LIFE CYCLE ANALYSIS OF PETROLEUM BASED POLYETHYLENE AND BIO-BASED POLYETHYLENE

NG WEI SIEN

UNIVERSITI TUNKU ABDUL RAHMAN

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NG WEI SIEN

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

Faculty of Engineering and Science
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DECLARATION

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

Signature : __________________________

Name : Ng Wei Sien

ID No. : 08UEB04612

Date : 17 May 2012

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"LIFE CYCLE ANALYSIS OF PETROLEUM BASED POLYETHYLENE AND BIO-BASED POLYETHYLENE"** was prepared by **NG WEI SIEN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Chemical Engineering at Universiti Tunku Abdul Rahman.

Approved by,

Signature : _________________________

Supervisor : Ms Bee Soo Tueen

Date : _________________________

Specially dedicated to
my beloved grandmother, mother, father and brothers

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ABSTRACT

With the world's fossil fuel depletion in supply, bio-based material is needed for the polyethylene production since it is renewable resources. The advantages of bio-based polyethylene production has to be weighed against environmental impacts before it is widespread produced. The system and boundary conditions that considered in the assessment would always affect the environmental impacts. This final year project reported a cradle to gate life cycle assessment (LCA) of petroleum based high density polyethylene and petroleum based low density polyethylene comparison with bio-based high density polyethylene and bio-based low density polyethylene. The life cycle stage that studied was the conversion of raw materials into resin of polyethylene. The environmental impact categories that considered were carcinogens, non-carcinogens, ionizing radiation, global warming, aquatic acidification, ozone layer depletion, aquatic eutrophication, respiratory organics, respiratory inorganics, land occupation, terrestrial ecotoxicity, terrestrial acid/nutri, aquatic ecotoxicity, non-renewable energy and mineral extraction. The geographical scope of this study reflected data from Europe. The energy requirements for production of bio-based HDPE and LDPE were 72.06MJ and 73.6 MJ respectively, which were lower compared to petroleum based HDPE and LDPE which were 76.7 MJ and 78.05 MJ. It was found that bio-based polyethylene was more beneficial compared to petroleum based polyethylene due to their environmental impacts and energy use. However, the production of petroleum based high density polyethylene has lower impacts in respiratory organics, aquatic acidification, aquatic eutrophication and mineral extraction. In overall, the results showed that bio-based high density polyethylene has the lowest damage impacts, followed by the bio-based low density polyethylene.

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LIST OF SYMBOLS / ABBREVIATIONS

ASTM	American Society for Testing and Materials
DALY	Disability adjusted life years
HDPE	High density polyethylene
ISO	International Standard Organization
LDPE	Low density polyethylene
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
PDF	Potentially disappeared fraction
PE	Polyethylene
PET	Polyethylene terephthalate
PS	Polystyrene
PVC	Polyvinly chloride
PUR	Polyurethane
TEG	Triethylene glycol

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CHAPTER 1

INTRODUCTION

1.1 Background

Life cycle assessment (LCA) is an environmental tool that compares a material's performance as an environmentally viable option to its functional alternatives (Madival et al., 2009). LCA uses to study the environmental aspects and potential impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal. A "cradle to grave" analogy is often drawn. LCA evaluates the environmental burdens associated with a product or process by identifying and quantifying energy and materials used and waste released to the environment.

Knowing that material composition is a fundamental determinant of sustainability, the substitution of petroleum based polymer with bio-based polymer is seen as a promising alternative because it will reduce the dependency of polymer on the fossil fuels, and environment impact. Bio-based polymers are more desirable than petroleum based polymers because they are considered environmentally favourable material, and they are derived from renewable resources (Madival et al., 2009). LCAs of bio-based polymers have shown reduced impacts and favourable results in terms of such environmental burdens as greenhouse gas emissions and energy use when compared to petroleum based polymers (Madival et al., 2009).

Polyethylene is comprised of long chains of the building block ethylene monomer. Bio-based polyethylene is produced from bioethanol, which is made from sugar cane. It can also be derived from sugar beet or from starch crops such as maize, wheat or other grains (Shen et al., 2009). While the petroleum based polyethylene is produced from natural gas or the naphtha section of crude oil.

Bio-based polyethylene and petroleum based polyethylene can be used for a large variety of different plastic applications. Both of them can be widely used for food packaging, shopping bags, detergent bottles, cosmetics and personal care, automotive parts, toys and others products.

1.2 Problem Statement

Concerns about the problem of scarcity of fossil fuel-based resources and climate change, the world today are driving an increasing demand for more suitable materials. A sustainable material is needed to reduce the impacts to occupational and public health as well as to the environment during its life cycle. However, to determine whether these materials are preferable form a sustainability perspective, a range of complex issues must be consider through the product life cycle analysis.

In this study, four materials which were petroleum based high density polyethylene (HDPE), petroleum based low density polyethylene (LDPE), bio-based high density polyethylene (HDPE) and bio-based low density polyethylene (LDPE) were examined. Based on these four materials, the following problems were identified:

1. What were the different of environmental footprint throughout their life cycle?
2. Was it the bio-based polyethylene have environmental advantages over the petroleum based polyethylene?

1.3 Objective

The objective of this study was to make a comparative analysis of the environmental footprint in the production of bio-based HDPE, bio-based LDPE, petroleum based HDPE and petroleum based LDPE through a life cycle assessment. Besides that, environmental, health and safety advantages of bio-based polyethylene over the petroleum-based polyethylene were also clarified.

1.4 Scope

This study contained a life cycle analysis for the production of petroleum based high density polyethylene (HDPE), petroleum based low density polyethylene (LDPE), bio-based high density polyethylene (HDPE) and bio-based low density polyethylene (LDPE). The scope of the study was from the raw material for the bio-based polyethylene and petroleum based polyethylene followed by the processes for their resin production only (cradle-to-gate) and excluded the impacts of use, recycle or disposal (cradle-to-grave).

The scope included the consideration of environmental impacts such as global warming (carbon dioxide emission), aquatic acidification, ozone layer depletion, aquatic eutrophication, non-renewable energy, land occupation, respiratory organics, respiratory inorganics, carcinogens, non-carcinogens, ionizing radiation, terrestrial ecotoxicity, terrestrial acid/nutri, mineral extraction and aquatic ecotoxicity as impact categories. The geographical scope of study reflected data from Europe.

A methodology was developed in order to determine the environmental, health and safety impacts of bio-based polyethylene and petroleum based polyethylene during their life cycle. Besides, literature review was conducted to obtain useful information to be used in the evaluation of environment impact of both different based polyethylenes.

CHAPTER 2

LITERATURE REVIEW

2.1 Petroleum Based Polyethylene

Petroleum based polyethylene is derived from either modifying natural gas (a methane, ethane, propane mix) or from the catalytic cracking of crude oil into gasoline. In a highly purified form, it is piped directly from the refinery to a separate polymerisation plant. Here, under the right conditions of temperature, pressure and catalysis, the double bond of the ethylene monomer opens up and many monomers link up to form long chains. The base monomer ethylene is a gas at room temperature, but when linked together as polymers, it forms tough, flexible plastic materials with a large variety of applications. The linking of molecules is referred to as polymerization (Siemens, 2007). In commercial polyethylene, the number of monomer repeat units ranges from 1000 to 10 000 (molecular weight ranges from 28 000 to 280 000) (Lepoutre, 2011).

Polyethylene (PE) is produced either in radical polymerization reactions or in catalytic polymerization reactions. Most PE molecules contain “branches“ in their chains which are formed spontaneously in case of radical polymerization or deliberately by copolymerization of ethylene with α−olefins in case of catalytic polymerization (Siemens, 2007).

PE resins are classified according to their density which partly depends on the type of branching. High density polyethylene (HDPE) has almost no branching and thus has stronger intermolecular forces. It is produced mainly in slurry and gas-phase polymerization processes. HDPE is a white opaque solid. While low density polyethylene (LDPE) has random long branching, with branches on branches. It is produced mainly in high-pressure polymerization processes. LDPE is a translucent solid (Siemens, 2007).

There are various commercial technologies used to manufacture polyethylene. Each technology produces unique combinations of polymer characteristics (Siemens, 2007).

2.1.1 Production of Petroleum Based Polyethylene

Polyethylene is made from ethane, which is found in natural gas. First, as third party need to get the ethane from the ground. Natural gas is found deep under the surface of the earth, usually in pockets of crude oil. Before the process of making polyethylene can begin, the oil must be pumped up to the surface, and the natural gas must be separated from the oil. Several difficult engineering problems arise when transporting natural gas to the surface (Haswell et al., 2009).

Deep within the earth, the crude oil is at a higher pressure than at the surface. This means that as the oil is pumped upwards, some of it converts from a liquid to a vapour. Knowing exactly what vapour/liquid fraction will exist during the pumping process is a difficult problem (Haswell et al., 2009).

The oil/gas mixture is drawn from the ground into a storage tank.

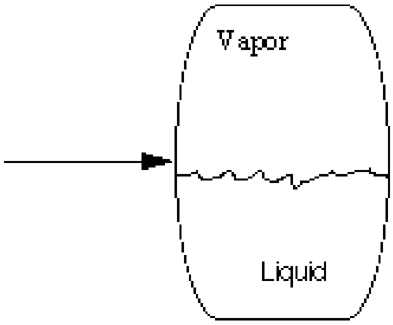

Figure 2.1: Storage Tank (Bian et al., 2009).

A set of distillation columns are used to separate the ethane from the other components in the natural gas (Bian et al., 2009).

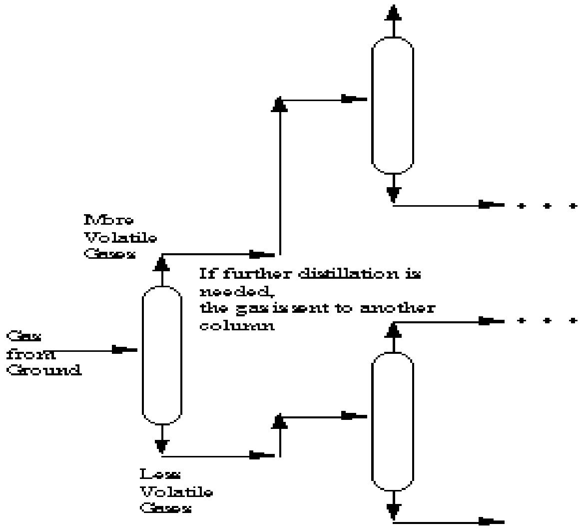

Figure 2.2: Distillation columns (Bian et al., 2009).

Obtaining ethylene from ethane usually involves a thermal cracking unit which is a plug flow reactor. The ethane enters the PFR where a furnace is used to hear the ethane to a very high temperature which causes the ethane to react (Bian et al., 2009).

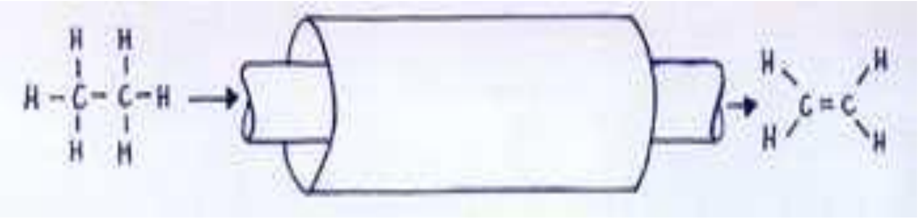

Figure 2.3: Conversion of Ethane to Ethylene through Plug Flow Reactor (Bian et al., 2009).

Ethylene purification is called ethylene fractionation, which separates ethylene as a highly pure overhead product, 99.9wt%, free of olefins, acetylenes, dienes, and water. Driers must be used to remove water since it is a poison for the catalyst in the polyethylene reactor. From distillation tower, ethylene can be split from the ethane. However, there would be some light ends that would go with ethylene. Those are let to react with hydrogen to give ethylene. The ethylene fractionator operates at 700-2800 kPa, with an overhead condenser temperature of -

40 to -90 ℃, and a bottom reboiler at -15 to -65 ℃. This separation requires a high reflux ratio and as many as 125 separation stages (Bian et al., 2009).

Conversion of purified ethylene gas to polyethylene is the most important step of the process. There are several of different processes that can be used to accomplish this conversion, but a common method used is to polymerize ethylene by means of a fluidized reactor bed. The fluidized reactor bed consists of metallic catalyst particles that are 'fluidized' by the flow of ethylene gas. The catalyst particles are suspended in the ethylene fluid since ethylene gas is pumped from the bottom of the reactor bed to the top. Metallic catalysts are very important for the process because the polymerization is impossible without it. Before the late 1970's, an organic peroxide catalyst was used to initiate polymerization. However, due to the organic peroxide catalyst is not as active as the metallic catalyst, pressures in excess of 100 times the pressure required with metallic catalysts were needed (Bian et al., 2009).

Ethylene must be compressed and heated before it is sent to the fluidized bed. Pressures in the range of 100-300 psi and a temperature of 100 degrees Celsius are needed for the reaction to proceed at a reasonable rate. Furthermore, a catalyst stream is also pumped with the ethylene stream into the reactor since catalyst is consumed in the reactor. The catalyst is not actually consumed, it is simply incorporated with the polyethylene product as polyethylene molecules remain stuck to the catalyst particle from which they were produced. For a single pass through the reactor, the conversion of ethylene is low and it is needed to recycle the unreacted ethylene. Unreacted ethylene gas is removed to the top of the reactor, where it is expanded and decompressed to separate the catalyst and low molecular weight polymer from the gas. Then the ethylene gas is recompressed and recycled back into the reactor after purification. When the reasonable conversions have been achieved, granular polyethylene is removed from the bottom of the reactor. A residence time of 3 to 5 hours will result in a 97% conversion of ethylene. By using mole balances, the flow in the fluidized bed reactor can be modelled. Since the polymerization of ethylene reaction is exothermic, large amounts of heat are liberated from the process. Heat is removed by cooling unreacted ethylene gas coming off the top of the reactor and recycling the cool gas back to the reactor. By using an energy balance, temperatures in the fluidized bed reactor can be modelled (Bian et al., 2009).

Polyethylene comes out of the reactor as granular powder, which is melted and flows through a film extruder. The flow rate required to make the polymer flow is determined by solving a boundary value problem (BVP), which comes from the momentum balance (Bian et al., 2009). Originally, bags were made directly from tubular film by wedding one end, but the tendency now is to make wide film on large machines and then make the bags by welding and cutting. The bubble diameter may be up to 2 meters for general purpose packaging, and larger for heavy gauge industrial film in the tubular film process. Additives are important in this process. Without the additives, the pressure of the windup rollers on the warm film forces the surfaces into such close contact that subsequently it may be impossible to separate them. Very fine silica can be used as an anti-blocking agent to overcome this problem. It can roughen the surface on a submicroscopic scale without significantly affecting the optical properties. The friction between the surfaces can be reduced by adding the slip agents (Bian et al., 2009).

LDPE is the preferred packaging material due to its limp feel, transparency, toughness, and the ability to rapidly take up the shape of the contents of the bag. Garbage bag is one of many widely practical uses of plastic bags (Bian et al., 2009).

2.2 Bio-based Polyethylene

Bio-based polyethylene is produced by bioethanol, which is made from sugar cane. The ethanol becomes ethylene after the dehydration process. Bio-based polyethylene can also be derived from sugar beet or from starch crops such as maize, wheat or other grains. The emergence of bio-based polyethylene is not a new phenomenon on the market. When oil prices fell in the early 1990s, bio-based plastic production is ceased and it was again replaced by petroleum based polyethylene. The production of bio-based polyethylene has again become attractive when oil price increased (Li et al, 2009).

2.2.1 Production of Bio-based Polyethylene

The process of producing bio-based polyethylene from sugar cane is shown in Figure 2.4. It begins with cleaning, slicing, shredding and milling the sugar cane stalks. The main product of milling is sugar cane juice. While the by-product of milling is sugar cane fibre, which is known as bagasse. Bagasse is used as a primary fuel source in the sugar mills. Sufficient heat is produced from the combustion of the bagasse to cover the needs of a sugar mill. Depending on the plant, exceed heat or electricity can be generated and sold to industrial users or to the grid (Li et al, 2009). The sugar cane juice has an average sucrose content of 12 - 13% and is fermented to ethanol according to the reaction below:

$$C_6H_{12}O_6 \rightarrow 2\ CH_3CH_2OH + 2\ CO_2 \qquad (2.1)$$

Ethanol is distilled to remove water and to yield an azeotropic mixture of hydrous ethanol (at 95.5 vol.-%). Distillation generates another byproduct, which is known as vinasse. It is used as a fertilizer (Li et al, 2009). After that, ethanol is dehydrated at high temperature over a solid catalyst to produce ethylene:

$$CH_3CH_2OH \rightarrow CH_2{=}CH_2 + H_2O \qquad (2.2)$$

Polyethylene is the product made of ethylene. There are different kinds of polyethylene, which are high density polyethylene (HDPE), low density polyethylene (LDPE) and linear low density polyethylene (LLDPE). LLDPE is a copolymer of ethylene and butene, hexane or octane. Other from these polyethylenes, ethylene can be used to produce PVC, PET, PS and polyols for polyurethanes (PUR) as well (Li et al, 2009).

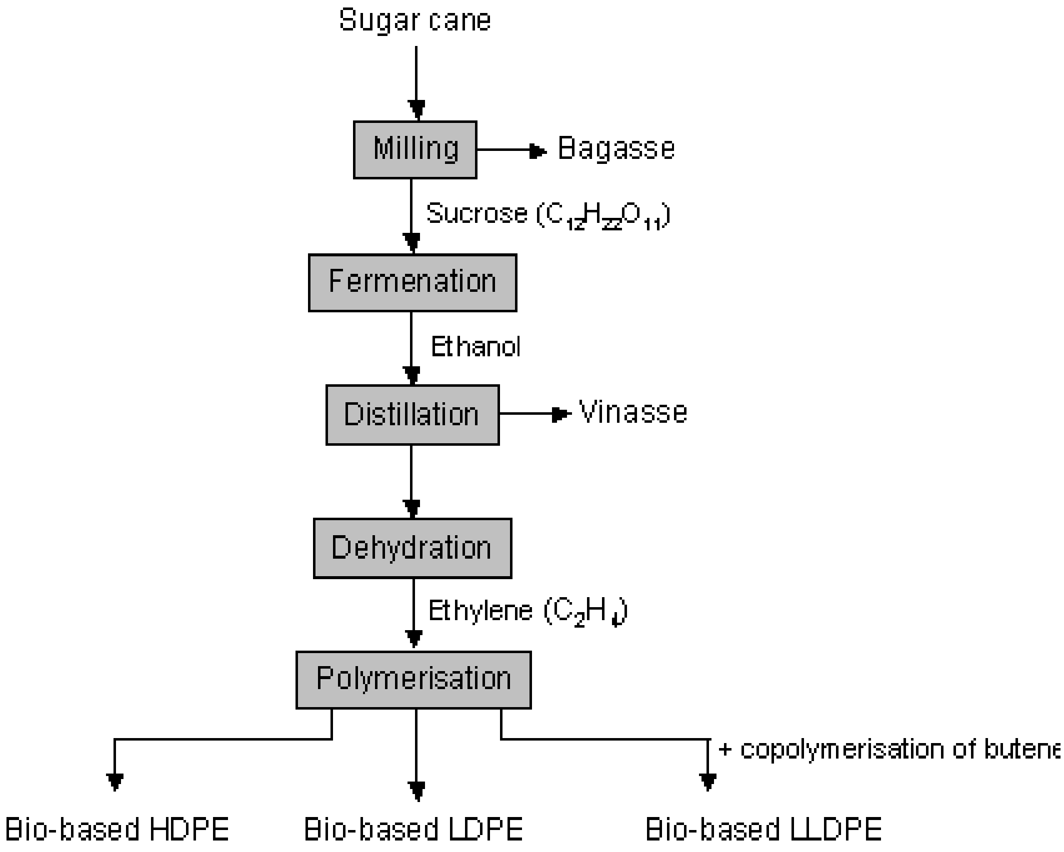

Figure 2.4: Overview of the production of bio-based PE (Li et al, 2009).

2.3 Characteristic of HDPE and LDPE

HDPE is produced in low pressure reactors and so is referred to as high density polyethylene. HDPE has the same repeat unit and is usually regarded as polyethylene with a density greater than 940 kg/m^3. It differs from LDPE in that it contains fewer side branches at 5 to 10 per 1000 carbon atoms on the backbone. Most of the side branches are short with long side branches being rare. The increased stiffness and density were found to be due to a much lower level of chain branching. Molecular weights are similar to low density polyethylene but crystallinities are usually high (50-85%) and densities range from 940 to 960 kg/m^3 (PE International, 2010).

Two main techniques are used for the production of HDPE: the suspension (slurry process) and the gas phase process. In gas phase polymerization, large fluidized bed reactors are used, operating at relatively high pressure (20 - 30 bar), with high ethylene recycle through a gas cooler to remove heat of polymerization (International Finance Corporation, 2007). HDPE is one of the most popular plastics in use today. HDPE resins can be tailored to be used in many applications such as film, crates, boxes, caps and closures, bottles and containers for food products, cosmetics, pharmaceuticals, household and industrial chemicals, toys, fuel tanks and other automotive parts, pipes for gas and water distribution (Czaplicka-Kolarz et al., 2010). A process flow diagram of a typical modern suspension process (slurry process) is shown in Figure 2.6.

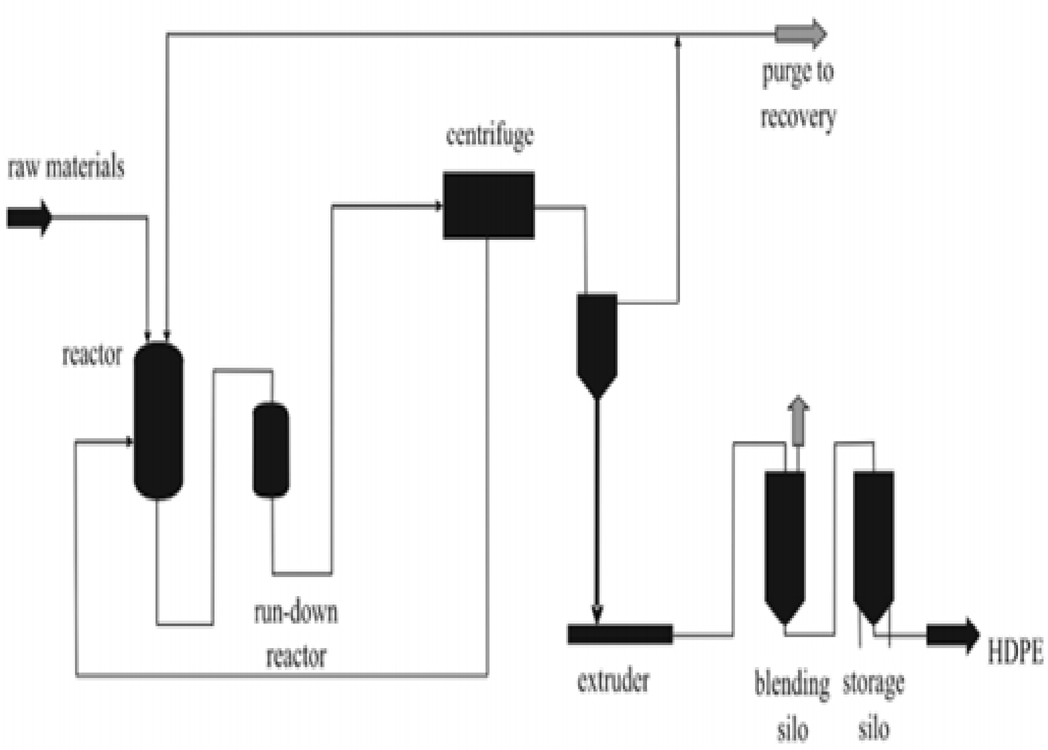

Figure 2.5: Flow diagram of a HDPE production (Czaplicka-Kolarz et al., 2010).

Low density polyethylene (LDPE) is a polyethylene produced by a high pressure process, and it is therefore often referred to as high pressure polyethylene. LDPE has traditionally been defined as polyethylene with a density less than 940 kg/m3. The polymer contains both long and short chain side branching with the number of branches being from 2 and 50 per 1000 carbon atoms on the carbon backbone. LDPE can be produced with chain lengths ranging from 50,000 to 100,000 repeat units, with crystallinities in the range 35 to 75% and with densities in the range 915 to 940 kg/m^3 (PE International, 2010).

The main technique which is used for the production of LDPE is autoclave and tubular high pressure technology. Ethylene is compressed up to 3000 bar and fed to the reactor, when the oxygen or organic peroxide is injected to initiate the radical polymerization at 140 – 180 ℃. Temperature of the reaction is high, peaking to more than 300 ℃. The ethylene polymer blend is continuously discharged to a high pressure at 250 bar separator, where polymer precipitates and most of the unreacted ethylene is recovered, recompressed and recycled to the reactor. Polymer is then fed to a low pressure separator, where degassing is completed. The molten polyethylene is then finished by extrusion and pelletizing (International Finance Corporation, 2007). A basic flow diagram for LDPE processes is shown in Figure 2.7.

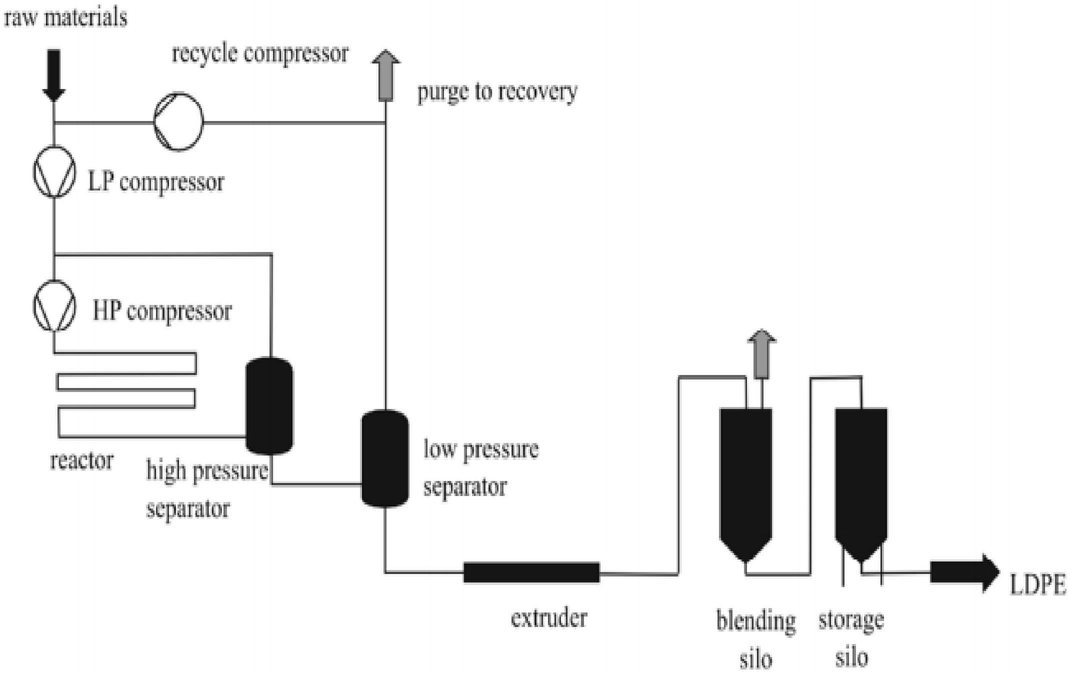

Figure 2.6: Flow diagram of a LDPE production (Czaplicka-Kolarz et al., 2010).

2.4 Properties

Chemical, physical and mechanical properties of bio-based polyethylene are exactly the same as petroleum based polyethylene. Bio-based polyethylene is suitable for mechanical recycling because of its thermoplastic properties. Both petroleum based polyethylene and bio-based polyethylene are not biodegradable (Shen et al., 2009).

2.5 Technical Substitution Potential

Bio-based polyethylene has potential to fully substitute the production of petroleum based polyethylene as it has the same properties as petroleum based polyethylene it. For processing bio-based polyethylene, the same machinery can be used as for petroleum based polyethylene.

2.6 Applications Today and Tomorrow

Although bio-based polyethylene is not yet produced in bulk, it will be commercially available and used in future. Bio-based polyethylene can be same as petroleum based polyethylene, be used for a large variety of different plastic applications. In the first phase, bio-based polyethylene will be produced for food packaging, for agricultural and industrial purposes, cosmetics and personal care, automotive parts and toys.

2.7 Life Cycle Assessment

Life Cycle Assessment (LCA) is an environmental assessment method to evaluate the environmental aspects and potential impacts of a product, process or technology has on the environment over the entire period of its life – from the extraction of the raw material through the manufacturing process, packaging processes, the use, reuse and maintenance of the product or technology, to its recycling or disposal as waste at the end of its useful life. There are four phases in an LCA study (ISO 14040, 2006):

1. Goal and scope definition,
2. Inventory analysis,
3. Impact assessment,
4. Interpretation of the study result.

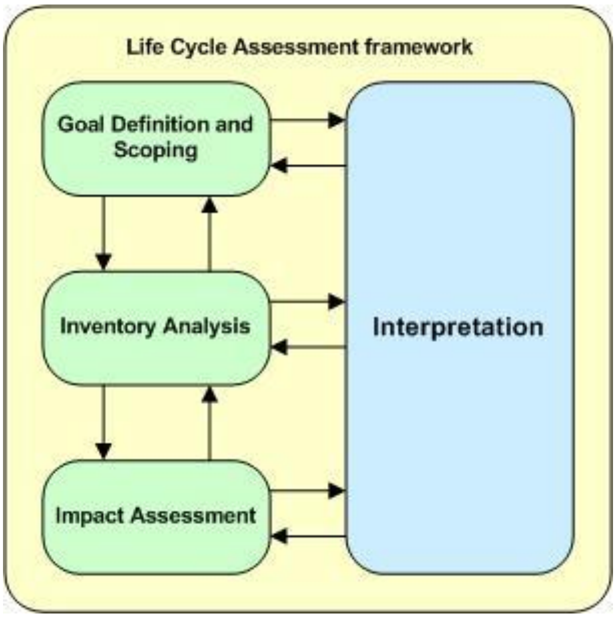

Figure 2.7: Stages of an LCA (ISO 14040, 2006).

LCI (Life Cycle Inventory) is the second phase of LCA involving the compilation and quantification of inputs and outputs for a product throughout its life cycle. It involves collection of the data necessary to meet the goals of the defined study. LCIA (Life Cycle Impact Assessment) is the third phase of LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impact for a product system throughout the life cycle of product (ISO 14040, 2006).

Carry out a full LCA analysis is a complex process, hence the use of certain limitations. Impact assessment analysis has been carried out only for production stage. The impact of construction of the process plant and equipment maintenance and impact of disposal were excluded (Harding et al., 2007).

Feed materials were analyzed in the process to assess the ecological risks posed by the polyethylene production. It is limited to basic materials based on inventory data contained in the reports of Best Available Techniques BAT, and the literature review. The LCA of chosen polyethylene production is carried out using SimaPro version 7.1 software, with Ecoinvent database and the Eco-indicator 99 and CML 2 baseline 2000 V2.03 assessments methods. The system boundary was from cradle to factory gate production of these polyolefins including all inputs, raw materials, energy, emissions and wastes. 1000 kg of HDPE and LDPE were the functional unit (Czaplicka-Kolarz et al., 2010). The evaluation of environmental impacts caused by the HDPE and LDPE production effects of three categories which were human health, ecosystem quality and resources in Pt per Mg products is shown in Table 2.1.

Table 2.1: Environmental impact assessment in three damage categories using Eco-indicator 99 method (Czaplicka-Kolarz et al., 2010).

Damage category	HDPE, Pt/Mg	LDPE, Pt/Mg
Human Health	64.9	78.3
Ecosystem Quality	12.9	15.9
Resources	240.8	261.7
Total	318.7	356.0

By using Eco-indicator 99 method, LCA analysis shows that LDPE production has more environmental impact than HDPE production. The total average eco-indicator value for HDPE is 318.7 Pt and for LDPE is 356 Pt per 1 Mg of product. It was noticed that the highest environment impact occurs in the category of "resources" amounts 240 Pt for HDPE and 261 Pt for LDPE. The category "resources" is 75% of risks posed by these processes. Ethylene production (87%) caused the highest impact on resources (Czaplicka-Kolarz et al., 2010).

There were eleven impact categories using Eco-indicator 99 assessment method for HDPE and LDPE production, in Pt on Mg products in Table 2.2. The second analysis was performed using CML 2 baseline 2000 V2.03 assessment method. Impact categories for 1Mg of HDPE and LDPE production is as shown in Table 2.3.

Table 2.2: Environmental impact assessment in eleven impact categories using Eco-indicator 99 method (Czaplicka-Kolarz et al., 2010).

Impact category	HDPE, Pt/Mg	LDPE, Pt/Mg
Carcinogens	2.9	3.7
Respiratory organics	0.6	0.5
Respiratory inorganics	47.3	56.9
Climate change	13.6	16.5
Radiation	0.3	0.5
Ozone layer	0.2	0.2
Ecotoxicity	7.4	8.9
Acidification/ Eutrophication	3.9	4.7
Land use	1.6	2.4
Minerals	0.1	0.2
Fossil fuels	240.8	261.5
Total	318.7	356

Table 2.3: Environmental impact assessment using CML method, per Mg (Czaplicka-Kolarz et al., 2010).

Impact category	Unit	HDPE	LDPE
Abiotic depletion	kg Sb eq	37.384	41.637
Global warming (GWP100)	kg CO2 eq	2529.882	3062.441
Ozone layer depletion (ODP)	kg CFC-11 eq	0.008	0.008
Human toxicity	kg 1.4-DB eq	3107.847	3464.226
Fresh water aquatic ecotoxicity	kg 1.4-DB eq	367.840	416.545
Marine aquatic ecotoxicity	kg 1.4-DB eq	1931013	2372936
Terrestrial ecotoxicity	kg 1.4-DB eq	30.541	36.783
Photochemical oxidation	kg C2H4	3.469	1.989
Acidification	kg SO2 eq	22.507	27.408
Eutrophication	kg PO4 eq	0.880	1.023

For HDPE, 2529.8 kg $CO_{2\ eq}$ was released in the atmosphere and for LDPE 3062.4 kg $CO_{2\ eq}$, per 1Mg of product. The highest impact on CO_2 equivalent in this production was due to ethylene. The next stage of the study was LCA analysis for the ethylene production. Life cycle inventory of ethylene production was developed based on literature data (Czaplicka-Kolarz et al., 2010).

Ethylene is the most important base chemical in the petrochemical industry. One of the alternative routes for the production of ethylene is from natural gas via oxidative coupling of methane. The process is economically unfeasible. However, recent studies suggested that this may be overcome by producing not only ethylene but also electricity, using the heat from the very exothermic coupling reaction. The major use of ethylene is conversion to low density and high-density polyethylene (Czaplicka-Kolarz et al., 2010).

Emissions from ethylene production are released to air and water. They consist of ethylene and propylene emissions to air, and methanol and propane/butane emissions to water. Naphtha occupies a major part in all impact categories in the case of ethylene, especially Photochemical Ozone Creation Potential (POCP). This is because of the processing of crude oil which causes volatile organic compound (VOC) emissions. Based on the LCA analysis found that the highest impact on the environment in the production of ethylene is naphtha refinery (almost 70%). For 1Mg ethylene production CO_2 equivalent is 2180 kg CO_2 eq (Czaplicka-Kolarz et al., 2010).

Economics and environmental issues are the main factors considered in the choice of feedstock and processes of ethylene production. There have been some improvements and advances within the conventional ethylene production technology in the past forty-five years. Researchers worked on increasing product yield, feedstock flexibility, and thermal efficiency in thermal cracking process. While in purification and recovery, there has been progress in different unit operations such as in distillation, refrigeration, and separation (Czaplicka-Kolarz et al., 2010).

Another life cycle inventory of petroleum based HDPE and LDPE production was developed by Boustead (2000), and presented in the SimaPro model of ETHESU (Frischknecht and Suter, 1996), is shown in Table 2.4. The LCA of the different polymer production methods is carried out using the LCA software package SimaPro version 7 and the CML 2 Baseline 2000 v2.03 assessment method. The system was defined as cradle to gate production of plastic granules, including all raw materials and agricultural inputs, detergent and enzyme use and wastewater treatment. It takes CO_2 uptake into account during the sugar cane growth for glucose requirements. The bagasse from the sugar cane, co-produced in the processing of sucrose, was used for electricity generation, thereby releasing a portion of CO_2 that was taken up during cultivation. Carbon dioxide released in other areas of production such as fossil electricity production was also taken into account (Harding et al., 2007).

Table 2.4: Values for HDPE and LDPE production as used in the LCA of Frischknecht and Suter (1996) (Harding et al., 2007).

	High density polyethylene	**Low density polyethylene**
Products		
Polyolefin (kg)	1000	1000
Feed		
Electricity (GJ)	1.5	3.0
Ethylene (kg)	1020	1050
Oil (kg)	13	50
Refinery gas (kg)	10	40
Emissions		
To air:		
NMVOC (kg)	-	0.007
Ethane (kg)	16	2.2
To water:		
Benzene (g)	0.00065	7.6
Toluene (g)	0.009	7
p-dimethyl-phthalate(g)	-	5.1
Phenols (g)	0.002	0.9
Dichloro-ethane (g)	-	0.22
Mercury (g)	-	0.018

While by using the CML2 Baseline 2000v2.03 method of assessment, the life cycle impact assessment (LCIA) of HDPE and LDPE is summarized in Table 2.5.

Table 2.5: LCIA of polymer production for 1000 kg of polymer product – CML 2 Baseline 2000 V2.03 (Harding et al., 2007).

Impact category	**Unit**	**HDPE**	**LDPE**
Abiotic depletion	kg Sb_{eq}	35.3	39.4
Global warming (GWP100)	kg $CO_{2\ eq}$	2510	3040
Ozone layer depletion (ODP)	kg CFC-11_{eq}	0.000766	0.0018
Human toxicity	kg 1,4-DB_{eq}	2590	2890
Fresh water aquatic ecotoxicity	kg 1,4-DB_{eq}	176	210
Marine aquatic ecotoxicity	kg 1,4-DB_{eq}	1230 000	1610 000
Terrestrial ecotoxicity	kg 1,4-DB_{eq}	33.7	40.3
Photochemical oxidation	kg C_2H_2	17.5	3.92
Acidification	kg $SO_{2\ eq}$	22.5	27.4
Eutrophication	kg $PO_4{}^{3-}{}_{eq}$	0.811	0.951

2.8 Life Cycle Assessment Standard

A set of international standards from the International Standard Organization (ISO) and American Society for Testing and Materials (ASTM) International were used as guidelines for the systematic approach and conduct of this study. The different standards used to achieve different motives were explained as follows:

- ASTM 7075-04 - Standard practice for evaluating and reporting environmental performance of bio based products.

- *ISO 14040 - LCA principles and framework.* This standard outlines the general principles and requirements for conducting and reporting an LCA study. This standard was used to familiarize with the basic framework of an LCA study and the terms mentioned along with. The scope of this standard specified that it did not describe the life cycle assessment technique in detail but just defined the following sections a) goal of the study, b) life cycle inventory analysis, c) life cycle assessment, d) life cycle interpretation, e) reporting, and f) critical review. The general framework to be followed in the study is as follows.

- *ISO 14041 - Environmental management - Life cycle assessment -Goal and scope definition* and *Inventory Analysis* - This standard described specifically the goal and inventory analysis of the study. With the help of this standard the goal and scope of the study, the functional unit and the system boundaries of the study were formed. Also the data categories, data quality, preparation of data collection and its validation were carried out.

- *ISO 14042 - Environmental management - Life cycle assessment - Life cycle impact assessment* - This standard dealt with the intricacies of the life cycle impact assessment procedure. This standard was used for the selection of impact categories, category indicators, and characterization models. The standard supports the assignment of the LCI results, calculation of category indicator results i.e (characterization), grouping, weighting, and data quality analysis. The classification and characterization factors were calculated within the software.

- *ISO 14043 - Environmental management - Life cycle assessment - Life cycle interpretation-* This standard discussed the issues related to life cycle interpretation procedure. It was helpful in structuring the information of the inventory phase and determining the significant issues with the inventory data, impact categories. It evaluated the appropriateness of the results by doing completeness check and sensitivity check. Conclusion and interpretation of the results on the basis of inventory analysis was done with this standard

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- *ISO 14044* - ISO 14044 (2006) Environmental Management - Life Cycle Assessment - requirements and guidelines 2006. This standard discussed the guidelines for defining the goal and scope of the study, inventory analysis, impact assessment and interpretation. It also provided guidelines for reporting of LCA results, and conditions for use of optional.

- *ISO 14049 - Environmental management - Life cycle assessment - Examples of application of ISO 14041 to goal and scope definition and inventory analysis-* This standard was used to study the given examples of developing function, distinguishing function of comparative systems, establishing inputs and outputs of unit processes and system boundaries, examples of allocations procedures.

CHAPTER 3

METHODOLOGY

3.1 Materials and Functional Unit under Consideration

The materials that were compared in this study were petroleum based polyethylene and bio-based polyethylene. In the accounting LCA of the final use of the material was not known. Thus, the mass unit of polymer has chose by using 1 kg of study material as the basis of comparison (functional unit) since this approach was most frequently used.

3.2 System Boundaries

In the analysis that was performed, the full life cycle of the product is not considered. On the contrary, break down of the full lifecycle was done in order to monitor smaller single stage processes by limiting the system boundaries for each investigation (Astropekakis, 2008). The life cycle stage that studied was conversion of raw materials into resin of polyethylene with various production processes. Resin of polyethylene is rigid, with high Young modulus and low elongation to failure. The type of manufacturing technology used for polyethylene was thermoplastics which was soften and melt reversibly when heated and harden when cooled. It can be easily recycled, though with a general degradation of its properties.

3.3 Standard Guideline

The framework of this study was defined according to ISO 14040 guidelines. The goal and scope definition of the problem and the inventory analysis were framed and conducted according to ISO 14041 recommendations. The life cycle assessment and interpretation were conducted according to ISO 14042, 14043 and 14044 respectively, and ISO 14049 was used for examples of developing function, distinguishing function of comparative systems, establishing inputs and outputs of unit processes and system boundaries, and examples of allocations procedures. ASTM 7075 was consulted to comply with U.S. standards (Madival et al., 2009). SimaPro™ software from Pre® consultants was used as the source for the life cycle inventory (LCI).

SimaPro™ 7.3 Demo version software from Pre consultants (The Netherlands) was used as the primary source for the life cycle inventory (LCI). This software is supported with databases for the LCI for over 2500 processes. Most of the data was obtained from the European Life Cycle Database (ELCD) version 2.0 and Ecoprofiles Plastic Europe 2005. Out of the various impact assessment methods available with the software, Impact 2002+ method was chosen, which was a combination of IMPACT 2002 Eco-Indicator 99, CML, and IPCC methods and the one which gave us the results with the desired format and units.

In this project, the life cycle analyses for based bio-based high density polyethylene and bio-based based low density polyethylene were obtained from European Life Cycle Database (ELCD) version 2.0. While for the life cycle analyses for petroleum high density polyethylene and petroleum low density polyethylene were obtained from Ecoprofiles Plastic Europe 2005.

3.4 Inventory Datasets and Assessment Methods

Data from different LCI database were processed by different comparison methods of the SimaPro software. A small presentation of the libraries and of the damage assessment methods used for the polymer comparison exercise were presented below.

3.4.1 LCI Libraries

The LCI data for bio-based polyethylene and petroleum based polyethylene were collected from the commercial SimaPro software. The following LCI data libraries of the SimaPro software were considered in this investigation.

3.4.1.1 European Life Cycle Database (ELCD)

The ELCD core database comprises of life cycle emission and resource consumption data from front-running EU-level business associations and other sources for key materials, energy carriers, transport, and waste management (Life Cycle Inventory). Focus is on data quality, consistency, and applicability. The respective data sets are officially provided and approved by the named business association (Pre. SimaPro, 2008).

3.4.1.2 Ecoprofiles Plastic Europe 2005

Ecoprofiles of plastics and related intermediates created by Boustead for Plastic Europe. The results are average calculated as the mean value of the participating companies weighted by their production. The inventory table includes raw materials, air emissions, water emissions and wastes from all operation traced back to the extraction of raw materials from the earth. These eco-profiles are an update of earlier data sets, using the latest data available. The inventory data in these ecoprofiles are given in more details than the previous ecoprofiles, and a number of methodological changes have been implemented (Pre. SimaPro, 2008).

3.4.2 Impact Assessment Methods

Different LCA impact assessment methods are available with the SimaPro software. The LCI data coming from the databases that have been just presented were analyzed with the use of various impact assessment methods. In this study, the IMPACT 2002+ method was chosen.

3.4.2.1 IMPACT 2002+

IMPACT 2002+ is an impact assessment methodology originally developed at the Swiss Federal Institute of Technology - Lausanne (EPFL), with current developments carried out by the same team of researchers now under the name of ecointesys-life cycle systems (Lausanne) (Pre. SimaPro, 2008). IMPACT 2002+ is mainly a combination between IMPACT 2002, Eco-indicator 99, CML and IPCC. IMPACT 2002+ method carries out the impact assessment by basically converting the LCI results into midpoint categories, which are impact categories, and then converting the impact categories into damage categories (the endpoint) by means of midpoint reference unit.

The impact categories consider in this method are carcinogens, non-carcinogens, ionizing radiation, global warming, aquatic acidification, ozone layer depletion, aquatic eutrophication, respiratory organics, respiratory inorganics, land occupation, terrestrial ecotoxicity, terrestrial acid/nutri, non-renewable energy, mineral extraction and aquatic ecotoxicity. The main focus of this study is the use of fossil resources versus the use of bio-based resources. Thus global warming and energy resources are two important impact categories. Though other impacts have also been taken into account. The respective midpoint reference units are shown in Table 3.1.

Table 3.1: Reference unit for each impact category.

Impact category	Reference unit
Carcinogens	kg chloroethylene equivalents into air (kg C_2H_3Cl $_{eq}$)
Non-carcinogens	kg chloroethylene equivalents into air (kg C_2H_3Cl $_{eq}$)
Respiratory inorganics	kg PM2.5 equivalents into air ("kg PM2.5 $_{eq}$)
Ionizing radiation	Bq C-14 equivalents into air (Bq C-14 $_{eq}$)
Ozone layer depletion	kg CFC-11 equivalents into air (kg CFC-11 $_{eq}$)
Respiratory organics	kg ethylene equivalents into air (kg C_2H_4 $_{eq}$)
Aquatic ecotoxity	kg triethylene glycol equivalents into water (kg TEG water)
Terrestrial ecotoxicity	kg triethylene glycol equivalents into soil (kg TEG soil)
Terrestrial asid/nutri	kg SO_2 equivalents into air (kg SO_2 $_{eq}$)
Land occupation	m^2 organic arable land (m^2org.arable)
Aquatic acidification	kg SO_2 equivalents into air (kg SO_2 $_{eq}$)
Aquatic eutrophication	kg PO_4--- equivalents into a P-limited water (kg PO_4 P-lim)
Global warming	kg CO_2 equivalents into air (kg CO_2 $_{eq}$)
Non-renewable energy	MJ primary non-renewable (MJ primary)
Mineral extraction	MJ surplus (MJ surplus)

The authors of IMPACT 2002+ suggest considering the four damage oriented impact categories human health, ecosystem quality, climate change, and resources separately for the interpretation phase of LCA. The respective damage units are DALY for Human health, PDF*m^2*yr for Ecosystem quality, kg_{eq} CO_2 into air (written "kg CO_2 $_{eq}$") for Climate change and MJ primary non-renewable (written "MJ primary") for Resources.

The carcinogens, non-carcinogens, ozone layer depletion, ionizing radiation, respiratory inorganics and respiratory organics fall under the human health damage category. The aquatic ecotoxicity, ozone layer depletion, terrestrial ecotoxicity, terrestrial acidi/nutri, land occupation, aquatic acidification and aquatic eutrophication fall under the ecosystem quality damage category. Global warming comes under the climate change damage category and the non-renewable energy and mineral extraction come under the resources damage category.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Impact Assessment Results

Petroleum based polymer is currently slowly replaced by the bio-based polymer as the shortage of the natural resource. It is believe that bio-based polyethylene produces a lower environmental footprint compared to petroleum based polyethylene. However, environmental studies that based on the production of petroleum based polyethylene and bio-based polyethylene are scarce. As a result, this final year project focused on the life cycle assessment of the conversion of raw materials into resin of petroleum based polyethylene and bio-based polyethylene. In this case, petroleum based HDPE, petroleum based LDPE, bio-based HDPE and bio-based LDPE were chosen to be compared.

Table 4.1 shows the contribution towards the total emission made by the production for each polyethylene. The result also can be viewed from the Figure 4.1 and Figure 4.2 which were showed in the graph form. The environmental impacts of HDPE and LDPE were of the same order of magnitude in all the impact categories for petroleum based and bio-based respectively. There were no impact for the ionizing radiation, ozone layer depletion and land occupation. All categories except carcinogen and non-carcinogen for petroleum based polyethylene had higher impacts for HDPE than LDPE. Out of the twelve effected environmental impact categories, bio-based HDPE showed a reduced environmental impact in eight categories. The impact categories that indicated lower effect of petroleum based HDPE were respiratory organics, aquatic acidification, aquatic eutrophication and mineral extraction. While the production of petroleum based and bio-based HDPE showed they were having same values of global warming and terrestrial acid/nutri.

Table 4.1: Environmental impact assessment in fifteen impact categories.

Impact category	Unit	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
Carcinogens	kg $C_2H_3Cl_{eq}$	0.391	0.128	**2.24E-07**	4.79E-07
Non-carcinogens	kg $C_2H_3Cl_{eq}$	0.448	1.37E-05	**2.61E-06**	5.76E-06
Respiratory inorganics	kg $PM2.5_{eq}$	0.00109	0.00125	**0.00107**	0.00125
Ionizing radiation	Bq $C\text{-}14_{eq}$	0	0	0	0
Ozone layer depletion	kg $CFC\text{-}11_{eq}$	0	0	0	0
Respiratory organics	kg $C_2H_{4\ eq}$	**0.000263**	0.00043	0.00268	0.00294
Aquatic ecotoxity	kg TEG water	5.64	13.6	**0.00226**	0.00873
Terrestrial ecotoxicity	kg TEG soil	0.0111	0.041	**0.0109**	0.0409
Terrestrial acid/nutri	kg $SO_{2\ eq}$	**0.0218**	0.0258	**0.0218**	0.0258
Land occupation	m2org.arable	0	0	0	0
Aquatic acidification	kg SO_2 eq	**0.00639**	0.00774	0.0064	0.0075
Aquatic eutrophication	kg PO_4 P-lim	**5.41E-06**	5.93E-06	6.42E-06	7.22E-06
Global warming	kg $CO_{2\ eq}$	**1.69**	1.82	**1.69**	1.82
Non-renewable energy	MJ primary	77.2	78.2	**71.5**	72.5
Mineral extraction	MJ surplus	**7.73E-05**	0.00136	8.68E-05	0.00139

Key: Bolded and underlined values are the lowest values in each impact category.

Figure 4.3 shows the normalized values for the emission produced by 1 kg of each polyethylene. Normalization values help to gain a better understanding of the true impact of the production system. Each total emission value in the Table 4.1 was divided by the reference (normal emission produced by one European citizen) as established by IMPACT 2002+. All the final impact indicators of Figure 4.3 have the same unit, which makes it easier to compare them. The highest normalized impact values for the four types of the polyethylene were respiratory inorganics, global warming and non-renewable energy.

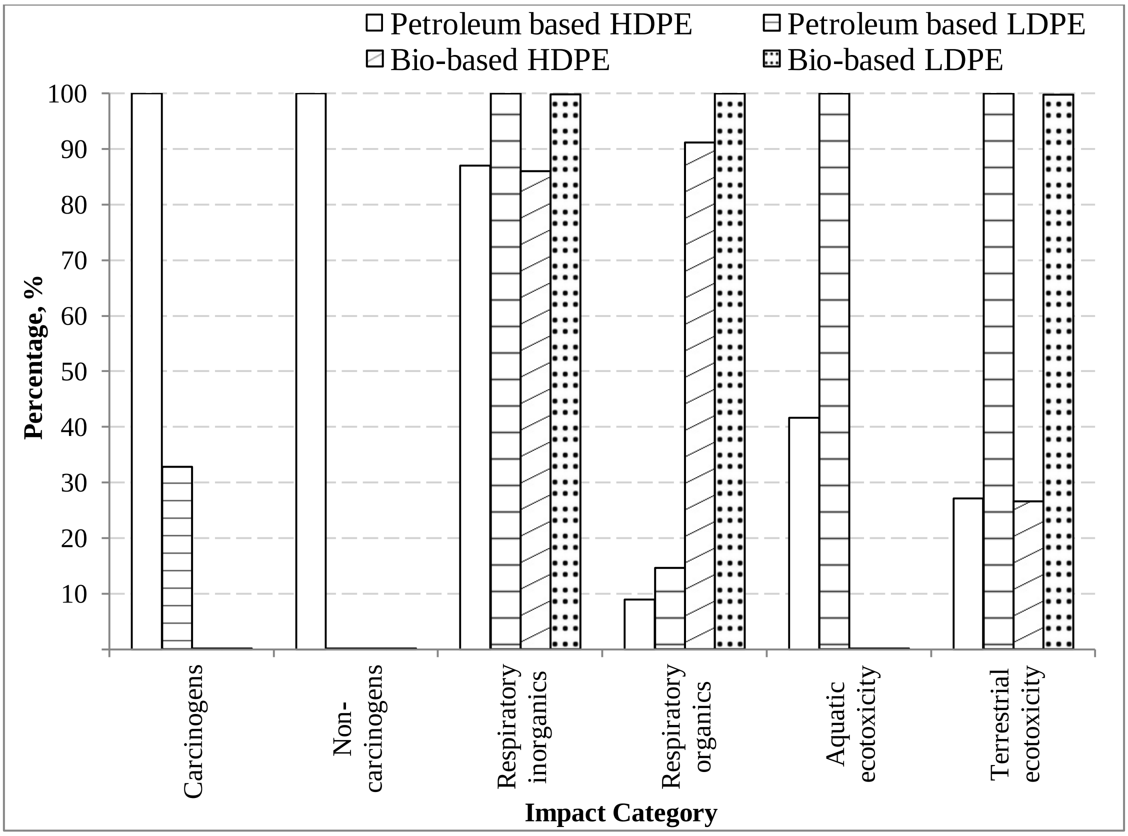

Figure 4.1: Results of environmental impact assessment (Part 1).

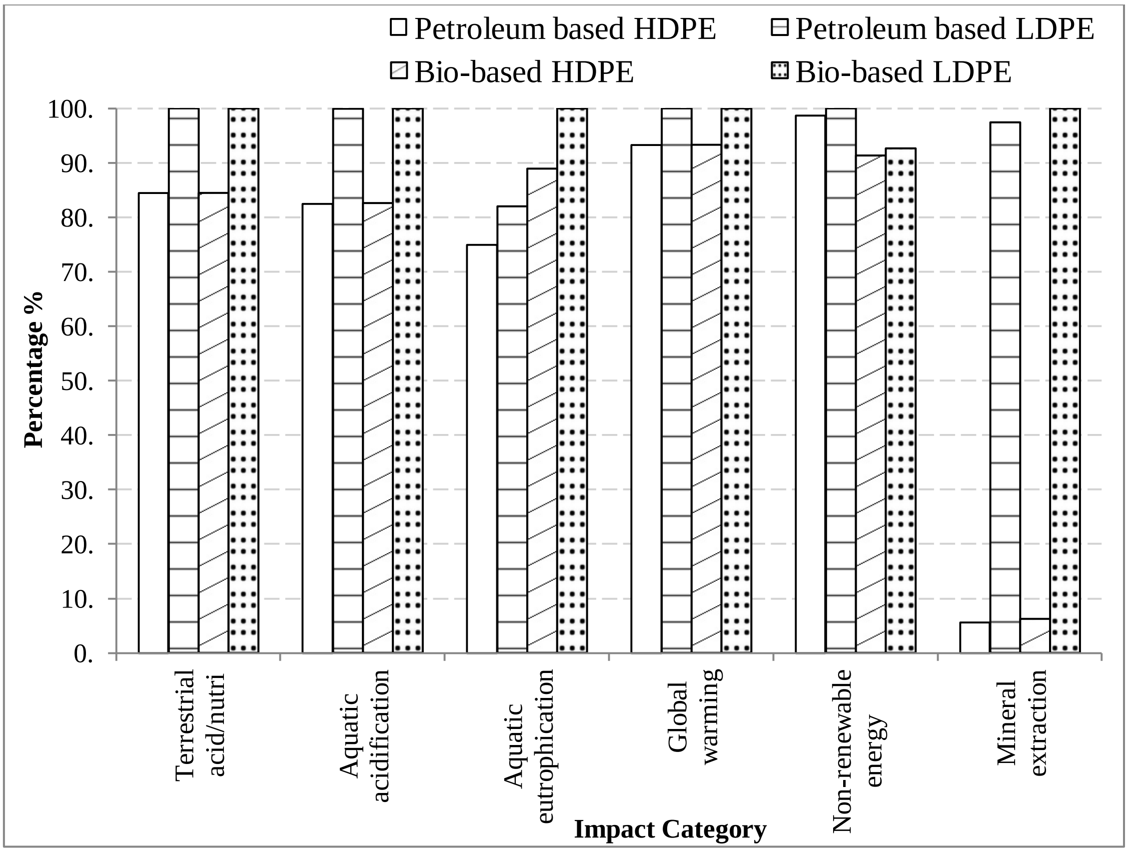

Figure 4.2: Results of environmental impact assessment (Part 2).

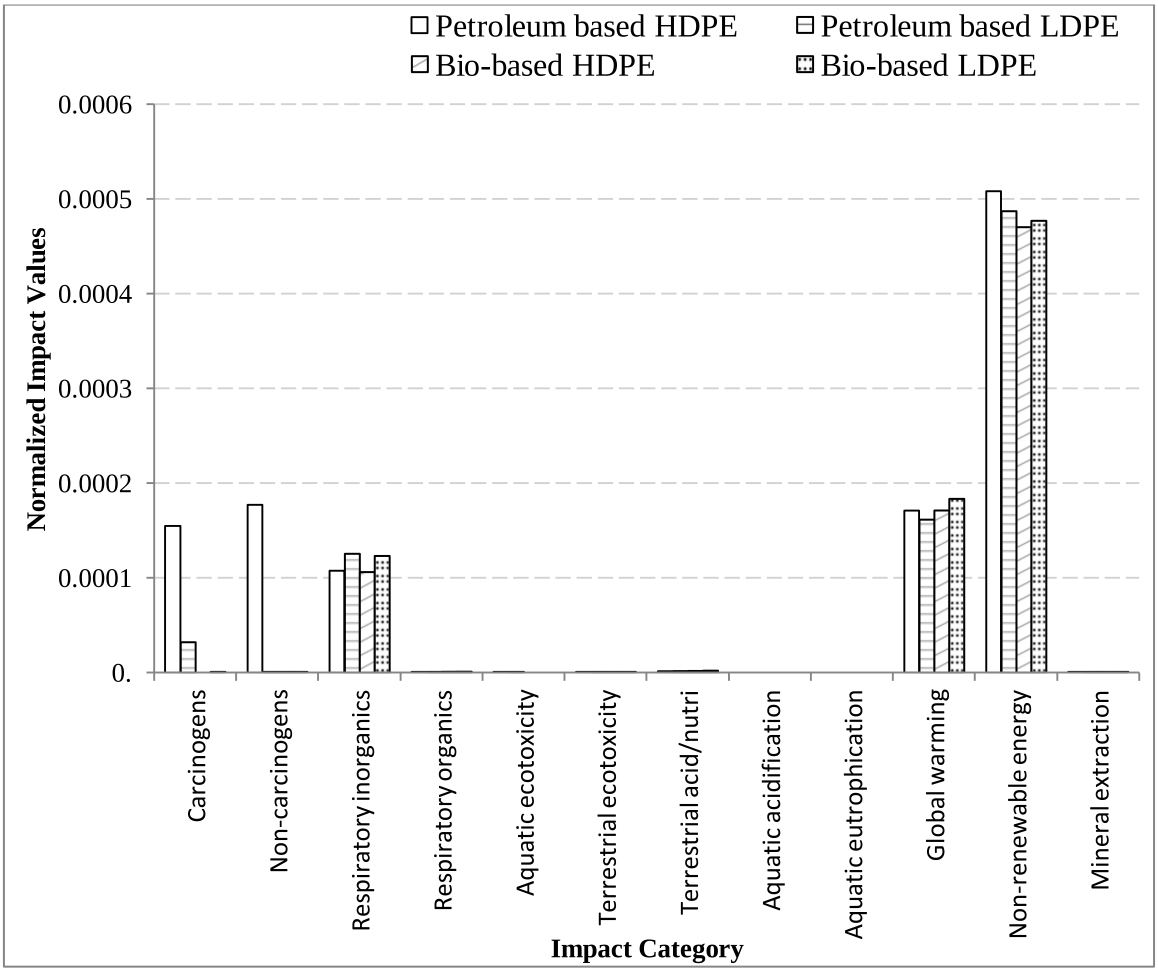

Figure 4.3: Normalized impact values comparing four different types of polyethylene.

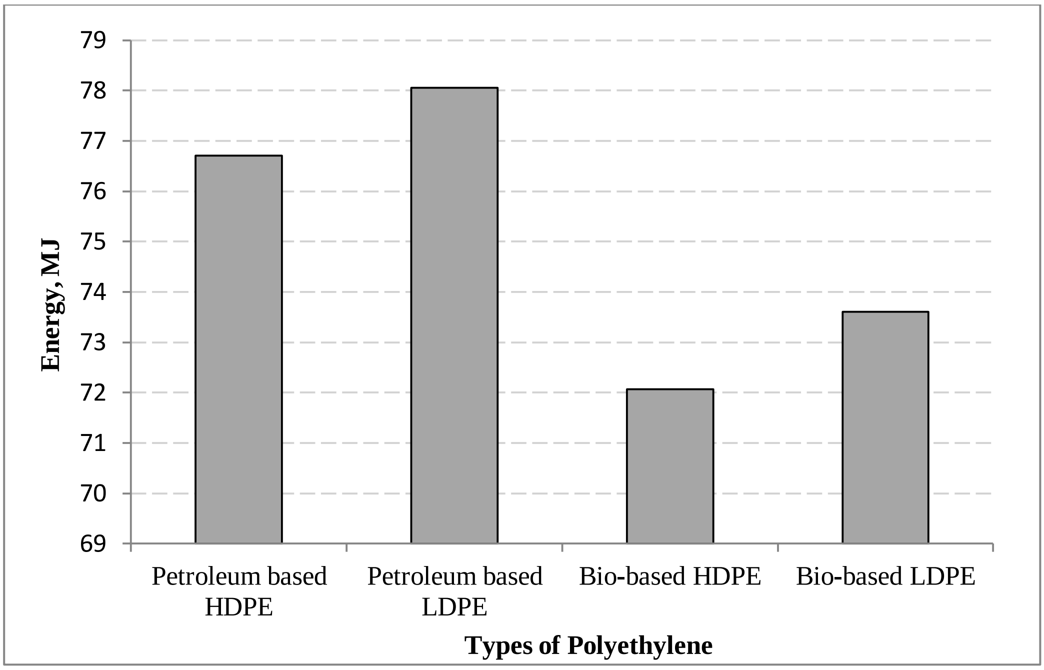

Figure 4.4: Energy requirement for four different types of polyethylene.

From Figure 4.4, as third party could notice that the energy requirements for the production of bio-based polyethylene were smaller than the production of petroleum based polyethylene. The energy was made up of non-renewable energy and renewable energy. Energy from oil, natural gas, coal and peat were known as non-renewable energy. While energy from water, solar, wind, geothermal, biomass and hydrogen were known as renewable energy. Bio-based HDPE would use lowest energy for its production because it used less energy from non-renewable resources such as natural gas and oil and used biomass as feedstock. There was always a higher energy needed to produce LDPE. This is due to production of LDPE was a high pressure process, as a result, higher energy was required.

4.1.1 Carcinogens

A carcinogen is a substance that is capable of causing cancer in humans or animals. If a substance is known to promote or aggravate cancer, but not necessarily cause cancer, it may also be called a carcinogen. The main factor that contributed to the carcinogens was airborne emission of the production of each polyethylene. Table 4.1 shows that petroleum based HDPE had produced the biggest value of chloroethylene equivalents into air. Emission of hydrocarbons of aromatic was the main cause that contributed to the chloroethylene, followed by the emission of arsenic, chromium and cadmium. Cancer are slow to develop and require prolong exposure to carcinogenic chemical. Thus, potential carcinogenic risks are only calculated for long term-term exposures (Environ, 2005). However, prolonged exposure to chloroethylene will linked to several kinds of cancer.

4.1.2 Non-carcinogens

Airborne emission and waterborne emission of polyethylene were the factors that affected the value of the non-carcinogens. As same as carcinogens, petroleum based HDPE had produced the biggest value of chloroethylene equivalents into air. In the production of petroleum based HDPE and LDPE, waterborne emission of dioxin, 2,3,7,8 tetracholodibenzo-p- was the main substance that caused non-carcinogens. Airborne emission of arsenic was the cause of non-carcinogens for the production of bio-based HDPE and LDPE.

A non-carcinogenic effect is any adverse response to a chemical that is not cancer. Any chemical can cause adverse health effects if given at a high enough doses. When the dose is sufficiently low, no adverse effect is observed. Indeed, increasing evidence suggests that low doses of chemicals have beneficial effects. A phenomenon is known as hormesis. Thus, in order to characterise the non-carcinogenic effect of a chemical, the key parameter is the threshold dose at which an adverse effect first become evident. Doses below the threshold are considered to be safe, while doses above the threshold may cause an adverse effect (Environ, 2005).

4.1.3 Respiratory inorganics

Respiratory inorganics is the respiratory effects resulting from winter smog caused by emissions of dust, sulphur and nitrogen oxides to air (Pre. SimaPro, 2008). It represents the respiratory health risks of inorganic particles. In this study, the values of respiratory inorganics were only affected by the airborne emission of production of polyethylene. Table 4.1 shows that petroleum based LDPE and bio-based LDPE had the same biggest values in the respiratory inorganics impact. Emission of nitrogen oxides, particulates < 10 μm and sulphur dioxide were the main substances that contributed to the respiratory inorganics for all types of polyethylene.

4.1.4 Respiratory organics

Respiratory organics is the respiratory effects resulting from summer smog, due to emissions of organic substances to air (Pre. SimaPro, 2008). Same as respiratory inorganics, respiratory organics only affected by the airborne emission of the production of polyethylene. Bio-based LDPE had produced the highest value of emission to the respiratory organics. Non-methane volatile organic compounds were the main substance that contributed to the respiratory organics.

4.1.5 Aquatic ecotoxicity

Aquatic ecotoxicity measure the potential toxicity impacts of water due to chemicals released into air, water and soil. The impact values of aquatic ecotoxicity for petroleum based HDPE and LDPE were affected by their airborne and waterborne emission, while for bio-based HDPE and LDPE were only affected by their airborne emission. From Table 4.1, we could notice that petroleum LDPE had the highest value of aquatic ecotoxicity. Copper and aluminium waterborne emission were the main substances that contributed to the aquatic ecotoxicity in the production of petroleum based HDPE and LDPE. Meanwhile, the substances that caused aquatic ecotoxicity in airborne emission were mercury, and zinc.

4.1.6 Terrestrial ecotoxicity

Terrestrial ecotoxicity estimated that the substances that have ecotoxic effects only by exposition through the aqueous phase in soil. Airborne emission of production of polyethylene was the main factor that caused terrestrial ecotoxicity, follow by the waterborne emission. Petroleum based LDPE had the biggest value of terrestrial ecotoxicity over the others polyethylene. Mercury and zinc emission were the main causes of terrestrial ecotoxicity. Bio-based HDPE and LDPE did not have waterborne emission that contributed to the terrestrial ecotoxicity. Thus, bio-based LDPE always had a lower value of terrestrial ecotoxicity over the petroleum based LDPE. It was the same for the bio-based HDPE and petroleum based HDPE.

4.1.7 Terrestrial acidification and nutrification

Terrestrial acidification and nutrification represents the increase in acidity and the potential impacts on terrestrial ecosystems due to chemicals released into air from each sector (kg SO_2 equivalent). In the life cycle analysis, it showed that terrestrial acid/nutri was mainly caused by the airborne emission of nitrogen oxides, sulfur dioxide and ammonia. Production of LDPE for both petroleum based and bio-based had produced larger value of terrestrial acid/nutri compared to the production of HDPE. This was because production of HDPE would produce less emission of nitrogen oxides and sulphur dioxide.

4.1.8 Aquatic acidification

Aquatic acidification refers to the increase in acidity to water due to chemicals released into air, water, and soil from each sector (kg SO_2 equivalent). Values of aquatic acidification for bio-based based HDPE and LDPE were affected by both airborne and waterborne emission throughout the process of the production its resins. While for petroleum based HDPE and LDPE, its aquatic acidification values were only influenced by airborne emission. In these cases, aquatic acidification was caused by the emission of sulfur dioxide, nitrogen oxides and others substances to the air. In the production of bio-based polyethylene, ammonia that released in the water caused the aquatic acidification.

4.1.9 Aquatic eutrophication

Aquatic eutrophication represents the potential impacts on aquatic ecosystems due to chemicals released into air, water, and soil from each sector (kg PO_4 P-lim). In this study, emission of chemical oxygen demand (COD), phosphate and phosphorus to the water contributed the aquatic eutrophication. The values of aquatic eutrophication for petroleum based HDPE and LDPE were mainly depended on the waterborne emission of COD and phosphorus, while bio-based HDPE and LDPE were depended on the COD and phosphate emission.

The lower petroleum HDPE value for aquatic eutrophication as compared to others due to the lower COD and phosphorus values accounted for by its resin production. Besides that, it was partially attributed to the agricultural component of bio-based HDPE and LDPE production. Phosphorus is an essential element for plant growth, and is applied to agricultural soils as commercial inorganic fertiliser, organic manure or sewage sludge. Fertilizer runoff from the conventional argriculture was the one of the causes of aquatic eutrophication. A certain critical soil level is necessary for economic crop production, but above this level, there is little increase in yield and risks of environmental loss increase. An excess supply of phosphorus with subsequent losses to the aquatic environment can lead to adverse effects on both the ecology and uses of receiving waters (Dils et al., 2001).

4.1.10 Global warming (carbon dioxide emission)

Global warming indicated that total of carbon dioxide was released to the air. It was measured by kg $CO_{2\ eq}$. By using the IMPACT 2002+ method of assessment, for 1 kg of bio-based HDPE and petroleum based HDPE produced, 1.69 kg of CO_2 equivalent would be released to the atmosphere, while for 1 kg of bio-based LDPE and petroleum based LDPE, 1.82 kg of CO_2 equivalent would be released. The highest impact on CO_2 equivalent was related to ethylene. The emission substances that mainly caused the global warming were carbon dioxide, carbon monoxide and methane.

Carbon dioxide and methane are the greenhouse gases which contribute to the global warming. Table 4.1 shows that the production of LDPE would have higher values of global warming compared to production of HDPE. This was because LDPE production required higher energy. As a result, the combustion of the fossil fuels used to generate energy was much higher. Larger combustion of fossil fuels would lead to higher carbon dioxide and carbon monoxide emission. Carbon monoxide was released when the fossil fuel was burned incompletely. It would oxidize to carbon dioxide through natural processes in the atmosphere.

There are many effects of global warming. The effects on animals, agriculture and human are scary. Two major effects are increase of temperature on the earth and rise of sea level. Increasing temperatures will lead to adverse effects on weather. This irregular weather will affect human activities. Higher temperature will faster evaporation of water and lead to drought in one part, and bring in heavy rain and causes flooding. Sea levels rise will result in a watery grave to several low lying areas, tiny islands and reclaimed portions of land.

4.1.11 Non-renewable energy

In this assessment, non-renewable energy included energy from oil, natural gas, coal and peat. The values of non-renewable energy were calculated from the raw materials that applied into the production process. Results show that the production of petroleum based polyethylene used a higher value of non-renewable energy over the bio-based polyethylene. This is due to bio-based polyethylene used less energy from natural resources such as natural gas and oil. The conventional use of non-renewable energy was reduced from the bio-based polyethylene production and shift to biomass feedstocks and renewable energy inputs. For the comparison between HDPE and LDPE for both petroleum based and bio-based, production of LDPE always showed a higher values of non-renewable energy. Production of LDPE was a high pressure process, thus, higher energy was required.

4.1.12 Mineral extraction

The values of mineral extraction were getting from raw materials that reacted in the process. Petroleum based and bio-based LDPE had the higher values of mineral extraction. Substances that counted into the mineral extraction were zinc, copper, lead, and others.

4.2 Damage Assessment Results

Life cycle analysis by using IMPACT 2002+ method showed that the petroleum based polyethylene production had more damage oriented impact than bio-based polyethylene production. Table 4.2 showed that the damage impact values for the production of four type of polyethylene. The damage impacts also showed in the graph form as shown in Figure 4.5. It was found that the highest impact on the environment occurs in the category of resources. Resources impact was the sum of the non-renewable energy consumption and mineral extraction. The resources damage was largely dominated by non-renewable energy consumption. This was caused by ethylene production.

Climate change in the damage category was the same category as global warming. Climate change impact was still expressed in kg $CO_{2\ eq}$ although it was consider as a damage category. From the unit of climate change impact, as third party could know that it was largely dominated by CO_2 emissions. Global climate change has been identified as perhaps the most important environmental issue of this century. Greenhouse gas emissions are not exactly the same as combusted fossil fuel emissions because several non-combustion gases can contribute to global climate change. For example, methane is a potent greenhouse gas that can emanate from the natural gas system leaks and industrial processes.

The ecosystem quality was the sum of the values of aquatic acidification, aquatic eutrophication, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acid/nutr and land occupation. PDF $\cdot m^2 \cdot yr$ (Potentially Disappeared Fraction of species per m^2

per year) is the unit to measure the impacts on ecosystems. The PDF ·m^2 ·yr represents the fraction of species disappeared on 1 m^2 of earth surface during one year (Humbert et al., 2005). From Table 4.2, it was noticed that petroleum based LDPE has the largest impact of ecosystem quality compared to others polyethylene. Petroleum based LDPE having an ecosystem quality score of 0.0278 PDF ·m2 ·yr imply the loss of 2.78% of species on 1 m^2 of earth surface during one year.

The human health was the sum of the values of carcinogens, non-carcinogens, respiratory inorganics and respiratory organics. DALY (Disability Adjusted Life Years) is the unit to measure the impacts on human health. DALY characterizes the disease severity, accounting for both mortality and morbidity. Mortality is the years of life lost (YLL) due to premature death. Morbidity relates to the time of life with lower quality due to an illness (Humbert et al., 2005). In this assessment, petroleum based HDPE has contributed the largest impact to human health. This meaned that the production of petroleum based HDPE having a human health score of 3.11 x 10^{-6} DALY implied the loss of 3.11 x 10^{-6} years of life over the overall population. The 3.11 x 10^{-6} year of life lost distributed over the overall population and not per person.

Table 4.2: Environmental impact assessment in four damage oriented impact categories.

Damage category	Unit	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
Human health	DALY	3.11E-06	1.23E-06	**7.58E-07**	8.79E-07
Ecosystem quality	PDF*m^2*yr	0.023	0.0278	**0.0228**	0.0272
Climate change	kg $CO_{2\ eq}$	**1.69**	1.82	**1.69**	1.82
Resources	MJ primary	77.2	78.2	**71.5**	72.5

Key: Bolded and underlined values are the lowest values in each impact category.

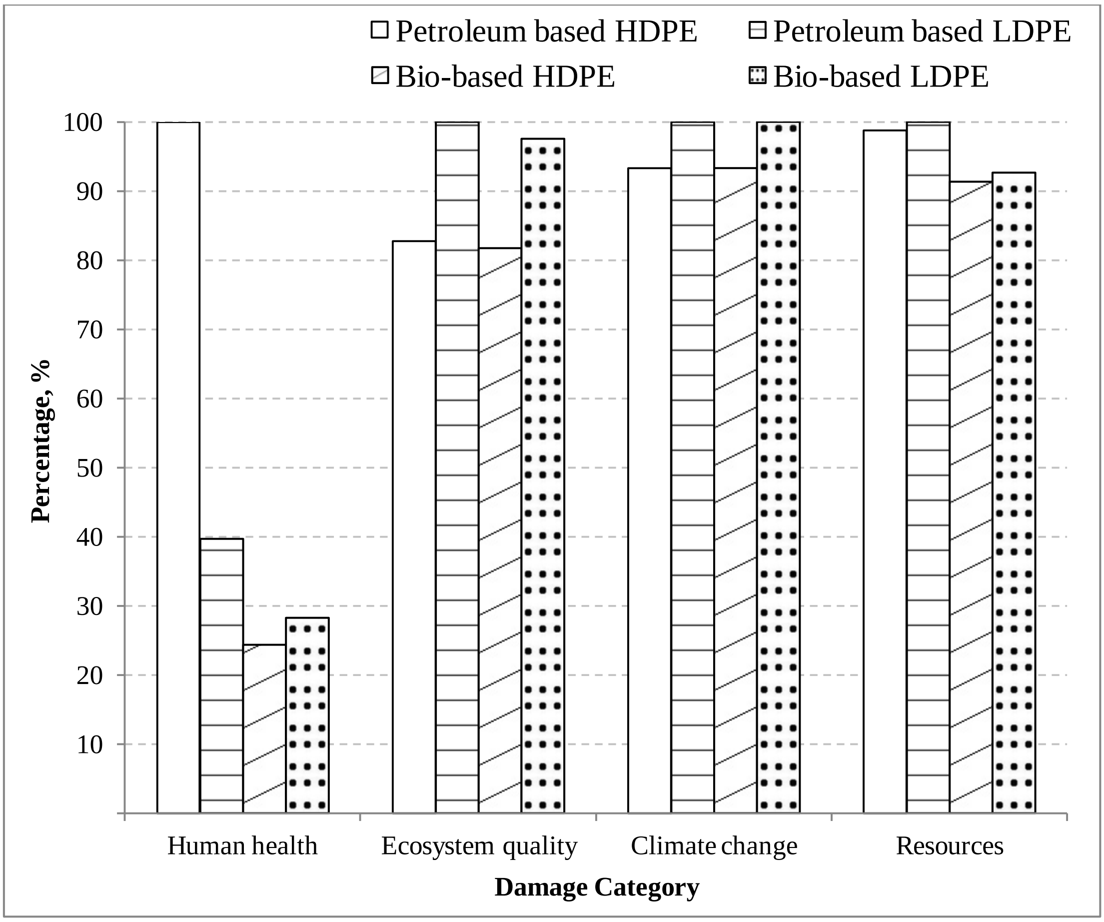

Figure 4.5: Environmental impact assessment in four damage oriented impact categories in graph form.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

Life cycle assessment helped to understand that if one arises from the knowledge of damage, it will be possible to have a wider perspective of the real impacts involved in the production. The production of bio-based polyethylene was more beneficial than petroleum based polyethylene in this full cradle-to-gate life cycle assessment study. From all the environmental impacts were compared, indicating environmental benefits of bio-based HDPE production over others polyethylene. For instance, the impact values of carcinogen and non-carcinogen for production of bio-based polyethylene was significantly reduced to 2.24×10^{-7} kg $C_2H_3Cl_{eq}$ and 2.61×10^{-6} respectively compared to petroleum based HDPE which released 0.391 kg $C_2H_3Cl_{eq}$ and 0.448 kg $C_2H_3Cl_{eq}$. Besides, aquatic ecotoxicity could be reduced a lot in the production of bio-based polyethylene. It reduced from 5.64 kg TEG water for production of petroleum based HDPE to 0.00226 kg TEG water for production of bio-based HDPE. Most of the environmental impacts were reduced in the production of bio-based polyethylene.

Energy requirement for the production of bio-based based polyethylene was low as well. The results showed that the energy requirements for production of bio-based HDPE and LDPE were 72.06MJ and 73.6 MJ, which were lower compared to petroleum based HDPE and LDPE which were 76.7 MJ and 78.05 MJ respectively. Petroleum based HDPE production had lower environmental burdens than others polyethylene production in respiratory organics, aquatic acidification, aquatic eutrophication, and mineral extraction. The use of fertiliser from the agriculture process and acid increased the eutrophication potential.

5.2 Recommendation

Full sized of life cycle analysis studies for bio-based polyethylene is indispensable to allow deriving conclusions and recommendations that are better underpinned and more focussed. To maximise the environmental benefits from bio-based polyethylene, further research and development will be necessary in order to optimise the production. Substantial scope for improvement can be expected from further technological progress (especially for bio-based polyethylene which is still in its infancy while the manufacture of petroleum based polyethylene has been optimised for decades). Some of the life cycle analysis discussed above was already outdated when drawn since substantial progress had been made in manufacturing and processing bio-based polyethylene. This mean that the real environmental impacts caused by bio-based polyethylene tend to be lower than established in the life cycle analysis studies reviewed. It is necessary to monitor continuously the various environmental impacts of production of petroleum based and bio-based polyethylene (Narayan and Patel, 2010).

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APPENDICES

APPENDIX A: Raw material comparison table for petroleum based polyethylene and bio-based polyethylene.

No.	Substance	Unit	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
1	Air	kg	0.0258	0.18	0.258	0.18
2	Aluminium, 24% in bauxite, 11% in crude ore, in ground	kg	x	x	5.04E-06	1.90E-05
3	Animal matter	kg	4.33E-10	9.30E-09	x	x
4	Barite, 15% in crude ore, in ground	kg	x	x	5.40E-08	7.26E-09
5	Baryte, in ground	kg	5.40E-08	7.26E-08	x	x
6	Bauxite, in ground	kg	5.04E-06	1.00E-05	x	x
7	Biomass	kg	0.0156	0.0194	x	x
8	Biomass, feedstock	MJ	x	x	0.128	0.159
9	Calcite, in ground	kg	7.63E-34	6.06E-34	0.000133	0.000239
10	Calcium sulfate, in ground	kg	3.30E-06	6.01E-06	x	x
11	Chromium, in ground	kg	1.02E-12	8.46E-13	1.02E-12	8.46E-13
12	Clay, bentonite, in ground	kg	3.30E-05	5.84E-05	3.30E-05	5.84E-05
13	Clay, unspecified, in ground	kg	2.80E-10	2.51E-09	2.80E-10	2.51E-09
14	Copper, in ground	kg	3.20E-09	6.82E-08	3.20E-09	6.82E-08
15	Dolomite, in ground	kg	2.13E-06	2.99E-06	2.13E-06	2.99E-06
16	Energy, from biomass	MJ	0.138	0.171	x	x
17	Energy, from coal	MJ	2.9	3.71	2.79	3.57
18	Energy, from coal, brown	MJ	4.30E-05	0.001	3.80E-05	0.000887
19	Energy, from gas, natural	MJ	30.4	31.8	27.4	28.7
20	Energy, from hydro power	MJ	0.583	0.924	x	x
21	Energy, from hydrogen	MJ	0.000186	0.000416	x	x
22	Energy, from oil	MJ	40.8	37.8	38.1	35.4
23	Energy, from peat	MJ	0.0169	0.0231	0.015	0.0188

No.	Substance	Unit	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
24	Energy, from sulphur	MJ	0.00048	0.00137	x	x
25	Energy, from uranium	MJ	3.13	4.9	3.13	4.9
26	Energy, from wood	MJ	1.94E-05	4.56E-05	1.81E-05	4.24E-05
27	Energy, geothermal	MJ	0.0273	0.0581	x	x
28	Energy, geothermal, converted	MJ	x	x	0.0273	0.0581
29	Energy, kinetic (in wind), converted	MJ	0.0159	0.0291	0.0159	0.0291
30	Energy, potential (in hydropower reservoir), converted	MJ	x	x	0.583	0.924
31	Energy, recovered	MJ	-1.31	-1.37	x	x
32	Energy, solar, converted	MJ	0.000104	0.000167	0.000104	0.000167
33	Energy, unspecified	MJ	0.00105	0.00254	x	x
34	Feldspar, in ground	kg	6.15E-17	9.23E-17	6.15E-17	9.23E-17
35	Ferromanganese	kg	1.58E-07	2.23E-07	x	x
36	Fluorspar, 92%, in ground	kg	x	x	3.16E-07	7.36E-07
37	Fluorspar, in ground	kg	3.16E-07	7.36E-07	x	x
38	Granite, in ground	kg	4.67E-15	3.71E-15	4.67E-15	3.71E-15
39	Gravel, in ground	kg	6.43E-07	8.99E-07	x	x
40	Gypsum, in ground	kg	x	x	3.30E-06	6.01E-06
41	Iron, 46% in ore, 25% in crude ore, in ground	kg	x	x	0.000174	0.000244
42	Iron, in ground	kg	0.000174	0.000244	x	x
43	Lead, in ground	kg	5.07E-07	4.85E-07	5.07E-07	4.85E-07
44	Limestone, in ground	kg	0.000133	0.000239	x	x
45	Magnesium, in ground	kg	1.44E--10	3.10E-09	1.44E--10	3.10E-09
46	Manganese, in ground	kg	x	x	1.31E-07	1.85E-07
47	Mercury, in ground	kg	7.08E-10	1.64E-09	7.08E-10	1.64E-09
48	Metamorphous rock, graphite containing, in ground	kg	x	x	1.10E-08	1.56E-08
49	Natural aggregate	kg	x	x	6.43E-07	8.99E-07
50	Nickel, in ground	kg	2.89E-10	6.20E-09	2.89E-10	6.20E-09
51	Nitrogen, in air	kg	0.169	0.0667	0.169	0.0667
52	Olivine, in ground	kg	1.63E-06	2.29E-06	1.63E-06	2.29E-06
53	Oxygen, in air	kg	3.30E-06	0.00165	3.30E-06	0.00165
54	Phosphorus pentoxide	kg	2.50E-12	4.90E-11	x	x
55	Phosphorus, in ground	kg	x	x	1.09E-12	2.15E-11
56	Potassium chloride	kg	6.31E-09	8.95E-08	6.30E-09	8.90E-08
57	Primary energy from waves	MJ	x	x	0.000355	0.000792

No.	Substance	Unit	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
58	Rutile, in ground	kg	1.10E-33	8.70E-34	x	x
59	Sand, quartz, in ground	kg	4.19E-36	2.74E-28	x	x
60	Sand, unspecified, in ground	kg	8.38E-05	0.000115	8.38E-05	0.000115
61	Shale, in ground	kg	9.35E-06	1.70E-05	x	x
62	Slate, in ground	kg	x	x	9.35E-06	1.70E-05
63	Sodium chloride, in ground	kg	0.000351	0.000759	0.000351	0.000759
64	Sodium nitrate	kg	4.33E-10	9.30E-09	x	x
65	Sodium nitrate, in ground	kg	x	x	4.33E-10	9.30E-09
67	Sulfur, in ground	kg	5.18E-05	0.000148	5.20E-05	0.000153
68	Talc, in ground	kg	8.80E-27	1.62E-26	8.80E-27	1.62E-26
69	Titanium, in ground	kg	x	x	6.25E-34	4.96E-34
70	Unspecified input	kg	5.87E-48	9.15E-07	x	x
71	Water, cooling, drinking	kg	0.159	0.857	x	x
72	Water, cooling, salt, ocean	kg	11.2	11.1	x	x
73	Water, cooling, surface	kg	0.0595	3.77	x	x
74	Water, cooling, unspecified natural origin/kg	kg	17.5	28.4	x	x
75	Water, cooling, well, in ground	kg	6.05E-08	0.109	x	x
76	Water, process, drinking	kg	1.75	1.41	x	x
77	Water, process, salt, ocean	kg	0.131	0.185	x	x
78	Water, process, surface	kg	0.97	0.914	x	x
79	Water, process, unspecified natural origin/kg	kg	0.428	0.429	x	x
80	Water, process, well, in ground	kg	0.0952	1.58E-05	x	x
81	Water, river	m^3	x	x	0.00103	0.00469
82	Water, salt, ocean	m^3	x	x	0.0114	0.0113
83	Water, unspecified natural origin/kg	kg	x	x	17.9	28.8
84	Water, well, in ground	m^3	x	x	9.52E-05	0.000109
85	Zinc, in ground	kg	1.51E-05	0.000325	1.51E-05	0.000325

APPENDIX B: Airborne emission comparison table for petroleum based polyethylene and bio-based polyethylene.

No.	Substance	Unit	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
1	Acidity, unspecified	kg	x	x	3.68E-17	6.75E-17
2	Aldehydes, unspecified	kg	1.47E-15	1.73E-08	x	x
3	Ammonia	kg	2.17E-10	3.97E-10	2.17E-10	3.97E-10
4	Antimony	kg	1.98E-11	4.21E-10	1.98E-11	4.21E-10
5	Arsenic	kg	1.23E-10	1.42E-10	1.23E-10	1.42E-10
6	Asbestos	kg	3.49E-15	7.14E-15	x	x
7	Benzene	kg	2.64E-18	9.98E-11	2.64E-18	9.98E-11
8	Benzene, ethyl-	kg	1.55E-19	1.09E-11	1.55E-19	1.09E-11
9	Cadmium	kg	5.26E-11	3.55E-10	5.26E-11	3.55E-10
10	Carbon dioxide	kg	1.57	1.69E+00	x	x
11	Carbon dioxide, land transformation	kg	x	x	1.57E+00	1.60E+00
12	Carbon disulfide	kg	1.48E-11	2.25E-11	1.48E-11	2.25E-11
13	Carbon monoxide	kg	0.0124	2.73E-03	x	x
14	Carbon monoxide, fossil	kg	x	x	0.0124	2.73E-03
15	Chlorinated fluorocarbons, soft	kg	1.32E-06	9.04E-07	x	x
16	Chlorine	kg	3.64E-11	7.43E-09	3.64E-11	7.43E-09
17	Chromium	kg	5.62E-10	6.77E-10	5.62E-10	6.77E-10
18	Copper	kg	2.26E-12	4.69E-11	2.26E-12	4.69E-11
19	Dinitrogen monoxide	kg	7.91E-13	1.41E-10	7.91E-13	1.41E-10
20	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	kg	3.17E-32	4.25E-32	3.17E-32	4.25E-32
21	Ethane, 1,2-dichloro-	kg	2.54E-11	1.81E-11	2.54E-11	1.81E-11
22	Ethane, chloro-	kg	5.02E-10	4.07E-10	x	x
23	Ethene	kg	1.62E-06	9.86E-07	1.62E-06	9.86E-07
24	Ethene, chloro-	kg	x	x	5.03E-10	4.07E-10
25	Fluorine	kg	1.65E-11	2.74E-10	1.65E-11	2.74E-10
26	Hydrocarbons, aromatic	kg	8.55E-05	3.63E-05	1.07E-18	5.83E-11
27	Hydrocarbons, chlorinated	kg	9.97E-10	2.08E-09	x	x

No.	Substance	Unit	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
28	Hydrocarbons, unspecified	kg	0.00409	0.00414	x	x
29	Hydrogen	kg	4.41E-05	4.46E-05	4.41E-05	4.46E-05
30	Hydrogen chloride	kg	6.17E-05	6.62E-05	6.17E-05	6.62E-05
31	Hydrogen cyanide	kg	4.89E-19	7.33E-19	4.89E-19	7.33E-19
32	Hydrogen fluoride	kg	1.81E-06	2.58E-06	1.81E-06	2.58E-06
33	Hydrogen sulphide	kg	5.84E-09	8.18E-09	5.84E-09	8.18E-09
34	Lead	kg	1.17E-09	8.40E-09	1.17E-09	8.40E-09
35	Mercaptans, unspecified	kg	4.29E-09	6.46E-09	x	x
36	Mercury	kg	2.38E-09	3.47E-09	2.38E-09	3.47E-09
37	Metals, unspecified	kg	1.74E-06	1.64E-06	x	x
38	Methane	kg	0.0142	1.63E-02	1.42E-02	1.63E-02
39	Methane, dichloro-, HCC-30	kg	2.96E-14	1.90E-11	2.96E-14	1.90E-11
40	Nickel	kg	1.40E-13	5.84E-11	1.40E-13	5.84E-11
41	Nitrogen oxides	kg	0.00323	0.00379	0.00323	0.00379
42	NMVOC, non-methane volatile organic compounds, unspecified origin	kg	0.00015	0.00049	0.00424	0.00463
43	Organic substances, unspecified	kg	5.95E-05	1.61E-04	x	x
44	Oxygen	kg	6.28E-24	2.97E-16	6.28E-24	2.97E-16
45	PAH, polycyclic aromatic hydrocarbons	kg	1.07E-18	5.83E-11	x	x
46	Particulates, < 10 µm	kg	0.000643	0.000694	6.45E-04	6.96E-04
47	Particulates, < 2.5 µm	kg	x	x	3.49E-15	7.14E-07
48	Propene	kg	1.20E-06	7.30E-07	1.20E-06	7.30E-07
49	Selenium	kg	x	x	7.92E-26	5.19E-18
50	Selenium compounds	kg	7.92E-26	5.19E-18	x	x
51	Silver	kg	2.29E-24	1.50E-16	2.29E-24	1.50E-16
52	Styrene	kg	2.18E-20	5.67E-13	2.18E-20	5.67E-13
53	Sulfur dioxide	kg	0.00408	0.00503	0.00408	0.00503
54	Sulfuric acid	kg	1.84E-15	3.37E-15	x	x
55	Toluene	kg	4.42E-19	1.95E-11	4.42E-19	1.95E-11
56	VOC, volatile organic compounds	kg	x	x	1.46E-04	1.99E-04
57	Xylene	kg	2.04E-19	9.35E-12	2.04E-19	9.35E-12
58	Zinc	kg	1.29E-09	2.54E-08	1.29E-09	2.54E-08

APPENDIX C: Waterborne emission comparison table for petroleum based polyethylene and bio-based polyethylene.

No.	Substance	Unit	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
1	Acidity, unspecified	kg	x	x	1.96E-06	4.84E-06
2	Acids, unspecified	kg	1.96E-06	4.85E-06	x	x
3	Aluminium	kg	5.57E-07	5.47E-07	5.57E-07	5.47E-07
4	Ammonia	kg	x	x	3.11E-06	2.84E-06
5	Ammonium, ion	kg	3.11E-06	2.84E-06	x	x
6	AOX, Adsorbable Organic Halogen as Cl	kg	1.05E-12	1.06E-12	1.05E-12	1.06E-12
7	Arsenic, ion	kg	1.98E-10	3.92E-10	1.98E-10	3.92E-10
8	Benzene	kg	5.58E-22	2.78E-12	5.58E-22	2.78E-12
9	BOD5, Biological Oxygen Demand	kg	2.09E-05	2.78E-05	2.09E-05	2.78E-05
10	Bromate	kg	5.5.E-10	6.58E-10	5.5.E-10	6.58E-10
11	Cadmium	kg	x	x	1.11E-11	2.31E-10
12	Cadmium, ion	kg	1.11E-11	2.31E-10	x	x
13	Calcium, ion	kg	2.89E-06	1.41E-07	2.89E-06	1.41E-07
14	Carbonate	kg	2.89E-05	4.09E-05	2.89E-05	4.09E-05
15	Chlorate	kg	9.94E-08	2.29E-07	9.94E-08	2.29E-07
16	Chloride	kg	0.000157	1.42E-04	0.000157	1.42E-04
17	Chlorinated solvents, unspecified	kg	5.76E-09	1.35E-08	x	x
18	Chlorine	kg	1.06E-09	1.41E-09	1.06E-09	1.41E-09
19	Chromium	kg	1.39E-12	2.56E-11	1.39E-12	2.56E-11
20	COD, Chemical Oxygen Demand	kg	0.00019	1.97E-04	0.00019	1.97E-04
21	Copper	kg	x	x	1.55E-07	5.43E-07
22	Copper, ion	kg	1.55E-07	5.43E-07	x	x
23	Cyanide	kg	1.65E-11	2.31E-11	1.65E-11	2.31E-11
24	Decane	kg	x	x	5.99E-06	1.09E-05
25	Detergent, oil	kg	5.99E-06	1.09E-05	x	x

No.	Substance	Unit	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
26	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	kg	9.81E-10	2.31E-16	9.81E-10	2.31E-16
27	DOC, Dissolved Organic Carbon	kg	9.94E-06	1.11E-05	x	x
28	Ethane, 1,1-dichloro-	kg	5.06E-13	4.12E-13	x	x
29	Ethane, 1,2-dichloro-	kg	x	x	5.06E-13	4.12E-13
30	Ethane, chloro-	kg	9.24E-12	7.53E-12	x	x
31	Ethane, chloro-	kg	x	x	9.24E-12	7.53E-12
32	Fluoride	kg	1.42E-09	2.18E-08	1.42E-09	2.18E-08
33	Hydrocarbons, unspecified	kg	4.35E-06	7.17E-06	4.35E-06	7.17E-06
34	Iron	kg	x	x	1.64E-08	8.70E-08
35	Iron, ion	kg	1.64E-08	8.70E-08	x	x
36	Lead	kg	1.17E-09	1.57E-09	1.17E-09	1.57E-09
37	Magnesium	kg	9.63E-10	1.35E-08	x	x
38	Manganese	kg	1.56E-10	3.32E-09	1.56E-10	3.32E-09
39	Mercury	kg	2.19E-10	2.70E-10	2.19E-10	2.70E-10
40	Metallic ions, unspecified	kg	7.12E-06	9.76E-06	x	x
41	Nickel	kg	x	x	3.72E-10	8.95E-10
42	Nickel, ion	kg	3.72E-10	8.95E-10	x	x
43	Nitrate	kg	2.25E-06	3.17E-06	2.25E-06	3.17E-06
44	Nitrogen	kg	x	x	1.10E-06	1.34E-06
45	Nitrogen, total	kg	1.10E-06	1.34E-06	x	x
46	Organic substances, unspecified	kg	1.34E-10	1.19E-10	x	x
47	Particulates, < 10 µm	kg	x	x	7.12E-06	9.76E-06
48	Particulates, > 10 µm	kg	x	x	1.95E-04	1.17E-04
49	Phenol	kg	1.87E-06	1.48E-06	1.87E-06	1.48E-06
50	Phosphorus	kg	x	x	2.24E-06	2.88E-06
51	Phosphorus, total	kg	4.02E-07	5.18E-07	x	x
52	Potassium, ion	kg	x	x	6.77E-07	7.42E-09
53	Potassium	kg	6.77E-07	7.42E-09	x	x
54	Silicon	kg	3.05E-20	4.58E-20	x	x
55	Sodium, ion	kg	7.70E-05	8.48E-05	9.84E-05	1.18E-04
56	Solved solids	kg	2.14E-05	3.36E-05	x	x
57	Strontium	kg	1.06E-11	2.49E-11	1.06E-11	2.49E-11
58	Sulfate	kg	8.29E-04	5.00E-04	8.29E-04	5.00E-04
59	Sulfur	kg	5.68E-13	4.82E-13	5.68E-13	4.82E-13
60	Suspended solids, unspecified	kg	1.95E-04	1.17E-04	x	x

No.	Substance	Unit	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
61	Tin	kg	x	x	7.49E-11	2.88E-16
62	Tin, ion	kg	7.49E-11	2.88E-16	x	x
63	TOC, Total Organic Carbon	kg	1.11E-05	1.38E-05	1.11E-05	1.38E-05
64	VOC, volatile organic compounds, unspecified origin	kg	x	x	9.95E-06	1.11E-05
65	Zinc	kg	x	x	1.33E-07	2.35E-07
66	Zinc, ion	kg	1.33E-07	2.35E-07	x	x

APPENDIX D: Final waste comparison table for petroleum based polyethylene and bio-based polyethylene.

No.	Substance	Unit	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
1	Chemical waste, inert	kg	0.00366	0.00235	7.20E-04	9.48E-04
2	Chemical waste, regulated	kg	2.04E-03	2.89E-03	2.04E-03	2.89E-03
3	Chemical waste, unspecified	kg	x	x	2.94E-03	1.41E-03
4	Coal tailings	kg	6.21E-05	1.30E-03	x	x
5	Compost	kg	4.27E-07	8.88E-06	x	x
6	Construction waste	kg	6.31E-10	7.21E-09	6.32E-10	7.21E-09
7	Food biomass waste, DK	kg	x	x	4.33E-10	9.30E-09
8	Metal waste	kg	7.91E-09	1.67E-07	x	x
9	Mineral waste	kg	1.94E-04	3.70E-04	1.94E-04	3.70E-04
10	Mineral waste, from mining	kg	x	x	0.0198	2.62E-02
11	Packaging waste, paper and board	kg	5.90E-10	1.24E-08	5.90E-10	1.24E-08
12	Packaging waste, plastic	kg	1.05E-12	8.64E-13	1.05E-12	8.64E-13
13	Packaging waste, steel	kg	x	x	1.98E-02	2.62E-02
14	Packaging waste, wood	kg	1.49E-10	3.10E-09	1.49E-10	3.10E-09
15	Plastic waste	kg	6.34E-04	1.93E-04	6.34E-04	1.93E-04
16	Slags and ashes	kg	0.00935	1.34E-02	x	x
17	Waste in incineration	kg	8.75E-04	8.97E-04	x	x
18	Waste returned to mine	kg	1.98E-02	2.62E-02	6.12E-05	1.30E-02
19	Waste to recycling	kg	4.49E-03	2.27E-03	x	x
20	Waste, industrial	kg	0.000856	-4.34E-04	0.000856	-4.34E-04
21	Waste, solid	kg	-0.00546	-9.05E-03	x	x
22	Waste, unspecified	kg	9.88E-04	9.33E-04	0.00132	0.00148
23	Wood waste	kg	4.39E-08	1.01E-07	4.39E-08	1.01E-07

APPENDIX E: Carcinogens comparison table for petroleum based polyethylene and bio-based polyethylene.

Unit: kg $C_2H_3Cl_{eq}$

No.	Substance	Compartment	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
1	Arsenic	Air	1.54E-07	1.77E-07	1.54E-07	1.77E-07
2	Benzene	Air	1.01E-22	3.83E-15	1.01E-22	3.83E-15
3	Benzene, ethyl	Air	3.67E-24	2.57E-16	3.67E-24	2.57E-16
4	Cadmium	Air	1.87E-09	1.26E-08	1.87E-09	1.26E-08
5	Chromium	Air	6.83E-08	8.24E-08	6.83E-08	8.24E-08
6	Dioxin,2,3,7,8 Tetrachlorodibenzo p-	Air	5.46E-23	7.31E-23	5.46E-23	7.31E-23
7	Ethane, 1,2-dichloro-	Air	6.28E-11	4.49E-11	6.28E-11	4.49E-11
8	Ethane, chloro-	Air	4.27E-11	3.46E-11	x	x
9	Ethane, chloro-	Air	x	x	5.02E-10	4.07E-10
10	Hydrocarbons, aromatic	Air	0.303	0.128	3.78E-15	2.06E-07
11	Methane, dichloro-, HCC-30	Air	5.73E-15	3.68E-12	5.73E-15	3.68E-12
12	PAH, polycyclic aromatic hydrocarbons	Air	3.78E-15	2.06E-07	x	x
13	Styrene	Air	2.88E-21	7.50E-14	2.88E-21	7.50E-14
14	Toluene	Air	9.01E-24	3.97E-16	9.01E-24	3.97E-16
15	Arsenic, ion	Water	1.97E-07	3.89E-07	0	0
16	Benzene	Water	6.59E-23	3.28E-13	0	0
17	Cadmium, ion	Water	7.71E-25	1.60E-23	x	x
18	Dioxin,2,3,7,8 Tetrachlorodibenzo p-	Water	0.0888	2.09E-08	0	0
19	Ethane, 1,2-dichloro-	Water	x	x	0	0
20	Ethane, chloro-	Water	4.95E-13	4.03E-13	x	x
21	Ethane, chloro-	Water	x	x	0	0

APPENDIX F: Non-carcinogens comparison table for petroleum based polyethylene and bio-based polyethylene.

Unit: kg $C_2H_3Cl_{eq}$

No.	Substance	Compartment	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
1	Ammonia	Air	1.11E-11	2.03E-11	1.11E-11	2.03E-11
2	Antimony	Air	3.20E-09	6.80E-08	3.20E-09	6.80E-08
3	Arsenic	Air	1.54E-06	1.78E-06	1.54E-06	1.78E-06
4	Benzene	Air	1.96E-17	7.40E-10	1.96E-17	7.40E-10
5	Benzene, ethyl	Air	3.10E-23	2.17E-15	3.10E-23	2.17E-15
6	Cadmium	Air	2.88E-08	1.94E-07	2.88E-08	1.94E-07
7	Carbon disulfide	Air	6.07E-13	9.22E-13	6.07E-13	9.22E-13
8	Chromium	Air	1.01E-08	1.22E-08	1.01E-08	1.22E-08
9	Copper	Air	4.60E-12	9.57E-11	4.60E-12	9.57E-11
10	Dioxin,2,3,7,8 Tetrachlorodibenzo p-	Air	2.76E-22	3.69E-22	2.76E-22	3.69E-22
11	Ethane, 1,2-dichloro-	Air	5.01E-13	3.58E-13	5.01E-13	3.58E-13
12	Ethane, chloro-	Air	x	x	3.62E-11	2.94E-11
13	Hydrocarbons, aromatic	Air	4.53E-08	1.92E-08	5.65E-22	3.08E-14
14	Hydrogen cyanide	Air	2.17E-20	3.26E-20	2.17E-20	3.26E-20
15	Hydrogen sulfide	Air	1.78E-09	2.49E-09	1.78E-09	2.49E-09
16	Lead	Air	3.06E-09	2.19E-08	3.06E-09	2.19E-08
17	Mercury	Air	9.07E-07	1.32E-06	9.07E-07	1.32E-06
18	Methane, dichloro-, HCC-30	Air	1.34E-15	8.60E-13	1.34E-15	8.60E-13
19	Nickel	Air	1.24E-12	5.18E-10	1.24E-12	5.18E-10
20	PAH, polycyclic aromatic hydrocarbons	Air	5.65E-22	3.08E-14	x	x
21	Selenium	Air	x	x	1.43E-23	9.34E-16
22	Styrene	Air	1.80E-23	4.68E-16	1.80E-23	4.68E-16

No.	Substance	Compartment	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
23	Toluene	Air	1.49E-21	6.58E-14	1.49E-21	6.58E-14
24	Xylene	Air	1.71E-21	7.86E-14	1.71E-21	7.86E-14
25	Zinc	Air	1.20E-07	2.36E-06	1.20E-07	2.36E-06
26	Aluminium	Water	1.14E-06	1.12E-06	0	0
27	Ammonia	Water	x	x	0	0
28	Arsenic, ion	Water	2.05E-06	4.05E-06	0	0
29	Benzene	Water	7.57E-22	3.77E-12	0	0
30	Cadmium, ion	Water	7.91E-22	1.65E-07	x	x
31	Chromium	Water	6.25E-12	1.15E-07	0	0
32	Copper, ion	Water	6.41E-07	2.24E-06	x	x
33	Dioxin,2,3,7,8 Tetrachlorodibenzo p-	Water	4.48E-01	1.05E-07	0	0
34	Ethane, 1,2-dichloro-	Water	x	x	0	0
35	Ethane, chloro-	Water	x	x	0	0
36	Lead	Water	1.26E-08	1.69E-08	0	0
37	Mercury	Water	1.74E-07	2.15E-07	0	0
38	Nickel, ion	Water	4.08E-09	9.79E-09	x	x
39	Phenol	Water	1.43E+00	1.14E-09	0	0
40	Zinc	Water	x	x	0	0

APPENDIX G: Respiratory inorganics comparison table for petroleum based polyethylene and bio-based polyethylene.

Unit: kg $PM2.5_{eq}$

No.	Substance	Compartment	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
1	Ammonia	Air	2.63E-11	4.82E-11	2.63E-11	4.82E-11
2	Carbon monoxide	Air	1.29E-05	2.85E-06	x	x
3	Nitrogen oxides	Air	0.000411	0.000482	0.000411	0.000482
4	Particulates, < 10 µm	Air	0.000344	0.000372	0.000345	0.000373
5	Particulates, < 2.5 µm	Air	x	x	3.49E-15	7.14E-15
6	Sulfur dioxide	Air	0.000318	0.000392	0.000318	0.000392

APPENDIX H: Respiratory organics comparison table for petroleum based polyethylene and bio-based polyethylene.

Unit: kg $C_2H_{4\ eq}$

No.	Substance	Compartment	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
1	Aldehydes, unspecified	Air	9.69E-16	1.14E-08	x	x
2	Benzene	Air	5.79E-19	2.19E-11	5.79E-19	2.19E-11
3	Benzene, ethyl	Air	1.11E-19	7.80E-12	1.11E-19	7.80E-12
4	Ethene	Air	1.62E-06	9.86E-07	1.62E-06	9.86E-07
5	Hydrocarbons, aromatic	Air	8.43E-05	3.58E-05	1.05E-18	5.75E-11
6	Hydrocarbons, chlorinated	Air	1.64E-10	3.42E-10	x	x
7	Methane	Air	8.53E-05	9.80E-05	8.53E-05	9.80E-05
8	Methane, dichloro, HCC-30	Air	2.02E-15	1.29E-12	2.02E-15	1.29E-12
9	NMVOC, non-methane volatile organic compounds, unspecified origin	Air	9.01E-05	2.94E-04	2.55E-03	2.78E-03
10	PAH. Polycyclic aromatic hydrocarbons	Air	1.05E-18	5.75E-11	x	x
11	Propene	Air	1.34E-06	8.16E-07	1.34E-06	8.16E-07
12	Toluene	Air	2.82E-19	1.24E-11	2.82E-19	1.24E-11
13	VOC, volatile organic compounds	Air	x	x	4.44E-05	6.03E-05
14	Xylene	Air	2.12E-19	9.70E-12	2.12E-19	9.70E-12

APPENDIX I: Aquatic ecotoxicity comparison table for petroleum based polyethylene and bio-based polyethylene.

Unit: kg TEG water

No.	Substance	Compartment	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
1	Ammonia	Air	8.54E-10	1.55E-09	8.54E-10	1.55E-09
2	Antimony	Air	5.86E-06	0.000125	5.86E-06	0.000125
3	Arsenic	Air	6.77E-06	7.80E-06	6.77E-06	7.80E-06
4	Benzene	Air	6.43E-20	2.43E-12	6.43E-20	2.43E-12
5	Benzene, ethyl	Air	1.72E-20	1.20E-12	1.72E-20	1.20E-12
6	Cadmium	Air	2.25E-05	1.52E-04	2.25E-05	1.52E-04
7	Chromium	Air	3.77E-05	4.54E-05	3.77E-05	4.54E-05
8	Copper	Air	6.63E-06	1.38E-04	6.63E-06	1.38E-04
9	Dioxin,2,3,7,8 Tetrachlorodibenzo p-	Air	1.25E-26	1.67E-26	1.25E-26	1.67E-26
10	Ethane, 1,2-dichloro-	Air	6.85E-11	4.89E-11	6.85E-11	4.89E-11
11	Ethane	Air	3.00E-09	1.83E-09	3.00E-09	1.83E-09
12	Ethane, chloro-	Air	x	x	8.20E-12	6.65E-12
13	Hydrocarbons, aromatic	Air	2.13E-01	9.06E-02	2.66E-15	1.45E-07
14	Lead	Air	4.70E-05	3.37E-04	4.70E-05	3.37E-04
15	Mercury	Air	1.87E-03	2.73E-03	1.87E-03	2.73E-03
16	Methane, dichloro-, HCC-30	Air	2.49E-14	1.60E-11	2.49E-14	1.60E-11
17	Nickel	Air	2.50E-08	1.04E-05	2.50E-08	1.04E-05
18	PAH, polycyclic aromatic hydrocarbons	Air	2.66E-15	1.45E-07	x	x
19	Propene	Air	4.27E-10	2.59E-10	4.27E-10	2.59E-10
20	Selenium	Air	x	x	3.78E-20	2.48E-12
21	Silver	Air	0.00E+00	0.00E+00	0	0
22	Styrene	Air	1.01E-21	2.64E-14	1.01E-21	2.64E-14

No.	Substance	Compartment	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
23	Toluene	Air	2.37E-20	1.05E-12	2.37E-20	1.05E-12
24	Xylene	Air	1.26E-20	5.76E-13	1.26E-20	5.76E-13
25	Zinc	Air	2.64E-04	5.19E-03	2.64E-04	5.19E-03
26	Aluminium	Water	2.00E+00	1.97	0	0
27	Ammonia	Water	x	x	0	0
28	Arsenic, ion	Water	7.70E-05	1.52E-04	0	0
29	Benzene	Water	6.04E-19	3.01E-09	0	0
30	Cadmium, ion	Water	3.23E-05	0.000672	x	x
31	Chromium	Water	6.28E-07	1.16E-05	0	0
32	Copper, ion	Water	3.19	11.2	x	x
33	Dioxin,2,3,7,8 Tetrachlorodibenzo p-	Water	0.0424	9.99E-09	0	0
34	Ethane, 1,2-dichloro-	Water	x	x	0	0
35	Ethane, chloro-	Water	x	x	0	0
36	Iron	Water	x	x	0	0
37	Iron, ion	Water	0	0	x	x
38	Lead	Water	0.000309	0.000415	0	0
39	Manganese	Water	0	0	0	0
40	Mercury	Water	0.00346	0.00427	0	0
41	Nickel, ion	Water	0.000474	0.00114	x	x
42	Phenol	Water	0.000319	0.000253	0	0
43	Zinc	Water	x	x	0	0
44	Zinc, ion	Water	0.187	0.329	x	x

APPENDIX J: Terrestrial ecotoxicity comparison table for petroleum based polyethylene and bio-based polyethylene.

Unit: kg TEG soil

No.	Substance	Compartment	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
1	Ammonia	Air	2.12E-09	3.89E-09	2.12E-09	3.89E-09
2	Antimony	Air	3.98E-07	8.48E-06	3.98E-07	8.48E-06
3	Arsenic	Air	5.16E-05	5.95E-05	5.16E-05	5.95E-05
4	Benzene	Air	1.24E-20	4.71E-13	1.24E-20	4.71E-13
5	Benzene, ethyl	Air	8.54E-22	5.99E-14	8.54E-22	5.99E-14
6	Cadmium	Air	4.80E-05	3.23E-04	4.80E-05	3.23E-04
7	Chromium	Air	2.14E-04	2.59E-04	2.14E-04	2.59E-04
8	Copper	Air	2.67E-06	5.55E-05	2.67E-06	5.55E-05
9	Dioxin,2,3,7,8 Tetrachlorodibenzo p-	Air	8.21E-30	1.10E-29	8.21E-30	1.10E-29
10	Ethane, 1,2-dichloro-	Air	2.03E-11	1.45E-11	2.03E-11	1.45E-11
11	Ethane	Air	1.19E-08	7.23E-09	1.19E-08	7.23E-09
12	Ethane, chloro-	Air	x	x	7.48E-12	6.07E-12
13	Hydrocarbons, aromatic	Air	2.07E-04	8.80E-05	2.59E-18	1.41E-10
14	Lead	Air	1.53E-04	1.10E-03	1.53E-04	1.10E-03
15	Mercury	Air	9.13E-03	1.33E-02	9.13E-03	1.33E-02
16	Methane, dichloro-, HCC-30	Air	1.47E-14	9.44E-12	1.47E-14	9.44E-12
17	Nickel	Air	7.86E-08	3.29E-05	7.86E-08	3.29E-05
18	PAH, polycyclic aromatic hydrocarbons	Air	2.59E-18	1.41E-10	x	x
19	Propene	Air	6.80E-10	4.13E-10	6.80E-10	4.13E-10
20	Selenium	Air	x	x	7.38E-22	4.84E-14
21	Silver	Air	0.00E+00	0.00E+00	0.00E+00	0.00E+00
22	Styrene	Air	4.39E-23	1.14E-15	4.39E-23	1.14E-15

No.	Substance	Compartment	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
23	Toluene	Air	1.84E-21	8.10E-14	1.84E-21	8.10E-14
24	Xylene	Air	3.16E-22	1.45E-14	3.16E-22	1.45E-14
25	Zinc	Air	1.31E-03	2.57E-02	1.31E-03	2.57E-02
26	Aluminium	Water	1.26E-14	1.24E-14	0	0
27	Ammonia	Water	x	x	0	0
28	Arsenic, ion	Water	0	0	0	0
29	Benzene	Water	3.78E-25	1.88E-15	0	0
30	Cadmium, ion	Water	1.68E-20	3.50E-19	x	x
31	Chromium	Water	0	0	0	0
32	Copper, ion	Water	0	0	x	x
33	Dioxin,2,3,7,8 Tetrachlorodibenzo p-	Water	9.36E-09	2.20E-15	0	0
34	Ethane, 1,2-dichloro-	Water	x	x	0	0
35	Ethane, chloro-	Water	x	x	0	0
36	Iron	Water	x	x	0	0
37	Iron, ion	Water	0	0	x	x
38	Lead	Water	0	0	0	0
39	Manganese	Water	0	0	0	0
40	Mercury	Water	1.52E-17	1.87E-17	0	0
41	Nickel, ion	Water	0	0	x	x
42	Phenol	Water	1.62E-09	1.28E-09	0	0
43	Zinc, ion	Water	x	x	0	0

APPENDIX K: Terrestrial acidification and nutrification comparison table for petroleum based polyethylene and bio-based polyethylene.

Unit: kg $SO_{2\ eq}$

No.	Substance	Compartment	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
1	Ammonia	Air	3.24E-09	5.94E-09	3.24E-09	5.94E-09
2	Nitrogen oxides	Air	0.0177	0.0208	0.0177	0.0208
3	Sulfur dioxide	Air	0.00408	0.00503	0.00408	0.00503

APPENDIX L: Aquatic acidification comparison table for petroleum based polyethylene and bio-based polyethylene.

Unit: kg $SO_{2\ eq}$

No.	Substance	Compartment	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
1	Ammonia	Air	4.07E-10	7.47E-10	4.07E-10	7.47E-10
2	Hydrogen chloride	Air	5.43E-05	5.82E-05	5.43E-05	5.82E-05
3	Hydrogen fluoride	Air	2.90E-06	4.12E-06	2.90E-06	4.12E-06
4	Hydrogen sulfide	Air	1.10E-08	1.54E-08	1.10E-08	1.54E-08
5	Nitrogen oxides	Air	2.26E-03	0.00265	2.26E-03	0.00265
6	Sulfur dioxide	Air	4.08E-03	0.00503	4.08E-03	0.00503
7	Sulfuric acid	Air	1.19E-15	2.19E-15	x	x
8	Ammonia	Water	x	x	5.84E-06	5.33E-06

APPENDIX M: Aquatic eutrophication comparison table for petroleum based polyethylene and bio-based polyethylene.

Unit: kg PO_4 P-lim

No.	Substance	Compartment	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
1	Ammonia	Air	0	0	0	0
2	Nitrogen oxides	Air	0	0	0	0
3	Ammonia	Water	x	x	0	0
4	Ammonium, ion	Water	0	0	x	x
5	COD, Chemical Oxygen Demand	Water	4.18E-06	4.34E-06	4.18E-06	4.34E-06
6	Nitrate	Water	0	0	0	0
7	Nitrogen	Water	x	x	0	0
8	Nitrogen, total	Water	0	0.00E+00	x	x
9	Phosphate	Water	x	x	2.24E-06	2.88E-06
10	Phosphorus, total	Water	1.23E-06	1.58E-06	x	x

APPENDIX N: Global warming comparison table for petroleum based polyethylene and bio-based polyethylene.

Unit: kg $CO_{2\ eq}$

No.	Substance	Compartment	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
1	Carbon dioxide	Air	1.57	1.69	x	x
2	Carbon dioxide, land transformation	Air	x	x	1.57	1.69
3	Carbon monoxide	Air	0.0194	0.00429	x	x
4	Carbon monoxide, fossil	Air	x	x	0.0194	0.00429
5	Dinitrogen monoxide	Air	1.23E-10	2.21E-08	1.23E-10	2.21E-08
6	Methane	Air	0.108	0.124	0.108	0.124
7	Methane, dichloro-, HCC-30	Air	8.88E-14	5.70E-11	8.88E-14	5.70E-11

APPENDIX O: Non-renewable energy comparison table for petroleum based polyethylene and bio-based polyethylene.

Unit: MJ primary

No.	Substance	Compartment	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
1	Energy, from coal	Raw	2.9	3.71	2.79	3.57
2	Energy, from coal, brown	Raw	4.30E-05	0.001	3.80E-05	0.000887
3	Energy, from gas, natural	Raw	30.4	31.8	27.4	28.7
4	Energy, from oil	Raw	40.8	37.8	38.1	35.4
5	Energy, from uranium	Raw	3.13	4.9	3.13	4.9
6	Energy, unspecified	Raw	0.00105	0.00254	x	x

APPENDIX P: Mineral extraction comparison table for petroleum based polyethylene and bio-based polyethylene.

Unit: MJ surplus

No.	Substance	Compartment	Petroleum based HDPE	Petroleum based LDPE	Bio-based HDPE	Bio-based LDPE
1	Aluminium, 24% in bauxite, 11% in crude ore, in ground	Raw	x	x	1.20E-05	4.52E-05
2	Bauxite, in ground	Raw	2.52E-06	9.50E-06	x	x
3	Chromium, in ground	Raw	9.34E-13	7.75E-13	9.34E-13	7.75E-13
4	Copper, in ground	Raw	1.17E-07	2.50E-06	1.17E-07	2.50E-06
5	Iron, 46% in ore, 25% in cride ore, in ground	Raw	x	x	8.89E-06	1.24E-05
6	Iron, in ground	Raw	8.89E-06	1.24E-05	x	x
7	Lead, in ground	Raw	3.73E-06	3.57E-06	3.73E-06	3.57E-06
8	Manganese, in ground	Raw	x	x	4.11E-08	5.79E-08
9	Mercury, in ground	Raw	1.17E-07	2.72E-07	1.17E-07	2.72E-07
10	Nickel, in ground	Raw	6.87E-09	1.47E-07	6.87E-09	1.47E-07
11	Zinc, in ground	Raw	6.19E-05	1.33E-03	6.19E-05	1.33E-03