Solutions, 2008).

In Malaysia, the technologies to produce polyol from palm oil and its derivatives were initiated in the early eighties (Salmiah and Yusof, 2010). In the Malaysian Palm Oil Board (MPOB), the process to produce polyol from palm oil (Kassim Shaari *et al.*, 2013; Abu Hassan *et al.*, 2011; 2008; Soi *et al.*, 2009) has been patented in Malaysia, Singapore, Indonesia, United Kingdom and US. There were many LCA studies on polyol, but studies done on polyol from palm oil was limited. Even though this study was conducted at pilot plant scale, there is a possibility that similar impact categories will be obtained if the study were to be conducted at commercial plant scale. But, the magnitude of the impact will be different for both studies.

Currently, GHG also becomes a main focus in sustainable discussions. GHG is defined as a gas in an atmosphere that absorbs and emits radiation within the thermal infrared range (Wikipedia, 2014). The GHG will be compared according to 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 (International Carbon Bank & Exchange, 2000).

METHODOLOGY

Goal

The study was carried out in order to evaluate and identify the potential environmental impacts, to quantify the GHG emissions from the production of palm polyol, and also to recommend alternatives to reduce the potential impacts generated from the production process, if any. On the other hand, by establishing LCA on the production of palm polyol, it can be used as a marketing tool to promote the utilisation of palm polyol globally.

Scope/System Boundary

The system boundary of the study covered the entire life cycle of the product which is ‘cradle-to-gate’ but limited to the pilot plant polyol gate. The system boundary starts from the production of oil palm seed germination at the nursery stage and ends at the production of palm polyol. Hence, the use and distribution of palm polyol is not included in this study. The life cycle phases (*Figure 1*) include raw materials and the transportation of raw materials according to ISO 14044 Standard (2006). The study also covered LCI and LCIA of palm polyol production. The functional unit of this study is the production of 1 t palm polyol.

Data Source and Inventory

Data used in this study were combination of primary and secondary data. Inventory data for the production of palm polyol was collected from the field, *i.e.* using the MPOB Polyol Pilot Plant. Primary data in this study included the amount and type of feed stocks, chemicals, energy, water and wastes that had been used and produced along the process flow to produce palm polyol (*Figure 2*). All data were collected from three batches of production cycle. Apart from the data within the palm polyol boundary itself, this study also used primary data from the upstream and midstream activities of the oil palm industry as listed in *Table 1*. The secondary data were mostly related to the process used, *i.e.* manufacturing of chemicals, energy mix, and lorry for transports. These data were derived from the Ecoinvent database. For road transportation, 15 t lorry running on diesel was used to deliver the raw materials, including the chemicals and feedstock, from the manufacturers to the pilot plant. The system boundary excluded the production of capital goods, *e.g.* machinery, buildings, vehicles manufacturing, vehicle maintenance and disposal, transport infrastructure and waste treatment. The data validation procedure was carried out on-site via actual measurements.

TABLE 1. INVENTORY DATA SOURCES FOR PALM POLYOL STUDY

Life cycle stage	Data source
Oil palm nursery	Halimah *et al*. (2010)
Oil palm plantation	Zulkifli *et al*. (2010)
Palm oil mill	Vijaya *et al*. (2010)
Fractionation of palm product	Tan *et al*. (2010)

Life Cycle Impact Assessment

For this study, life cycle impact assessment (LCIA) was applied at midpoint approach according to ISO 14044 (impact categories selection, characterisation and weighting phase). The impact assessment method applied was Eco-indicator 99, incorporated into the SimaPro 8.0.2. software developed by Pre Consultant, Netherlands. Eco-indicator 99 is consistent and almost a complete modelling to evaluate the damage caused by a large number of relevant impact categories and almost with complete specifications of all the technical uncertainties. Three scenarios were carried out for the palm polyol production based on the methodology chosen. A list of the scenarios is shown in *Table 2.*

GREENHOUSE GAS

The GHG emissions was quantified using the IPCC TAR 2007 as shown in *Table 3.*

RESULTS AND DISCUSSIONS

The results from all the scenarios of palm polyol production are described in the following sections.

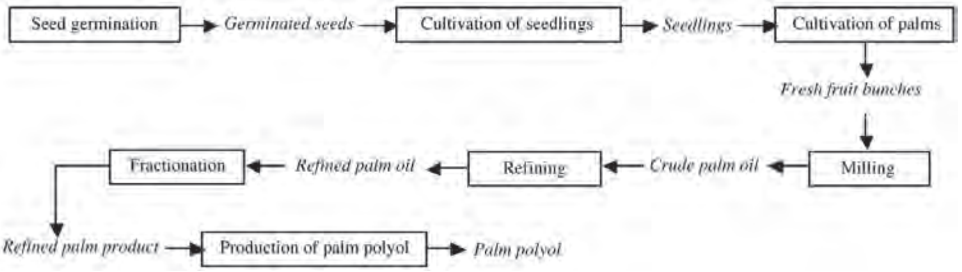

Figure 1. System boundary of palm polyol production.

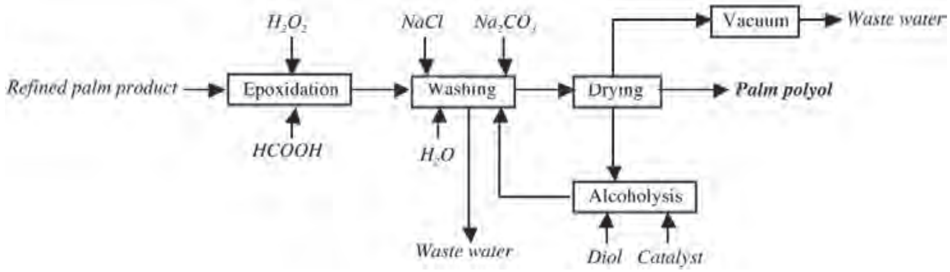

Figure 2. Process flow chart for the palm polyol production.

TABLE 2. SCENARIOS OF LIFE CYCLE ASSESSMENT (LCA) STUDY OF PALM POLYOL PRODUCTION

Scenario	Criteria	Rationale
Scenario 1	Production of palm polyol using continued land use (oil palm to oil palm) with biogas capture	Base case study for palm polyol (best approach for oil palm upstream studies)
Scenario 2	Production of palm polyol using continued land use (oil palm to oil palm) with biogas capture (using biomass as an energy source)	Alternative scenario - electricity contribute highest impact; replacement of energy source (energy from national grid)
Scenario 3	Production of polyol using data from Plastics*Europe* Eco-profiles (only data for carbon dioxide and fuel)	Reference case for petrochemical polyols (Boustead, 2005)

TABLE 3. GLOBAL WARMING POTENTIALS INDEX FOR SELECTED GREENHOUSE GASSES

Greenhouse gas	Global warming potential index for 100 years
CO_2	1
CH_4	23
N_2O	296
HFC-23	12 000
HFC-134a	1 300
SF_6	22 200

Note: IPCC TAR (2007).

Life Cycle Inventory

The focus of the life cycle inventory (LCI) is on the inventory data for palm polyol production that has been calculated to quantify all the environmental input and output of the functional unit within the system boundary. There are two main processes to produce palm polyol, *i.e.* epoxidation of unsaturated oil (refined palm product) and alcoholysis of epoxidised palm oil (EPO) (Abu Hassan *et al.*, 2011).

For electricity input, the calculation was based on the electricity usage by the pilot plant equipment that were operated and used during the production. The source for electricity was from the national grid provided by the Tenaga Nasional Berhad (TNB). There were several equipment that used electricity, such as stirrer inside the reactors, pump, cooling tower motor, and electrical boiler. There was no steam used during the palm polyol process and all the energy for heating came from the electricity as an energy carrier. In the analysis under the contribution from transport, all distances were considered as half of a round trip and lorry loads were full load weights and made empty return trips. Quantification of the environmental load from transportation was determined by using the Ecoinvent database. Energy used for palm polyol production via the chemical processes *i.e.* epoxidation, washing, drying and alcoholysis, was estimated based on the operation period. There were no emission produced during the chemical process; assuming the chemical reactions during the production are completed.

Life Cycle Impact Assessment (LCIA)

The characterisation and weighting results were conducted for both Scenarios 1 and 2. The system boundary starts at oil palm seed germination and ends at the production of palm polyol. The LCIA results presented in this article were based on the production of 1 t of palm polyol. In order to assess the relative importance of each impact category, characterisation and weighting phase were performed using Eco-indicator 99. There were 11 impact categories taken into account for the impact assessment.

Scenario 1. LCIA was conducted for the production of 1 t palm polyol using the pilot plant. The system boundary included:
- oil palm nursery;
- oil palm plantation [oil palm to oil palm (OP to OP) with continued land use];
- palm oil mill (with biogas capture at the mill);
- refinery (for refined palm product); and
- palm polyol plant (using electricity from national grid).

The characterisation and weighting results are as shown in *Figures* 3 and 4, respectively.

The continued land use and biogas capture scenario are the best scenarios for the upstream and midstream activities for oil palm industry. According to *Figure 4*, three impact categories *i.e.* respiratory inorganics, climate change and fossil fuels have the highest environmental burden compared to others. These three impact categories show that the most significant element is electricity, with the

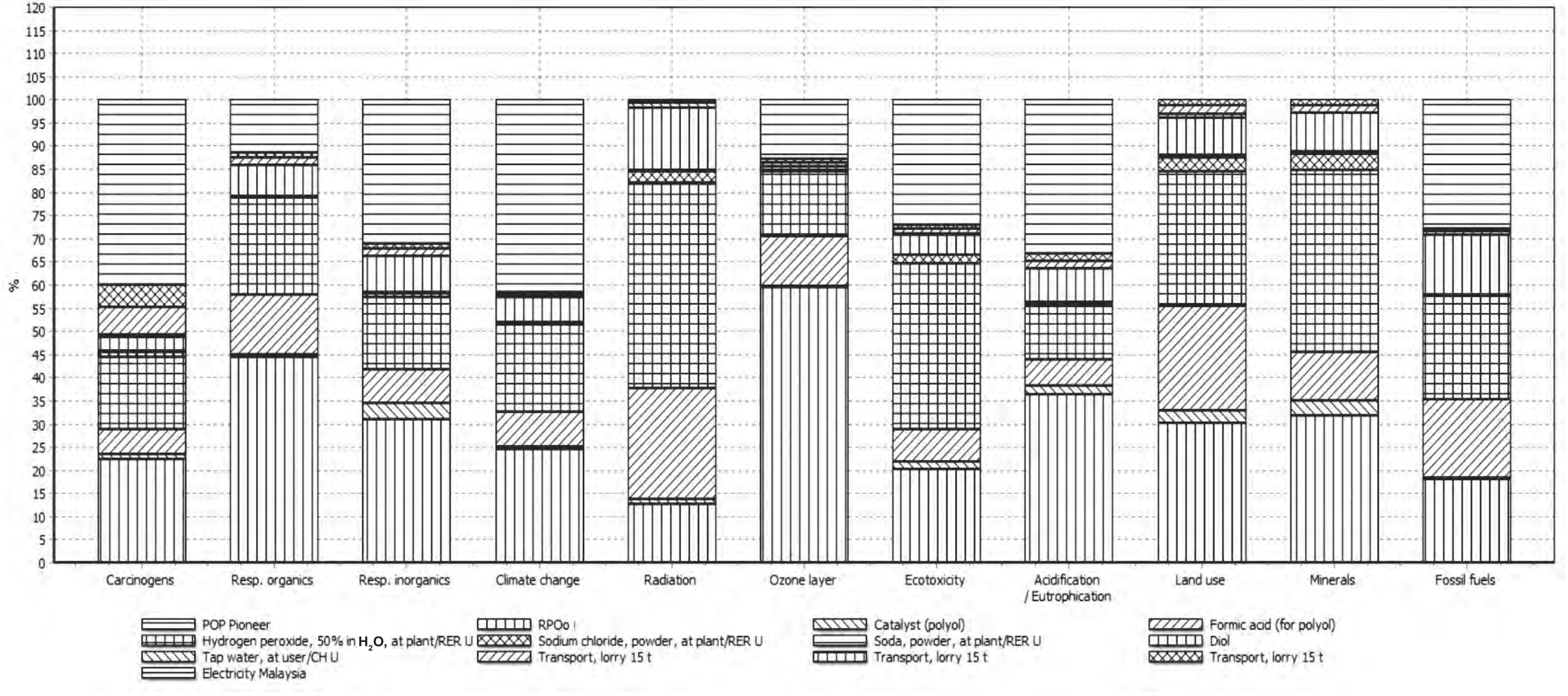

Figure 3. Characterisation of life cycle impact assessment (LCIA) for production of 1 t palm polyol – Scenario 1.

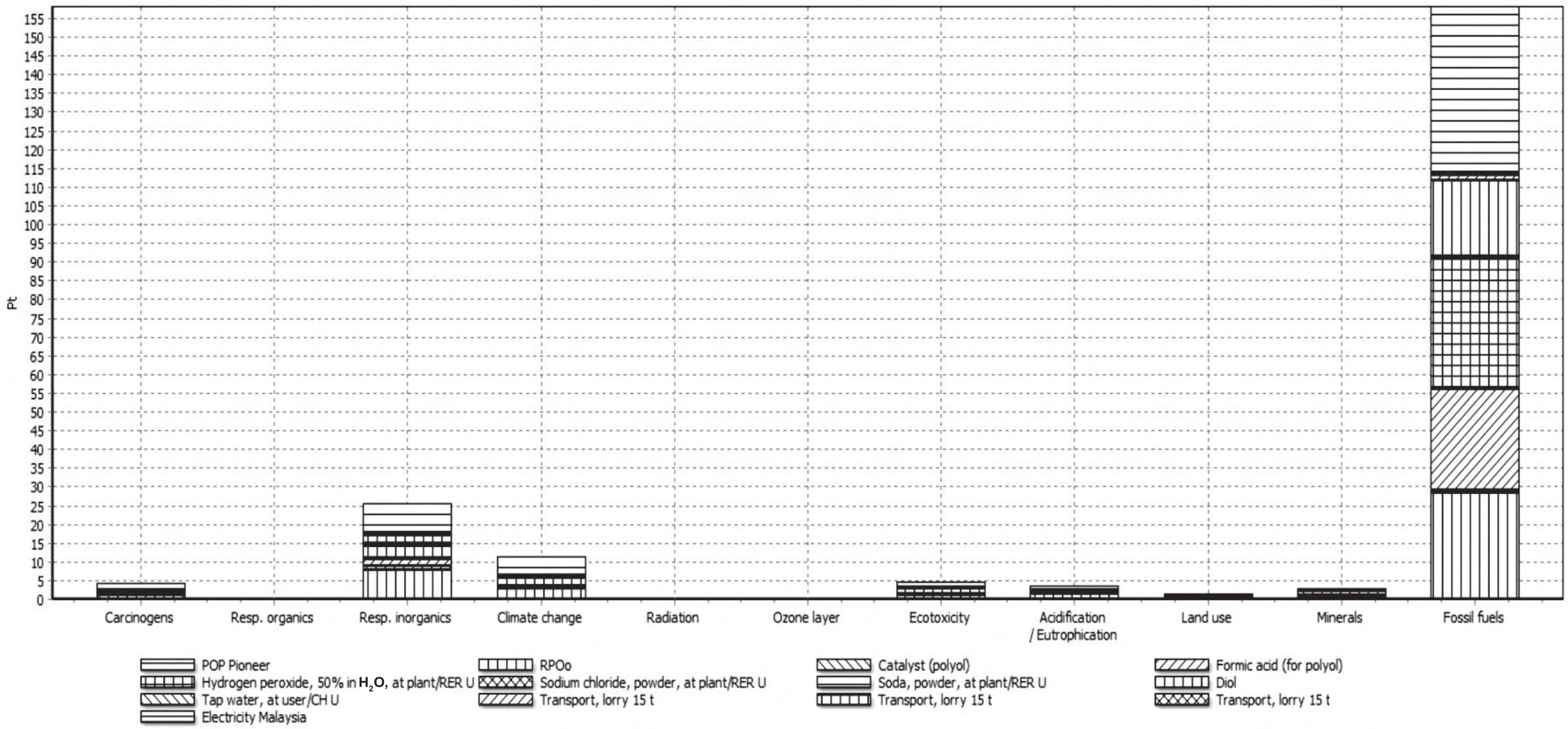

Figure 4. Weighting of life cycle impact assessment (LCIA) for production of 1 t palm polyol – Scenario 1.

contribution ranges from 28% to 42%, followed by the impact contribution from the production of hydrogen peroxide, palm product and formic acid to fossil fuels impact category, amounting to 22%, 18% and 17%, respectively. These chemicals are used during the epoxidation and alcoholysis of palm polyol. Hydrogen peroxide contributed about 21% of greenhouse gas emissions from the total greenhouse gas emissions. Impact on respiratory inorganics is mainly associated with the emissions to the atmosphere originating from the upstream refined palm product activities such as production of fertiliser, fuel for transportation and machinery (Tan *et al.*, 2010). Only 2% from the total impact was caused by transportation of raw materials, feedstock and chemicals.

Climate change plays less significant role in the system. However, it became significant in the upstream study since the capturing of methane gas happened at the palm oil mill (Vijaya *et al.*, 2010). Sumiani *et al.* (2007) also reported that the climate change is weighted lightly by Eco-indicator 99 due to the inadequate precision in models estimating global warming impact.

Scenario 2. LCIA was conducted for the production of 1 t palm polyol using the pilot plant. The system boundary included:

- oil palm nursery;
- oil palm plantation [oil palm to oil palm (OP to OP) with continued land use];
- palm oil mill (with biogas capture at the mill);
- refinery (for refined palm product); and
- palm polyol plant (using energy produced from oil palm biomass).

Figures 5 and *6* show the characterisation and weighting results of palm polyol by replacing the national grid electricity with the electricity generated at palm oil mill using oil palm biomass.

To support the environmental awareness programme by the Malaysian government, the green approach for energy source from oil palm biomass was chosen to counter the high impact on fossil fuels category contributed by the energy from national grid (source from natural gas and coal) produced during the palm polyol production. This approach is an alternative way in looking for better environmental performance of palm polyol production (Scenario 2).

As commonly known, oil palm biomass (shell and mesocarp fibre) are actually wastes from the fresh fruit bunch (FFB) and recycled as boiler fuel. In the palm oil mill, shell and mesocarp fibre are considered as valuable by-products and 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). In certain cases, the electricity produced from these renewable resources is also used to supply to the national grid as energy source. As in Scenario 1, the total non-renewable primary energy demand of palm polyol is 4.97 MJ kg^{-1}.

By using shell and mesocarp fibre as fuels, the impact on climate change category can be reduced around 42% as compared to using electricity from the national grid as shown in *Figure 6*. However, this reduction is not the main focus of this study. The impact under fossil fuels category arising from the use of electricity decreased about 29% by using the oil palm biomass as an energy source. The respiratory inorganics impact also reduced by about 33% compared to when using non-renewable energy source. Again, these results confirmed that the largest contributor of palm polyol productions was from the use of electricity. In addition, this approach can also help to reduce the depletion of fossil fuels and also cut down the GHG emissions from the entire process for palm polyol production.

However, it should be noted that the above discussion on reduction of impact values are assumptions meant to illustrate the possibility of alternative scenario (Scenario 2). It could be achieved if the approach is really implemented later. The most sustainable way is the integration of polyol plant with the integrated palm oil plants, *i.e.* palm oil mill and palm oil refinery. The energy produced from the integrated palm oil plant can then be consumed by the polyol plant for their process. At that time, the impact from electricity will become insignificant and the replacement of energy using oil palm biomass will become the positive factor in the overall LCA boundary. It can also help to reduce the GHG emissions, maximise the applications and add value to oil palm biomass.

GHG Emissions

Table 4 describes the GHG emissions for both Scenarios 1 and 2, where the electricity is shown as a main contributor of GHG emissions compared to other parameters.

The largest GHG contribution for palm polyol production comes from the consumption of electricity from the grid that is used for the pilot plant process, which emits 819.72 kg CO_2 eq/t palm polyol. When the electricity from grid is replaced by the energy from biomass, the GHG for the palm polyol process will be reduced about 63% from the present GHG values.

Figure 7 shows GHG contribution from all stages in palm polyol production. GHG was calculated using the GWP as shown in *Table 3*. As mentioned in *Table 4*, 1.10 t of refined palm product is required to produce 1 t of palm polyol. By using the same data as in *Table 4*, the GHG emissions for 1 t of palm

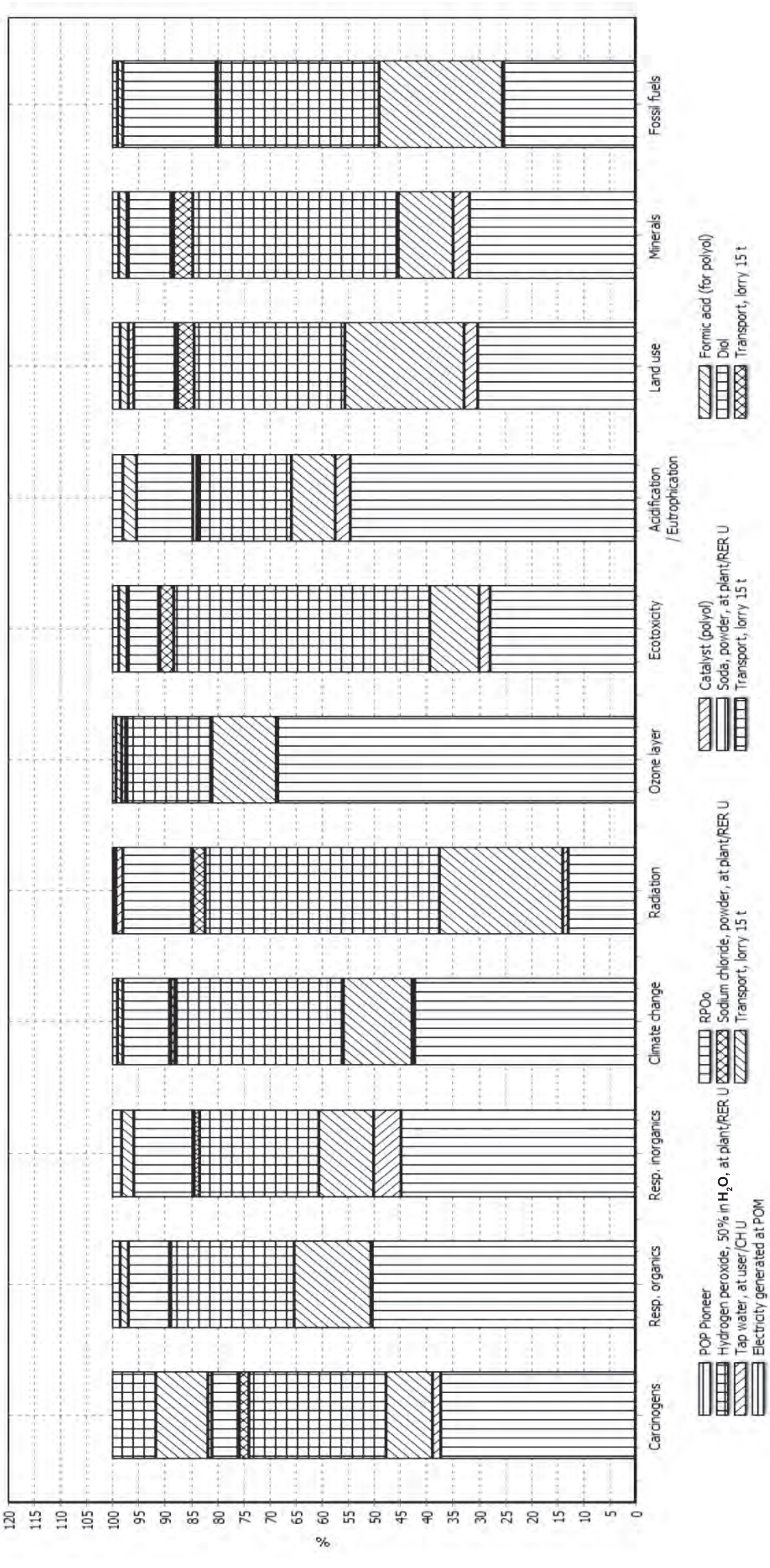

Figure 5. Characterisation of life cycle impact assessment (LCIA) for production of 1 t palm polyol - Scenario 2.

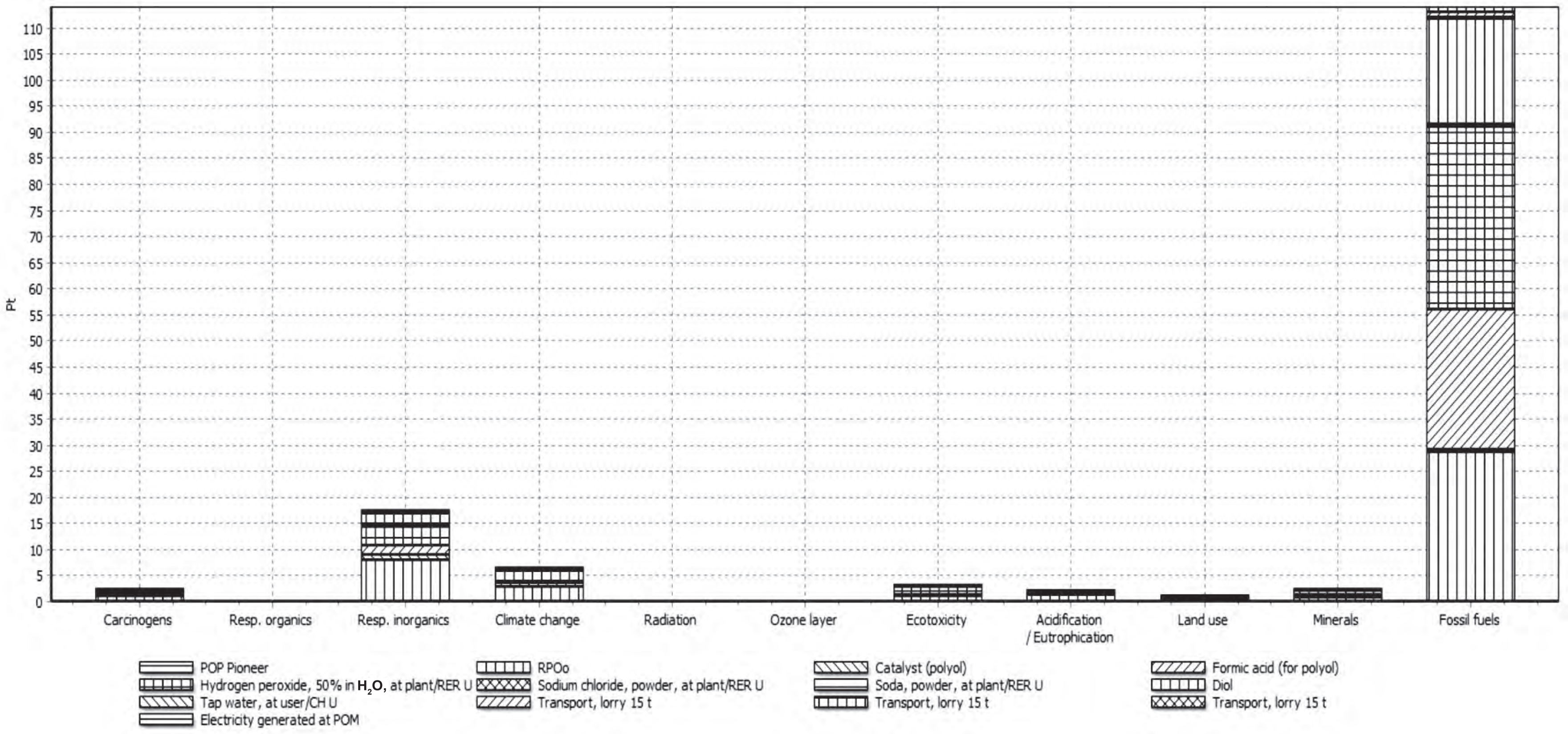

Figure 6. Weighting of life cycle impact assessment (LCIA) for production of 1 t palm polyol – Scenario 2.

TABLE 4. THE GREENHOUSE GAS (GHG) EMISSIONS FOR 1 t OF PALM POLYOL

Parameter	GHG emissions for 1 t palm polyol (kg CO_2 eq / 1000 kg palm polyol)	
	Scenario 1	Scenario 2
Refined palm product (obtained from refinery with biogas capture and continued land use)	438.26	438.26
Electricity from grid	819.72	Not applicable (using biomass)
Chemicals (as listed in *Table 3*)	25.56	25.56
Transport of feedstock and chemicals to plant	23.59	23.59
Total emission from 'cradle-to-gate' of palm polyol production	1 307.87	488.15

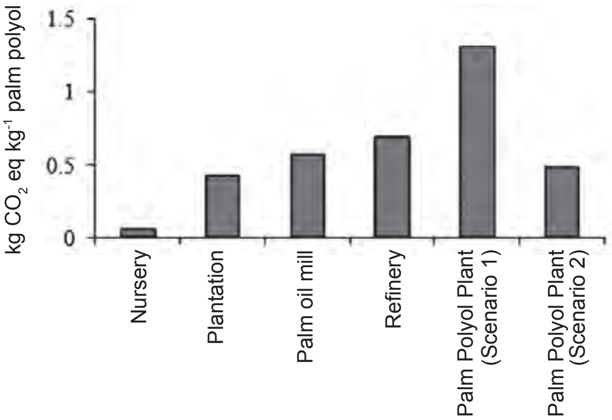

Figure 7. Greenhouse gas (GHG) emissions contributed by each stage during palm polyol production (with 0.05% cut-off criteria).

polyol for both scenarios were calculated and the GHG inventory with more than 0.05% (>0.05% cut-off criteria) to the process was included.

All the data for GHG calculations were obtained individually at each stage in order to produce 1 kg of palm polyol based on GHG value reported by Choo *et al.* (2011). The GHG emissions for both Scenarios 1 and 2 at upstream level (nursery until refinery) are the same but it was different at the polyol plant since the scenario of study is different. The GHG contributions from nursery only contributed minimal impact compared to others. In the plantation stage, continued land use was considered in replanting of oil palms and the major portion of the GHG emissions was from nitrogen-based fertiliser (Choo *et al.*, 2011). Thus, there are no land use change from conversion of secondary or degraded forest or conversion of other tree crops to oil palm. For the palm oil mill, biogas capture facility was used with 85% biogas capture during CPO production. This biogas facility helps to reduce GHG emissions on palm oil mill as proved by Vijaya *et al.* (2011). The biogas captured from palm oil mill is also used as a renewable energy to facilitate energy demand for the mills.

In order to reduce the burden to the environment, the wastes from oil palm biomass, *i.e.* shell and mesocarp fibre, by-products from CPO production were reused as fuel for boiler to generate the energy and reduce the usage of energy from the national grid in palm oil mill. Thus, it can reduce dependency on fossil fuels and move towards the use of renewable fuels. In addition, it has benefited the oil palm industry since the biomass is not considered as wastes generated from the CPO production but rather seen as by-products. 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 GHG emissions for Scenario 1 is higher than Scenario 2 since there is an impact generated during the electricity production. Scenario 2, give the lowest GHG emissions due to the replacement of electricity with the energy produced from the oil palm biomass. It is able to reduce the GHG emissions almost 63% from the normal approach (Scenario 1).

As studied by Pollack (2004), the total fuel energy represents the fuel value of the materials extracted from the earth plus the energy needed to process them into the final product. Value of carbon dioxide for petroleum-based polyol also covered the 'cradle-to-gate' scenario, which is 3500 g kg^{-1} CO_2 eq. with fuel energy ranges between 61.54 MJ kg^{-1} to 93.16 MJ kg^{-1}. However, the palm polyol shows the lowest values in both carbon dioxide equivalents and also in fuel energy compared to the polyol produced from petroleum-based (*Table 5*) by considering 1 kg production of polyol as the functional unit.

From this study, the production of palm polyol using the energy from biomass as an alternative source can reduce 69% of the GHG emissions. The amount of GHG emitted from the palm polyol system using Scenario 1 and Scenario 2 using 'cradle-to-gate' was found to be 1.31 kg CO_2 eq per kg palm polyol and 0.49 kg CO_2 eq per kg palm polyol, respectively (*Figure 8*).

CONCLUSION AND RECOMMENDATIONS

Based on the LCIA results, in the production of palm polyol, the impacts are mainly associated with the electricity consumption and chemical used during the polyol production. If Scenario 2 is implemented in the future, the impact from electricity consumption can be reduced by almost half from the present value. Excluding the contribution of energy from oil palm biomass, the total non-renewable energy demand of palm polyol production which is 4.97 MJ per kg polyol is still comparable to petroleum-based polyol, 61.54 MJ per kg polyol as reported by Pollack (2004) and 93.16 MJ per kg polyol (2005) and 87.9 MJ per kg polyol by Cargill (2008). So, it clearly shows that the lower energy value (MJ per kg polyol) favours the palm polyol process.

However, it should be noted that the study for palm polyol can have a better view and understanding if it can be done precisely at commercial palm polyol plant using their data that can strongly support these findings. Hopefully, this study can be used as a starting point for LCA study on commercial production of palm polyol especially in Malaysia which can be used to assess the effectiveness of their processes and their contribution to environment in order to balance the sustainability of the earth.

ACKNOWLEDGEMENT

The authors would like to thank the Director-General of MPOB for the permission to publish this article. Thanks are also extended to polyol production team of Advanced Oleochemical Technology Division, Aziz Abd Hamid, Puaat Sapar and Mohd Ridzuan Zakaria for their contributions and supports for this study.

TABLE 5. COMPARISON OF CARBON DIOXIDE EQUIVALENTS AND FUEL ENERGY USED DURING THE PALM POLYOL PRODUCTION BASED ON POLYOL STUDY USING PALM-BASED AND PETROLEUM-BASED AS FEEDSTOCKS

Item	Palm polyol[1]	Petroleum-based polyol[2]	Petroleum-based polyol[3]	Petroleum-based polyol[4]
Carbon dioxide (100 years eq.)	1 308 g kg^{-1}	3 590 g kg^{-1}	3 500 g kg^{-1}	3 500 g kg^{-1}
Fuel energy	4.97 MJ kg^{-1}	61.54 MJ kg^{-1}	87.9 MJ kg^{-1}	93.16 MJ kg^{-1}

Note: [1] LCI value based on the Scenario 1 figure.
[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 Plastic*Europe* study by Boustead (2005).

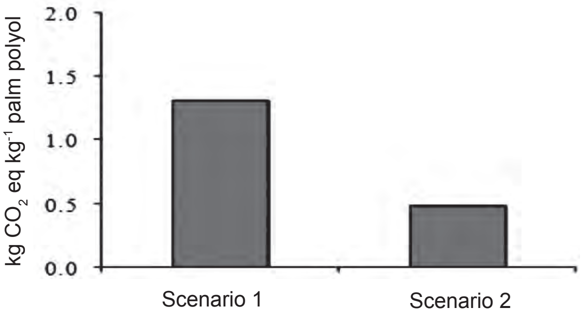

Figure 8. Greenhouse gas (GHG) emissions from two different scenarios.

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