INVESTIGATION OF THE AVAILABILITY OF BIODEGRADABLE POLYMERS IN MALAYSIA AND ITS IMPACT TO ENVIRONMENT ISSUES IN MALAYSIA

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Mechanical Engineering

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April 2022

DECLARATION

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

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"INVESTIGATION OF THE AVAILABILITY OF BIODEGRADABLE POLYMERS IN MALAYSIA AND ITS IMPACT TO ENVIRONMENTAL ISSUES IN MALAYSIA"** was prepared by **NG JIA XUAN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Mechanical Engineering at Universiti Tunku Abdul Rahman.

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ACKNOWLEDGEMENTS

First and foremost, I am extremely grateful to my supervisor, Dr. Bee Soo Tueen for her invaluable advice, guidance and her enormous patience throughout the development of the research. Secondly, I would like to thank to my friends, Law Yung Siang and Ernest Hiew Sheng Chen for their informations sharing throughout this one year to conduct the analysis for this project. Finally, I would like to express my gratitude to my parents for their supporting and caring throughout these years in my study and acted as my spiritual support when I felt exhausted.

ABSTRACT

Biodegradable polymers are created and highly recommended as the replacement to the non-biodegradable polymers to reduce the burden to the environment. In this project, two types of biodegradable polymers which are polylactic acid (PLA) and polyvinyl alcohol (PVA) have been selected to conduct in this project. To investigate the availability of the PLA and PVA in Malaysia, the environmental impacts to produce these biodegradable polymers in Malaysia have been analysed through the life cycle assessment (LCA). The production method adapted for PLA, the raw material used is DL-lactic acid, which is produced through the chemical synthesis. Then, the production method adapted for PVA, the raw material used is ethylene, which is easy to access in Malaysia. The LCA for 1 ton of PLA and PVA was conducted in the cradle-to-gate manner through a software named OpenLCA. The databases used in this project were taken from Ecoinvent 3.8 that is accessible through OpenLCA, and the ReCiPe (H) 2016 is the method used to analyse the environmental impacts generated from the production of PLA and PVA. The net consequences of the environmental impact to produce 1 ton of PLA in Malaysia was 5.52E+04 which is harmful to the environment due to the chemical synthesis used for the production of its raw material, lactic acid. The endpoint impact is the damage of human health from the water consumption affected by Tin Octoate. Then, the net consequences of the environmental impact for the PVA in Malaysia was -4.18E+08 which is friendly to the environment due to the activated carbon-supported catalyst used in the production process, the Palladium (II) Chloride. The endpoint impact is good for the human health from the global warming reduction that affected by Palladium (II) Chloride. Therefore, the availability of the PVA is better and more suitable to produce in Malaysia compared to the PLA.

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LIST OF SYMBOLS / ABBREVIATIONS

c_p	specific heat capacity, J/(kg·K)
h	height, m
K_d	discharge coefficient
M	mass flow rate, kg/s
P	pressure, kPa
P_b	back pressure, kPa
R	mass flow rate ratio
T	temperature, K
v	specific volume, m^3

α	homogeneous void fraction
η	pressure ratio
ρ	density, kg/m^3
ω	compressible flow parameter

ID	inner diameter, m
MAP	maximum allowable pressure, kPa
MAWP	maximum allowable working pressure, kPa
OD	outer diameter, m
RV	relief valve

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Plastic littering and the problems associated with its persistence in the environment have become a major focus of both research and the news in recent years. In a study of 2019 commissioned by the World Wide Fund for Nature (WWF) showed that Malaysia has ranked in the second in Asia for annual per capita plastic use. According to Kaur (2021), even though the Malaysia's recycling rate has been increasing year after year, but it is still considered as low compared to the other developing country. Besides, Malaysia as one of the largest plastic production industries in this global, the low-cost customers are constantly given single-use plastic bags and end up our landfills are filled with these cheap quality polymers. Not to mention, the overall waste generated by Malaysian was at 16.78 kg per person. Therefore, besides promoting plastic recycling, biodegradable polymers have been viewed as a feasible alternative to commodity plastics.

For several years, development of biodegradable polymers has been accelerating due to their promise of solving existing problems especially in combat to the plastic waste problem (Haider et al., 2019). Biodegradable, as the name given is a material that biodegrade naturally in the environment because of the action of naturally occurring micro-organism such as fungi, algae, and bacteria (Lambert and Wagner, 2017). With this characteristic, it greatly helps in lower the burden of the environment especially for the country that highly using the landfill disposed method like Malaysia. Therefore, biodegradable polymers are strongly preferable to replace the conventional polymers especially for those specific commercial objectives where environmental market price is critical (Manfra et al., 2021).

However, the environmental protection has strongly related to economic development and social development (Nörmann and Maier-Speredelozzi, 2016). From the availability of the raw material of the biodegradable polymer to its manufacturing process until the end of product, the total carbon footprint created is one of the crucial environmental problems that need to be looked after. Besides, the manufacturing cost will thus affect the product cost and the market demand of the product even though the product is environmentally friendly. Hence, it will affect the availability of the product to the market. In addition, the disposed method used will also indirectly affect the awareness of the society to environmental issue. On that account, Life Cycle Assessment (LCA) was adapted to access the environmental issues from a certain product.

LCA is an approach to do the environmental management and accounting for a product. It tooks them into the considerations from all facets of resource consumption and environmental pollution. The raw material extraction, manufacturing, transportation and distribution, application and disposed method were all considered through LCA. Therefore, it was able to rate all the different types of potential environmental issues associated with the product.

1.2 Importance of the Study

Polymer is a material that exists in this world more than 100 years and it has been used in a huge and growing range of applications. Besides, polymer has become an important material we relied on for our daily used with providing multiple benefits to modern day living. Even though we noticed the very harmful impact brought from conventional polymer to the environment, but plastics are still indispensable in our lives. Therefore, biodegradable polymers were created and highly recommended as the replacement to the conventional polymer to reduce the negative impacts to the environment.

Biodegradable polymers are recommended to replace the conventional polymers that are basically due to it used up less than 100 years to biodegrade when decomposed in landfills which is more way better than the conventional type that needs up to 1000 years to decompose in landfills. However, the carbon extraction during the manufacturing process is considered as one of the serious environmental issues that to be ignored. Besides, the economic and social development were also the crucial relation to the environmental protection. The life cycle of the biodegradable polymer, the disposed method used in Malaysia, the cost of the biodegradable products and the awareness of the society to the environment were all related and affected each other in direct and indirect way.

The importance of this study was to identify how the life cycle affects the availability of the biodegradable polymers in Malaysia and the environmental impact bought from this issue in Malaysia. To analyse the overall environmental impact towards this issue, the Life Cycle Assessment was conducted through this study.

1.3 Problem Statement

The environmental issue of the single-used polymer has received global attention due to its strong presence in marine and freshwater organisms and it used decades to degrade in the field (Touchaleaume et al., 2016; Zaki et al., 2021). Therefore, it brought up the population of usage of biodegradable polymers as it is superior to conventional polymers in terms of environmental stewardship. However, the knowledge on the environmental distribution and ecological risks of the manufacturing process of biodegradable polymers is still limited, although their production and application continue to improve (Zhao et al., 2020).

According to Maga, Hiebel and Thonemann (2019), the lower global warming issue goes along with the greater savings in main energy demand and less fossil resource depletion. The main environmental impact brings out from the life cycle of biodegradable polymer is carbon extraction from the manufacturing process and the transportation. Besides, according to Agarwal (2020), the environmental acceptability, sustainability, and degradability in a complicated natural environment took into account in order to determine whether biodegradable polymers could be one of the solutions to the plastic waste problem. One of the common materials used to produce biodegradable polymer, the polylactic acid (PLA) was actually non-degradable in the seawater and the biodegradability of other biodegradable polymers was also highly dependent on the environment in which they end up (Haider et al., 2019).

Furthermore, according to Nörmann and Maier-Speredelozzi (2016), the three components of sustainability which the economic development, social development, and environmental protection are the components that

affect each other in any real-world application. For instance, the availability of the raw material and the life cycle will affect the cost of the product, then the cost will affect the demand of the product in the market. Thus, it will affect the availability of the biodegradable polymer in our country. Anyway, the usage of the biodegradable polymers has gone in a strong uptrend. Understand the life cycle and the environmental issues to produce the biodegradable polymers in Malaysia is a way to determine the suitability of the production at current condition in Malaysia, and to detect the scarcities to reach and balance the three components of sustainability, therefore the solutions can be carried out.
The problem statements of this investigation were:

1) What are the production methods of biodegradable polymers adapted in Malaysia and the accessibility of the raw material?
2) What is the ability to solve the environmental problems from producing the biodegradable polymers in Malaysia?
3) Is the production of biodegradable polymers suitable to be adapted in Malaysia?

1.4 Aim and Objectives

In this analysis, the research of availability of biodegradable polymers in Malaysia was conducted. The Life Cycle Assessment (LCA) applied in this project was basically a systems analysis tool that aimed to identify the environmental impacts caused by the production of biodegradable polymers in Malaysia. Biodegradable polymer is a well-known green material that has been used to replace the conventional plastic. However, the attainability of raw materials and the cost of manufacturing process to produce the biodegradable polymers will affect the environmental issue of the biodegradable polymers in Malaysia. Hence, the availability of the biodegradable polymers in Malaysia will be affected. Therefore, the availability of the raw materials of the biodegradable polymers in Malaysia and its environmental impacts in Malaysia was studied and discussed in a detailed methodology. Provided with the support of LCA, the environmental characteristic to produce the biodegradable polymers in Malaysia can be analysed and studied to investigate the availability of the biodegradable polymer in Malaysia.

The main objectives of this investigation were:

1) To identify the life cycle inventory (LCI) of biodegradable polymers in Malaysia.
2) To identify the environmental impacts resulted from the producing of biodegradable polymers in Malaysia.
3) To compare the life cycle impact assessment (LCIA) of selected biodegradable polymers.

1.5 Scope and Limitation of the Study

Life cycle assessment (LCA) is a very comprehensive tools in matching with the environmental impact in full range as it goes through the life cycle. In this project, the LCA of polylactic acid polymer (PLA) and polyvinyl alcohol polymer (PVA) in Malaysia were analysed in a cradle-to-gate manner. Which means the system boundary selected that limit the LCA in this project was starting from the raw material extraction until production of these biodegradable polymers. The LCA for two of these biodegradable polymers includes of some stages, which including the raw material extraction, raw material transportation, manufacturing process and the energy consumption of the processes. The outcome of the LCA was highly reliant on the life cycle inventory (LCI). The Ecoinvent 3.8 database was used in this work. The Ecoinvent database was a life cycle inventory database of common materials and processes that the OpenLCA software will use to generate and analyse a holistic picture of a product's potential impact. Besides, the Life Cycle Impact Assessment (LCIA) will assess the environmental impacts of the biodegradable polymers analysed in this project. This project also uses the ReCiPe (H) 2016 effect evaluation approach.

Transportation is one of the contributors that contributed a substantial number of environmental wastes. Transportation consumes the majority of the world's petroleum and contributes significantly to air pollution by emitting nitrox oxides, carbon dioxide, carbon monoxide, and particulate matter. Not to mention, the additional consequences, such as noise pollution. In the manufacturing process of these two types of biodegradable polymer, each of them required different raw materials and they were transported from different sources. The attainability of the raw materials in Malaysia will affect the number of product and the cost to get the raw materials. On that account, it will affect the product cost and the demand of the product in the market even though the product is environmentally friendly.

In addition, the manufacturing method used in this project is one of the crucial stages that affect the environmental impact of the biodegradable polymer. The geographical location of Malaysia that will affect the availability of the raw materials production in Malaysia. The manufacturing method chosen to produce these biodegradable polymers in Malaysia must include the concern of the easy accessibility of the raw materials from local or nearest country.

1.6 Contribution of the Study

We are living in a world that is both modernised and globalised where the polymer has become one of the daily usages in our life. To against the bad environment impact from the conventional polymer to our global, biodegradable polymers were created to numerously replaced the conventional polymer. Anyway, throughout the LCA of the production of the biodegradable polymer helps to identify and understand the environmental impact brings to Malaysia. Therefore, by understanding the environmental impacts brought from the availability of the raw materials in Malaysia will help to determine the availability of the biodegradable in Malaysia.

1.7 Outline of the Report

In this report, the Chapter 1 included the general introduction, the importance of study, problem statement, objectives, scope of study, the contribution of study and the outline of the report. Meanwhile in Chapter 2, the literature review of the 2 types of biodegradable polymers were conducted which are polylactic acid (PLA) and polyvinyl alcohol (PVA). The life cycle for each type of biopolymers were briefly explained in this chapter. Besides, the Life Cycle Assessment (LCA) and the tools were also explained about in this chapter. In Chapter 3, the methodologies of this project were explained. The data for the Life Cycle Inventory (LCI) were collected and the LCA analysis were conducted through this chapter. In Chapter 4, the results which are the environmental impacts generated in midpoint and endpoint approach were discussed in this chapter. Lastly, the conclusion of the availability of the biodegradable polymers in Malaysia was explained. The limitation of this study and the recommendations for the future study were discussed in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Biodegradable polymers are generally considered as eco-friendly polymers that is suitable to replace the conventional polymers. Anyway, there are a lot of different types of polymers that are biodegradable in different way with their different characteristics. In this chapter, the life cycle, characteristic, the environmental impacts of the production and the availability polylactic acid (PLA) and polyvinyl alcohol (PVA) polymer in Malaysia were thoroughly discussed. The tools and database to do the Life Cycle Assessment (LCA) were also revealed in this section.

2.2 Biodegradable Polymer

2.2.1 Polylactic Acid (PLA)

Polylactic acid (PLA) can be considered as the most prevalent type of commercial biodegradable polymer worldwide. According to Komesu et al. (2017), there are 2 types of the methods to produce the raw material, lactic acid of PLA using in this worldwide which are through the biological synthesis and chemical synthesis. For the biological synthesis, the lactic acid was a chemical created by the fermentation of starch found commonly in sugar and cone. The lactic acid formed throughout biological synthesis is optically L (+) lactic acid or D (-) lactic acid. For the chemical synthesis, the lactic acid created by the hydrolysis from petrochemical product. The lactic acid formed throughout the chemical synthesis is only racemic DL-lactic acid. Due to the good mechanical and chemical properties presented in PLA polymer, agriculture, packaging, and biomedical industries were all using it. Besides, PLA goods are primarily disposed of in landfills or composting. Figure 2.1 shows the mind map for the biological synthesis and the Figure 2.2 shows the mind map for chemical synthesis.

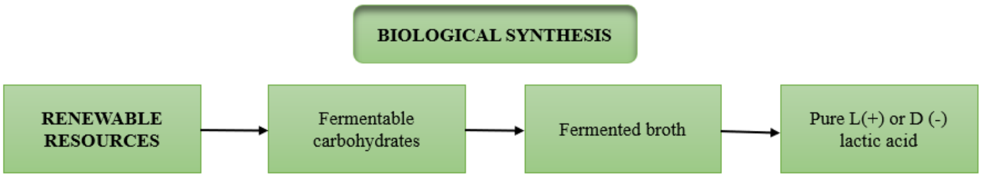


Figure 2.1: Mind Map for Biological Synthesis

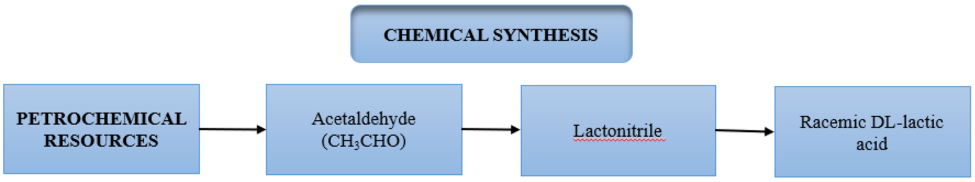


Figure 2.2: Mind Map for Chemical Synthesis

According to Rezvani Ghomi et al. (2021), to discover the key drivers influencing PLA's environmental features, the life cycle of PLA is examined through waste management scenarios. The pathway of PLA life cycle with potential emissions has been divided into four stages which are including the feedstock collection and its conversion, manufacturing, application and end of life (EoL). During the first stage of life cycle, there were three main steps consist in PLA manufacturing. Bio-based supplies like sugarcane or corn were harvested and delivered to a processing facility. The feedstock was then transformed to lactic acid via a sugar or starch fermentation process. This was the most often used lactic acid manufacturing technology because it was the most cost-effective and produces pure lactic acid.

2.2.1.1 Feedstock Collection and Conversion

For the biological synthesis, based on Pahola, Omid J and Uisung (2019), the corn will be transported to a corn wet mill (CWM) once the corn was harvested. At the CWM, the foreign matter was removed and the particulates and analysed to determine its composition. To make a high purity starch solution, the maize will be soaked in water or sulphur dioxide solution for 36 hours at 51 °C. The enzymes were added to the liquid starch in a reactor vessel, after which the dextrose was created and filtered out. After that, the dextrose was then fermented into lactic acid under anaerobic conditions using nitrogen gas.

Sugarcane is grown in 47 provinces in Thailand, accounting for around 8% of the country's total arable area. To ease the harvest process, 90% of the farmers are using the method of open burning to remove the residues from the field and only the small size of the plantings makes automated harvesting difficult. The sugar cane was crushed to extract the juice, and the bagasse was burned to provide energy and heat in the sugar mill. Clarification of cane juice was accomplished through the use of heat and trace amounts of chemicals to adjust the pH and prevent sucrose inversion. The clarified juice was evaporated, crystallised, and centrifuged to produced raw sugar. Through the fermentation process, the lactic acid was produced by control the pH value using lime resulting in the formation of calcium lactate then the final lactic acid was formed through purification process (Morão and de Bie, 2019).

Coming to the chemical synthesis, the production of the lactic acid was employing the lactonitrile by using the acrylonitrile technology. When lactonitrile has been made, hydrogen cyanide (HCN) was added to liquid acetaldehyde (CH_3CHO) under high pressure in the presence of a base catalyst (Komesu et al., 2017).

2.2.1.2 Manufacturing Process

At the second stage which is the manufacturing process of the PLA, there are different production procedure for different natural source used and different types of PLA isomers. PLA is one of the biodegradable thermoplastics, the pellets of thermoplastic starch were produced by extrusion (Soares et al., 2013). For thermoplastic, the shape can be changed at a certain elevated temperature and solidified through cooling process. According to (Pahola, Omid J and Uisung, 2019), the purified L-lactic acid solution was evaporated to remove the water, and the solution was deposited into the prepolymer reactor. The molten L-lactide solution was purified by distillation. After that, the purified L-lactic molecules will then go through a ring-opening plasticization reaction that will be catalysed by tin (II) 2-ethylhexanoate. Then, the high molecular-weight PLA was devolatilised, crystallised, and pelletised. Meanwhile, based on (Morão and de Bie, 2019), the PLA produced by sugarcane was produced by polymerizing lactide, which was synthesised from purified lactic acid. The polymer was purified further to make PLA pallets.

Same goes to the lactonitrile, after recovering the lactonitrile, it was purified and hydrolyzed with sulfuric acid (H_2SO_4) to produce lactic acid and ammonium salt ($(NH_4)_2SO_4$). After that, the esterification of lactic acid with methanol (CH_3OH) was recovered, purified by distillation, and hydrolyzed with acidified water to generate lactic acid and methanol. Then, the methanol has been separated and recycled through distillation.

2.2.1.3 Application

The applications for PLA are majoring in packaging industry especially in food packaging. From the fresh product such as fruits, vegetables, and salad containers in the retail markets until drinking cup, disposable cutlery and plates at the fast-food restaurant are all made from biodegradable polymers. Due to the fact that these types of productions come into contact with acidic mixtures at varying temperatures, the physical, mechanical, and optical properties of PLA must be customised for each application. PLA, on the other hand, has been widely used in many biomedical applications due to its biocompatibility, such as screws for craniomaxillofacial bone fixation.

2.2.1.4 End of Life

In Malaysia, the EoL options using are including landfilling, composting and recycling (Chen et al., 2021). Even though PLA is biodegradable, it is not permitted for littering or self-composting in the environment. PLA products are considered stable when landfilling in soil and only have a minor impact on the environment because it was discovered that only one percent of them will degrade after 100 years. However, due to the cheaper price and properties stability of the synthetic polymers, some PLA products were fabricated as promising synthesis biopolymer and this type of polymer is difficult to degrade in a natural environment. Furthermore, most of the PLA products are designed for a short life span, but they are reusable.

Based on Cosate de Andrade et al. (2016), three EoL scenarios for PLA were investigated: chemical recycling, mechanical recycling, and composting. In mechanical recycling process. The PLA residuals were firstly going through the separation process, then the residuals being grinded into smaller sizes. After that, the grinded residuals were sent to washing, drying and extrusion processes. In the extrusion process, 0.6% of chain extender was added which allows the mechanical recycled PLA capable of replacing the polymer produced by the traditional method. Lastly, the residuals were being cooled and the granulation and sieving process has been made.

In the chemical recycling process, it is divided in hydrolysis and polymerization stages. In hydrolysis step, the PLA residuals will go through separation process, then being grinded into smaller sizes, then washing process. There are 40% of PLA and distilled water were added in the reactor together with the grinded residuals and the temperature keep constant at 180 °C for 2 hours. After that, the cooling process has been made to make the lactic acid impurities to become 25 °C. During the decantation and filtration process, the precipitation agent was added to remove the impurities that mixed in the lactic acid. Lastly, the evaporation process was made to remove the water then the concentrated lactic acid was successfully recycled.

After the hydrolysis step, the polymerization step was conducted to produce the recycled PLA. In the polymerization step, the concentrated lactic acid went through the prepolymer production to remove the water and left the oligomers. Next, the oligomers went through the lactide production, the tin ethanoate was added during the process to again remove the water and left the lactide. Then, the lactide will go through the ring open polymerization process with again added the tin ethanoate to produce the PLA. Lastly, the PLA will go through the extrusion and the recycled PLA was produced.

Composting has the simplest process for the EoL of PLA. The PLA residuals is firstly going through the separation process then being grinded into small sizes. Lastly, the residuals will go through the compost degradation process and the carbon dioxide will being released during the process.

2.2.2 Polyvinyl Alcohol Polymer

Polyvinyl alcohol polymer (PVA) is a widely used biodegradable polymer that can be biodegraded in the presence of appropriately acclimated microorganisms. PVA is one of the widely used biodegradable polymers for those applications that need to be dissolved or dispersed in water due to it’s water-soluble characteristic. In this report, the environmental consequences and life cycle of the PVA were examined due to the increased awareness of microplastic appearance in the aquatic environment, which will damage human health and the ecology.

2.2.2.1 Feedstock Collection and Conversion

According to Emblem (2012), Ethylene vinyl acetate (EVA) is the major raw material used to make PVA. EVA is a random copolymer of ethylene and various proportions of vinyl acetate (VA). VA was made from ethylene by a palladium catalyst reaction with oxygen and acetic acid. (Adam, 2021). While ethylene is commercially generated by steam splitting a variety of hydrocarbon feedstocks (ICIS, 2010). Based on Chad (2018), the hydrocarbon is the organic compound that occur naturally in crude oil, like petroleum and natural gas.

2.2.2.2 Manufacturing Process

PVA is produced by hydrolysis of polyvinyl acetate (PVAc). According to Nasibi et al. (2020), the PVAc has been made by polymerizing of VA and then partially hydrolyzing it to become PVA. During the polymerization process for the VA to become PVAc, methanol was added as the solvent to create the polymerization reaction in the VA. In the conversion from PVAc to become PVA, there are three hydrolysis methods are applicable for the process which are aminolysis, acidolysis and alkaline hydrolysis. On industrial scales, the alkaline alcohol is the most used hydrolysis method because this method ester interchange with methanol, and with the presence of sodium hydroxide to hydrolyze the acetate groups. The physical properties and specific functional applications were determined by the degree of polymerization and hydrolysis. Therefore, the aqueous saponification agent will be gradually added during the polymerization and hydrolysis processes until the degree targeted reached. Lastly, the PVA was precipitated, rinsed, and dried.

2.2.2.3 Applications

Due to its odourless, tasteless, and non-toxic properties, PVA is frequently used as a moisture barrier film for food supplement tablets and foods containing inclusions, as well as dry food containing inclusions that must be protected from moisture absorption. Besides that, PVA has been utilised in a variety of industries, including textiles, paper, 3D printing, and food packaging, due to its strong chemical and heat resilience and low manufacturing cost. Different manufacturing processes such as melt blow extrusion, injection molding and many more are used to manufacture the product and different degree of hydrolysis is used for different applications (Chiellini et al., 2003).

2.2.2.4 End of Life

The End of Life (EoL) of PVA polymers are mostly will be soluble in water due to the “water-soluble” characteristic. However, different application of the PVA polymers have different biodegrade composite which will affect the degradation rate of the PVA polymer in different environment, including when it has disposed in water.

2.3 Environmental Impact

Environmental impact has become the main concerned for every new developing product in recent years. The products that made from green materials are tends to have more superiority in the market. However, to study the actual environmental impact from a product, the total environmental impact during the course of a product's life cycle must be understanded and analysed then only we can decide whether the product is good for our environment. In this subtopic, the carbon footprint and the marine toxicity carried out by the PLA and PVA biodegradable polymers has been analysed.

2.3.1 Carbon Footprint

When talking about the environmental impact, carbon footprint is the most concerned impact from every industry. According to Zhao et al. (2018), the data of energy used and emission factors of the PLA that used the corn as their raw material was collected. In Table 2.1 shows the energy consumption and the carbon dioxide (CO_2) emissions for the production of one ton of PLA resin in cradle-to-gate manner. It was clearly shows that the largest CO_2 contribution is mainly comes from the process to produce lactic acid which has contributed in the total of 4.73 t of CO_2 from the process.

Table 2.1: One ton PLA Production Energy Consumptions and CO_2 Emissions (Zhao et al., 2018)

Process	**Material Consummed**	**Energy Consummed (MJ)**	**CO_2 Emissions (t)**
Corn planting and harvesting	Diesel 2.09 Kg	2.5E+03	-4.26
Starch Processing	Electrical energy 610 KW	6.2E+03	0.50
Lactic acid processing	Fuel 0.54 t Electrical energy 2000 KW	44.2E+03	4.73
PLA processing	Electrical energy 1000 KW	9.6E+03	0.87
Aggregate	-	62.5E+03	1.84

From another research, the PVA, which is also named as PVOH, the main contributor for the emission of CO_2 is from the process to produce the vinyl acetate which has shown in Figure 2.3. In the article also mentioned to produce the PVA, the total energy consumption of the production required 165 MJ, and 81 % of the energy consumption was consumed during the production of vinyl acetate (Anthony et al., 2017).

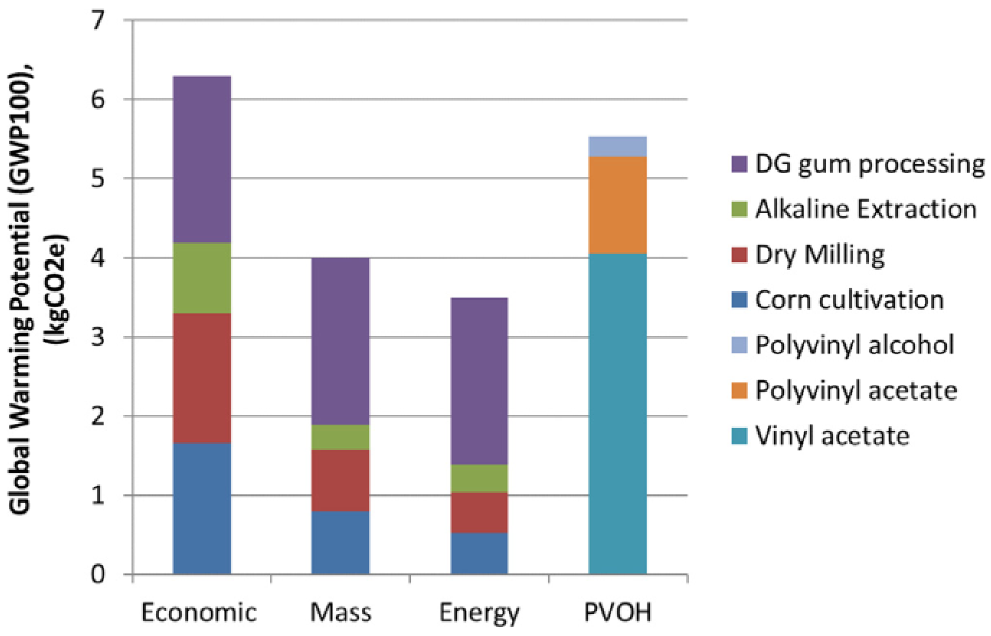


Figure 2.3: Global Warming Potential (GWP) associated with production of 1 kg DG Gum and PVOH (Anthony et al., 2017)

In Table 2.2 shows the share of greenhouse gas (GHG) emissions for the production of PLA by using corn as the raw material. Even when the manufacturing and transportation of the material inputs were considered, electricity and natural gas account for the majority of GHG emissions during the conversion process (Pahola, Omid J and Uisung, 2019).

Table 2.2: Cradle-to-Gate GHG Emissions (Pahola, Omid J and Uisung, 2019)

Input	**tons CO_2e/ton PLA**	**% Contribution**
Materials	0.09	2.9
Feedstock	0.31	10.1
Electricity	0.94	30.8
Coal	0.02	0.8
Natural Gas	1.36	44.6
Residual Oil	0.32	10.5
Electricity	0.94	30.8

In Table 2.3 describes the amount of energy from fossil fuel sources that required to produce one ton of PLA. The fossil fuels used in the production of electricity, as well as those consumed directly and upstream during the manufacturing of material inputs, were included in these figures.

Table 2.3: Fossil Fuel Consumption during PLA Production Broken Down by Fuel Type (Pahola, Omid J and Uisung, 2019)

Process	Fuel Type	mm Btu/ton PLA	% Total energy
Feedstock	Natural Gas	0.72	2.1
	Petroleum	0.35	1.0
	Coal	0.02	0.0
	Subtotal	**1.09**	**3.2**
Conversion	Natural Gas	23.24	68.8
	Petroleum	3.64	10.5
	Coal	6.02	17.7
	Subtotal	**32.91**	**97.1**
Total		**33.88**	**100**

To be conclude, the higher amount of the energy consumption of the process does not indicates the higher contribution of the CO_2 to the environment. No matter is PLA or PVA, the highest CO_2 contribution is the process to produce the raw material of both biodegradable polymer which is the lactic acid and vinyl alcohol.

In another research, the environmental footprint of PLA manufactured in Thailand utilising sugarcane as a raw material has been collected from cradle to grave. According to (Morão and de Bie, 2019), the CO_2 uptake from the atmosphere which is also called as biogenic carbon was 1.833 kg CO_2/kg PLA. The global warming potential (GWP) of PLA is 501 kg CO_2 eq/ton PLA from cradle to grave. The Figure 2.4 shows GWP potential at different stages of the production system. The CO_2 intake from the environment by growing sugarcane, which was 1833 kg CO_2/ton PLA and was the most CO_2 created among the many stages of PLA manufacturing, was used as the starting point for the GWP of PLA.

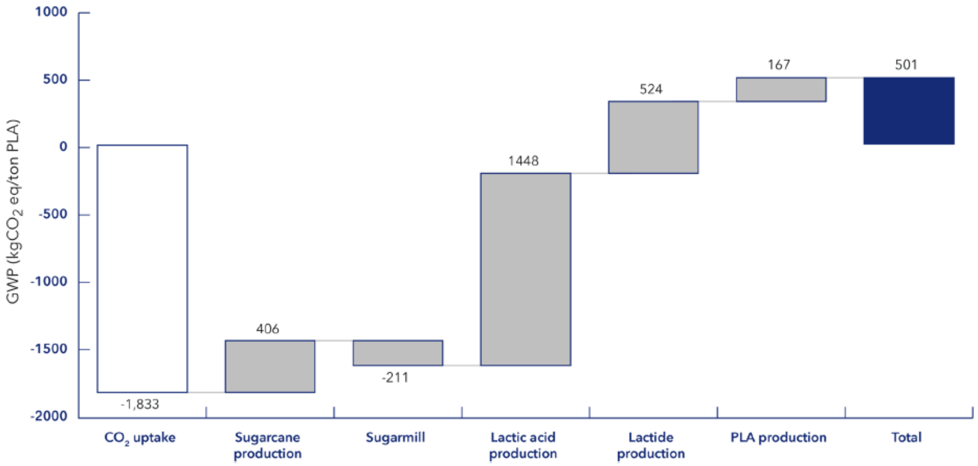


Figure 2.4: GWP potential in different stages of PLA production (Morão and de Bie, 2019)

During the EoL of PLA, the environmental impact caused to the climate change was analysed per 1 kg of the PLA. To complete the initial 1 kg of PLA, 0.04 kg of unprocessed PLA and 0.96 kg of recycled PLA was combined in the mechanical recycling. In chemical recycling, 0.03 kg of unprocessed PLA and 0.97 kg of recycled PLA was combined and for the composting, 1 kg of unprocessed PLA and 0.33 kg of compost was combined. By refer to the Figure 2.5, the composting method has contributed the largest amount of carbon dioxide to cause the climate change (Cosate de Andrade et al., 2016).

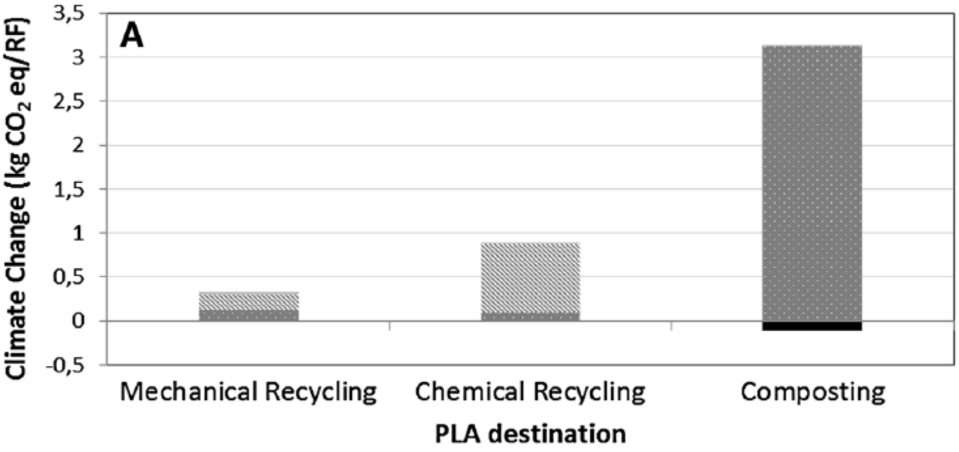


Figure 2.5: Climate Change of the three evaluated PLA destinations (Cosate de Andrade et al., 2016)

2.3.2 Marine Pollution

Marine pollution that caused by the presence of microplastic has gained the attentions of the public. However, microplastic is not the only reason to cause the marine pollution, but the oil spills, industrial effluents, chemicals and there are many other factors that will also cause the aqueous environment to be contaminated.

PVA is one of the water-soluble polymers that being used in world-wide. PVA is one of the biodegradable polymers that considered as friendly to the environment. According to (Byrne et al., 2021), PVA biodegradation was explored, and the presence of sewage sludge and wastewater containing bacterial species commonly associated with PVA was discovered. Even so, PVA has a very low predicted hydrophobicity and as a result it has a very slow tendency to absorb to organic carbon. Therefore, PVA has no potential to activate the sludge and consequently does not accumulate in aquatic environment.

PLA is one of the famous biodegradable polymers due to its strong chemical and mechanical properties. However, PLA is found to be a non-water-soluble polymer and it cannot be biodegraded in water. According to (Deroiné et al., 2014), the ageing of PLA was investigated in different temperature and different aqueous environments. It was shown the water uptake within PLA and the mechanical properties of PLA was loss at above 40 °C in distilled water. Besides, due to the lack of mineral salts that aid water transport within the polymer, the breakdown rate in distilled water was shown to be faster than in saltwater. Though, PLA was degraded after 6 months in both distilled water and seawater at 40 °C. Therefore, PLA was encouraged determined to have little degradation at least after 6 months in seawater due to the limited temperature range of seawater.

2.4 Availability of Biodegradable Polymers in Malaysia

The most common raw materials used to extract the lactic acid for PLA are the sugar extracted from sugarcane and the starch extracted from corn. To consider the geographic location of Malaysia, corn is not a very suitable agriculture in Malaysia as corn does best with the warm and sunny growing weather (Harold, 2021). Meanwhile, the cultivation of sugarcane in Malaysia is only concentrate in the Northwest of peninsular Malaysia which are in Perlis and Kedah (Fiji, 2021). Due to lack of these two main materials in Malaysia, there was research conducted to use the palm oil waste and transformed it into the fermentable sugar to produce the bio-based polymer.

Malaysia produces more than 80 million tonnes of biomass each year, making it the world's second largest producer of palm oil. Palm oil biomass also consists of hemicellulose and cellulose that can be converted into sugar monomer. Just like the sugarcane, the sugar monomer can be utilised as a fermentation substrate for a variety of products, including polymer. Pre-treatment process is a must to remove the lignin that protect the cellulose and hemicellulose. The physical, chemical, physico-chemical, biological and combination pre-treatment were conducted to investigate the performance and efficiency of the pre-treatment. Unfortunately, the suitability and efficiency of the pre-treatment were considered based on the energy and time consumption. Therefore, using palm oil to extract the lactic acid was non-cost effective and it was not worth to apply this method to produce the PLA (Rizal et al., 2018).

Anyway, Malaysia PLA product manufacturers are still can get the PLA resins exported from other countries like China, Thailand, United State and many more. These global PLA producers produced their PLA resins from different raw materials such as sugarcane, bamboo, and corn with different cost.

Different from PLA, there are several PVA manufacturers found in Malaysia. There are in the total of 3 companies who produce the PVA in Malayisa from the Tradeindia website. These 3 companies are located at Sarawak. The production method for the PVA for these 3 companies are did not mentioned. However, Malaysia is one of the crude oil production countries in this worldwide, the raw materials to produce the PVA is relatively easy to be accessed in Malaysia.

2.5 Life Cycle Assessment

The term "life cycle assessment" refers to a systematic examination of a product's or service's possible environmental implications over the course of its entire life cycle. During the LCA, the entire life cycle starting from the raw material feedstock collection and conversion until the product has reached the end of its useful life was evaluated to get the data of the potential environmental impact produced. In this assessment, the LCA was used to compare the life cycle of two different products, PLA and PVA, and how these life cycle affected the end product's environmental effect.

There are total of 4 stages consist in the LCA which are “Goal and Scope”, “Life Cycle Inventory”, “Life Cycle Impact Assessment” and “Life Cycle Interpretation”.

2.5.1 System Boundaries

System boundaries defined the limit of the processes throughout the entire product of the life cycle. System boundaries defined the product life cycle in a clear and easy way. There are a few types of system boundaries in LCA.

2.5.1.1 Cradle-To-Grave

There are a few types of life cycle consisted for the life cycle of a product. The "cradle-to-grave" product life cycle consists of five stages, beginning with the extraction of raw materials and concluding with the manufacturing stage, during which the raw material is transformed into a finished product. After that, the distribution of the product to the end user is the next step, followed by the user's use of the product. Finally, when a product reaches the end of its useful life, the user takes action.

2.5.1.2 Cradle-To-Gate

For the cradle-to-gate type, it only evaluates a product once it has left the production and is on its way to the consumer. Therefore, the cradle-to-gate study starts with the extraction of raw materials, the production process, and transportation to the end user, reducing the complexity of an LCA significantly.

2.5.1.3 Cradle-To-Cradle

For the cradle-to-cradle type, it also consists of 5 steps of a product life cycle. The different between this cradle-to cradle type and the cradle-to-grave type is it replaced the end of life of the product to recycle. Starting from the raw material extraction, manufacturing process, transportation, application, then recycle the product.

2.5.2 Definition of the Goal and Scope

The first stage in a Life Cycle Assessment (LCA) is to identify the purpose and scope description. According to Environmental Management Life Cycle Assessment (2017), the purpose and scope of the assessment is to determine the size of the product life cycle that will be considered, as well as the length of time that the evaluation will be used. The required resources and time, the study's objective, the application, the system boundaries, the evaluation technique, and the fundamental assumptions and constraints are just a few of the parameters. Thus, the purpose and scope definitions will serve as a compass for the entire life cycle assessment process, ensuring that the most pertinent results are obtained precisely.

According to Morão and de Bie (2019), the journal recorded about the LCA by using the sugarcane to produce the PLA. The goal was to quantify the environmental footprint of PLA produced at Total Corbion PLA site in Rayong, Thailand. The scope of the LCA was the entire value chain which including the growing of sugarcane. However, the system boundary used was in cradle-to-gate manner as the PLA is an intermediate used product formulated by third parties.

2.5.3 Life Cycle Inventory

The LCA's second stage is the Life Cycle Inventory (LCI). The LCI involves the modelling of the product system, data gathering, data description, and data verification. The inputs data related to the functional unit defined in the goal and scope definition such as energy, materials, chemicals and the outputs such as water emissions, air emissions or solid waste are all the factors must be included and affecting the result of the LCI analysis. However, the factors are taken into account in different ways depending on the region. For example, a location that is more reliant on renewable energy supplies or fossil fuels reduces the environmental impact of product transportation. These differences could lead to differences in assumptions and restrictions in the LCA research.

According to Morão and de Bie (2019), there were two databases used to conduct the LCA which are Agri-footprint V2.0 for the agriculture process of growing the sugarcane, and the Ecoinvent V3.3 for the rest of the inputs and outputs datasets.

2.5.4 Life Cycle Impact Assessment

The third stage of the LCA is the Life Cycle Impact Assessment (LCIA). The LCIA converts the LCI's basic flows into their possible contributions to the environmental consequences addressed in the LCA. The LCIA approach and the classification of effect categories are the major processes to be chosen throughout LCIA.

2.5.4.1 Method of Impact Categories

The impact categories are defined in accordance with the first stage's purpose and scope. The method of impact category is separated into midpoint and endpoint indicator. The midpoint indicator examines the environmental consequences that occur earlier in the cause-effect chain before the endpoint is reached, whereas the endpoint indicator examines the environmental impacts that occur at the end of the cause-effect chain. Consider a dangerous chemical's cause-and-effect chain. The discharge of the emission into groundwater may allow it to flow into the lake, where the chemical concentration may reach to a harmful level, killing fish and reducing the overall population of fish. In the end, the fish species might go extinct and having negative impact on the ither species that rely on the fish for food. Therefore, the midpoint indication had a reduced level of uncertainty in terms of accuracy, whereas the endpoint indicator required more modelling to understand the environmental mechanism but was easier to understand by decision makers. (Trompeta et al., 2016). Figure 2.6 shows the impact pathway from midpoint indicators to endpoint indicators.

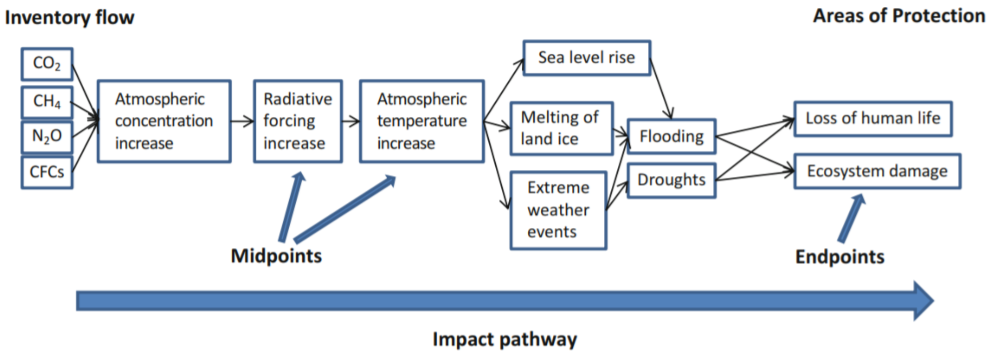


Figure 2.6: Impact Pathway (Hauschild and Huijbregts, n.d.)

2.5.4.2 ReCiPe Method

Many manufacturers employ the ReCiPe approach, which is one of the most extensively used LCIA methods. For the determination of both midpoint and endpoint characterization factors, the ReCiPe technique provides a harmonised implementation of cause-effect pathways. According to ReCiPe - PRé Sustainability (2016), the ReCiPe technique assesses 18 midpoint indicators and three endpoint indicators. Each midpoint and endpoint approach has components based on the three cultural viewpoints, which provided a set of options on topics such as time and expectations in order to avoid future damages for effective management or future technological advancement as shown in Figure 2.7.

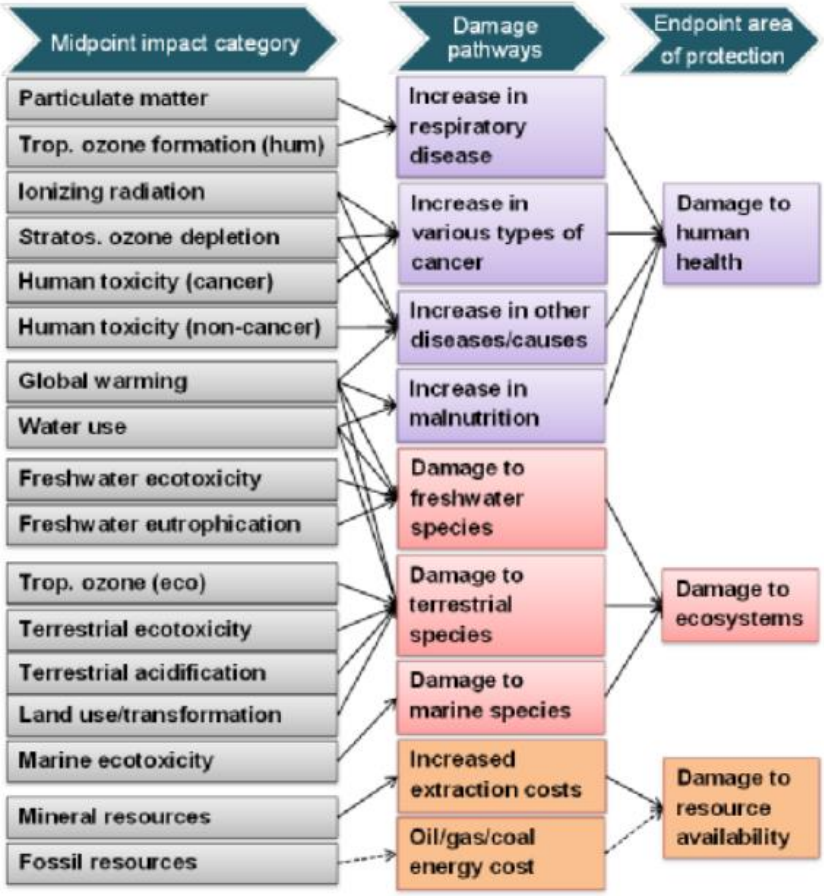


Figure 2.7: Overview of Structure ReCiPe (ReCiPe - PRé Sustainability, 2016)

2.5.5 Life Cycle Interpretation

Interpretation of the results is the most important and it is the final stage in the LCA. This stage entails combining the findings from the LCI and the LCIA.

The first step in interpreting the results of an LCA is to ensure that the data are accurate and that they correspond to the study's purpose. The identification of data elements was accomplished. Examining the sensitivity of these key data points, evaluating the study's completeness and consistency, and formulating conclusions and recommendations based on a thorough understanding of how the LCA was conducted and the results obtained (Skone, 2000). In a word, it is a significant contribution to an analysis, sensitivity analysis, and an analysis of uncertainty that results in a conclusion about whether the aim and scope's goals can be reached.

2.6 LCA Tools

The overall LCA can be very technical and long calculations if it is being conducted manually. For each stage of the life cycle framework, a sizable portion of the database's data is required to conduct a study. Therefore, the LCA tools and software is the solution to make the process easier. The basic LCA tool enable a LCA accordance with the ISO 14040 standards with qualifying the environmental issues of a product throughout its entire lifespan (David, 2011).

2.6.1 OpenLCA

OpenLCA is an open source and free software to do the LCA analysis. OpenLCA provides fast and reliable calculation for the LCA in very detail insights into the calculation and analysis results. It identified the primary drivers throughout the life cycle based on the process, flow, and impact categories and visualised the results with a map. Besides, openLCA is user-friendly, with a range of languages available, best-in-class import and export capabilities, and seamless integration of life cycle costing and social evaluation into the life cycle model.

Further, openLCA is versatile and able to meet the needs from different user group. OpenLCA is the world's largest database of data sets and databases for LCA software. Some of them are free and some of them are needed to be purchased. Ecoinvent is the world's largest open database of life cycle inventories which has cover the large variety of sectors and it is free to be used on the openLCA.

2.7 Limitation of LCA

The limitations of LCA might occasionally lead to distrust of the LCA results. LCA studies are depending on the assumptions and conditions that access the real world in a simplified model. The scope of research, functional unit, and system limits were specified by the LCA user during the LCA, which may differ from one study to the next, resulting in various LCA outcomes. Besides, performing an LCA study needed large amount of data. The study will not lead to solid conclusion if the data collection is poor or if it is not enough data are available (Yvonne van der Meer, 2018).

Further, LCA has always focused on the environmental impacts but neglecting the social impacts. The economic development, social development, and environmental protection which are act as the three pillars of sustainability are the components that affect each other in any real-world applications. Therefore, it is vital to thoroughly introduce both economic and social issues to improve the complexity of LCA. For instance, the carbon emission occurrence will be higher if the production activities are higher. Hence, It will have a long-term impact on people's social elements, with both beneficial and negative health consequences (SEMTRIO, 2021).

2.8 Summary

Throughout this chapter, to understand the purpose of life cycle, the life cycle of two selected biodegradable polymer which are PLA and PVA were descript in cradle-to-grave and cradle-to-gate manner. Besides, the production methods for both selected biodegradable polymers used in this worldwide were explained in the part of the conversion of raw materials and the manufacturing process. Further, there are total 4 stages to conduct the life cycle of a product. The software to conduct the LCA is named openLCA, and the database that is free to be accessed through openLCA is named Ecoinvent.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The International Organization of Standardization (ISO) has developed a standard methodology for life cycle assessment (LCA) that is defined in the ISO 14040 series (ISO). The four key stages of the LCA framework, including goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and life cycle interpretation, were carried out in this methodology to perform the LCA of the polylactic acid (PLA) and polyvinyl alcohol (PVA).

3.2 Project Flowchart

A project flowchart showed how a project being conducted in step-by-step. At the beginning stage, the introduction of the project was explained, and the research background was done. Therefore, the output which was the problem statements, and the objectives were generated to direct the overall project. Then, the literature review has been conducted. The research on the 2 types of biodegradable polymers which were polylactic acid (PLA) and polyvinyl alcohol (PVA), the availability of these biodegradable polymers in Malaysia, the life cycle assessment (LCA) and the LCA tools and methods were conducted in this section. Then, the goal and scope of the LCA was set in the methodology. During the methodology, the data was collected, and the results related to the environmental impacts were generated throughout the LCA. After that, the environmental impacts for both PLA and PVA were analysed to determine the availability these biodegradable polymers in Malaysia. Figure 3.1 showed the flowchart of this project.

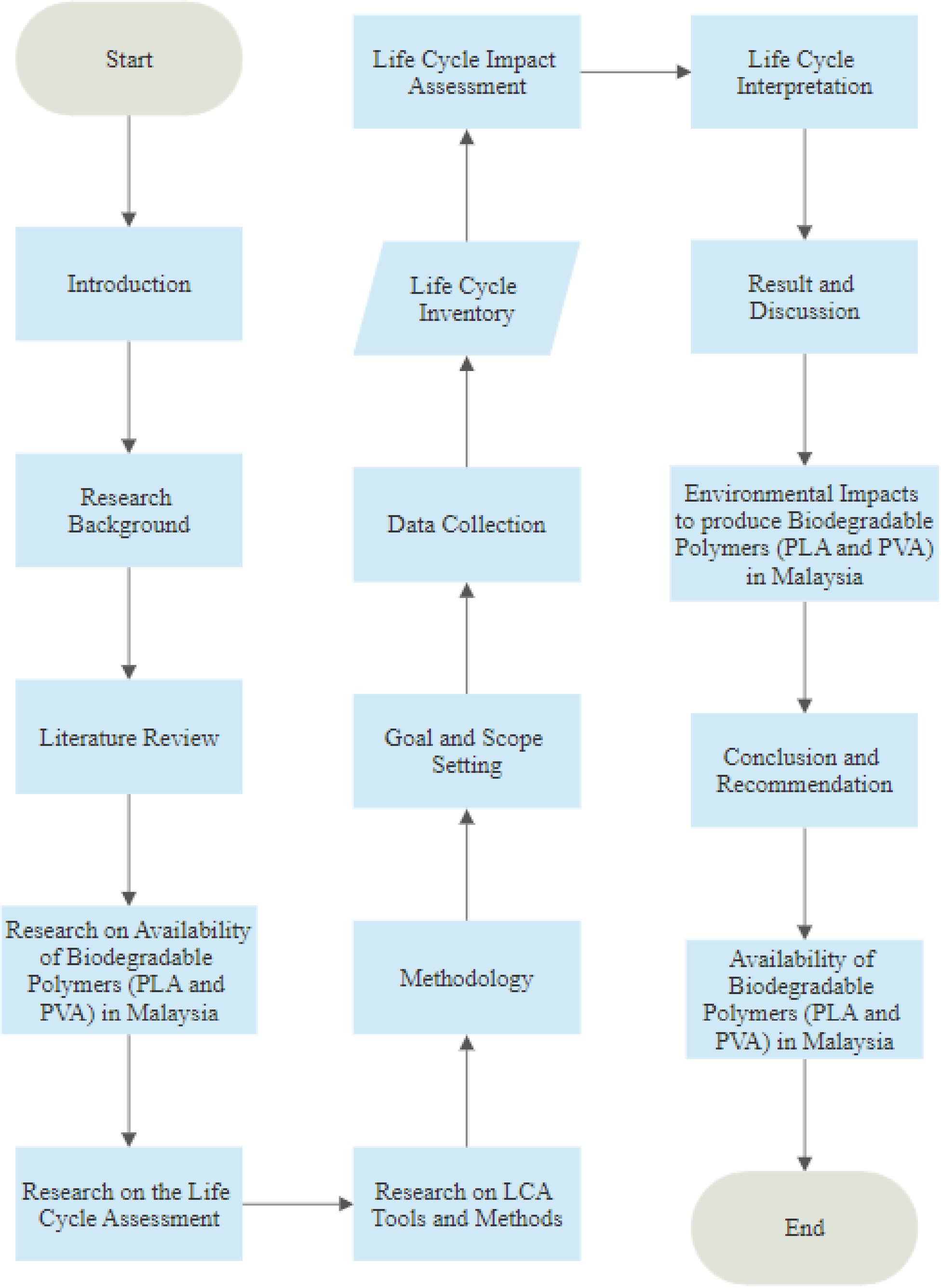


Figure 3.1: Project Flowchart

3.3 Life Cycle Assessment (LCA)

3.3.1 Goal and Scope

The goal of this LCA is to identify the environmental issues associated with the productions of polylactic acid biodegradable polymer (PLA) and polyvinyl alcohol biodegradable polymer (PVA) in Malaysia. The production method and the differences to produce both PLA and PVA were studied, and the production method selected to do the LCA was based on the appropriateness of environment and the geographical location of Malaysia. Besides, the study of the energy inputs associated with both forms of biodegradable polymers, as well as their embodied energy is one of the goals to access in the LCA.

In this project, PLA and PVA have a cradle-to-gate system boundary, which means that the processes only entail the extraction of raw materials till the transportation to the manufacturer of PLA and PVA resins. The raw materials that are manufactured in Malaysia was consider as one of the criteria to analyse the availability of the PLA and PVA in Malaysia. Therefore, the selection of the raw materials that available in Malaysia were prioritised, despite the possibility of low transportation impacts may happen if the raw materials were transported from the same manufacturer from other country.

Due to the limitation of dataset of the biological synthesis, the method chosen to produce the lactic acid was through the chemical synthesis. Therefore, the type of lactic acid produced from the chemical synthesis, which was the DL-lactic acid was the main raw material to produce the PLA in this project. The DL-lactic acid produced through the chemical synthesis was basically produced from the petrochemical resources which including the hydrogen cyanide (HCN) to the presence of lactonitrile. Malaysia as one of the crude oil productions in this worldwide, the targeted main raw material to produce the lactic acid in this project is petrochemical resources that can be produced in Malaysia (U.S. Energy Information Administration, 2022). However, there was found no manufacturer that produce the lactonitrile or even the HCN in Malaysia, so the DL-lactic acid in this project was set to purchase and import from other country.

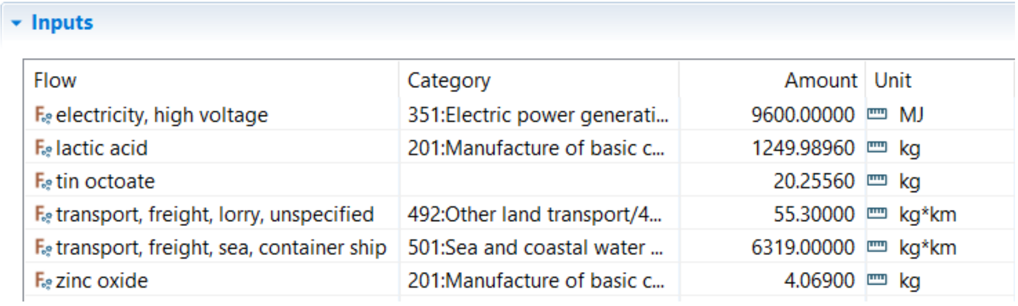
Petrochemicals industry is one of the leading industrial in Malaysia. There is found a few infrastructures that produce the raw materials of PVA, which are both ethylene and vinyl acetate in Malaysia (Petrochemical Industry in Malaysia, 2010). Ethylene was found more common to be produced compared to vinyl acetate in Malaysia. Therefore, the production method selected to produce the PVA in this project is starting from ethylene which will ease the PVA producer to get the raw material in Malaysia and to enhance the availability of PVA in Malaysia.

The ReCiPe method used in this methodology was Hierachist perspective which was using the 100 years of time horizon (ReCiPe 2016, 2017). Besides, the functional unit used in this study was 1 ton of PLA and PVA. For instance, how much the carbon footprint will be generated to produce 1 ton of PLA. In addition, the targeted location to produce the PLA and PVA in this project is located at Shah Alam, Selangor. To consider manufacturing the PLA and PVA in large amount, and to consider the raw materials or the chemicals, some are in powder form, and some are liquid form. The transportation for these chemicals in bulking, the method of shipment chosen were using lorry for the land transport and using container ship for the sea transport (Bilogistik, 2016).

3.3.2 Life Cycle Inventory (LCI)

The input and output of the LCA will be listed in this section. The inputs to do the LCA were including the raw materials, catalyst, energy consumption and transportation. For the outputs was the substance or object that after the inputs went through a process. The databases were selected from Ecoinvent 3.8 to conduct this analysis (Wernet et al., 2016).

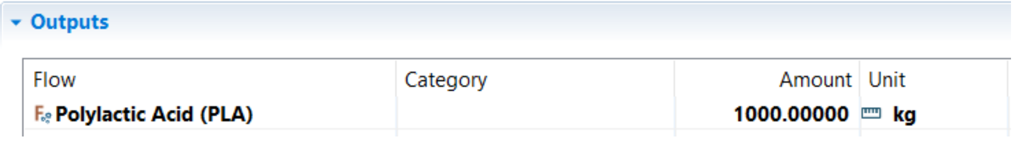
Figure 3.2 and Figure 3.3 showed the inputs and outputs to produce 1 tons of PLA in openLCA (GreenDelta, 2006). The raw material in the inputs section is DL-lactic acid. The catalysts were tin octoate and zinc oxide. Lorry was selected for the land transportation and the container ship was selected for the sea transportation. To consider the high voltage required for the large production of PLA, the dataset of electricity with high voltage was selected for the energy consumption in this LCA.



Inputs

Flow	Category	Amount	Unit
electricity, high voltage	351:Electric power generati...	9600.00000	MJ
lactic acid	201:Manufacture of basic c...	1249.98960	kg
tin octoate		20.25560	kg
transport, freight, lorry, unspecified	492:Other land transport/4...	55.30000	kg*km
transport, freight, sea, container ship	501:Sea and coastal water ...	6319.00000	kg*km
zinc oxide	201:Manufacture of basic c...	4.06900	kg

Figure 3.2: Inputs of Polylactic Acid (PLA) (GreenDelta, 2006)

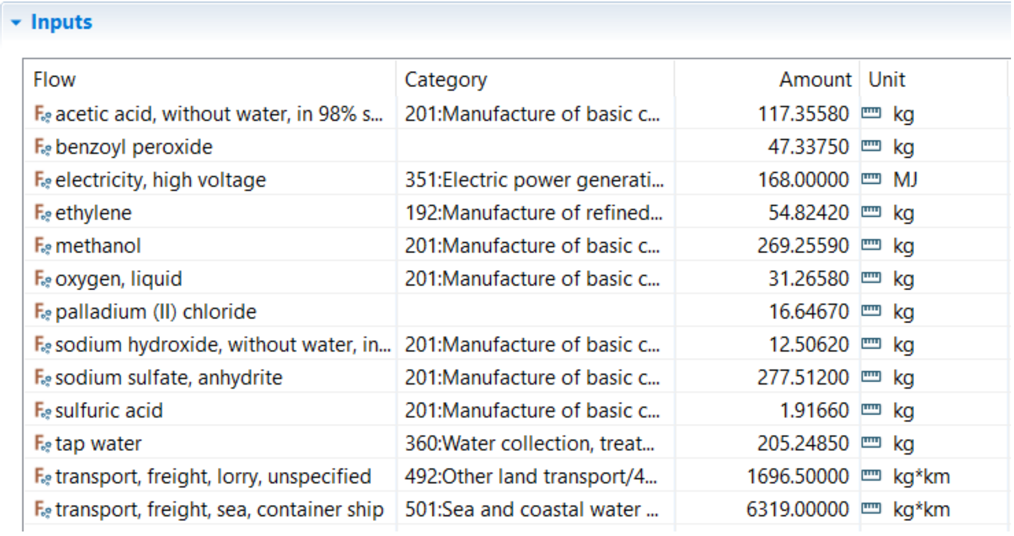


Outputs

Flow	Category	Amount	Unit
Polylactic Acid (PLA)		**1000.00000**	**kg**

Figure 3.3: Outputs of Polylactic Acid (PLA) (GreenDelta, 2006)

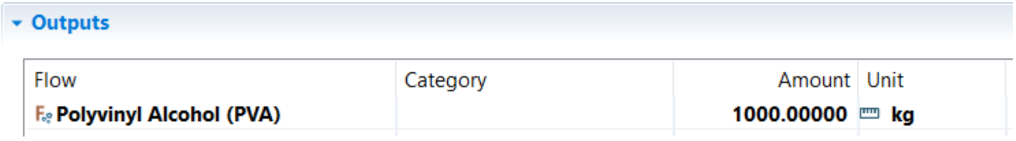
Figure 3.4 and Figure 3.5 showed the inputs and outputs to produce 1 ton of PVA in openLCA (GreenDelta, 2006). The monomer in the inputs section is ethylene. The catalysts and initiator were acetic acid, benzoyl peroxide, methanol, oxygen, palladium (II) chloride, sodium hydroxide, sodium sulphate, sulfuric acid and water. Lorry was selected for the land transportation and the container ship was selected for the sea transportation. To consider the high voltage required for the large production of PVA, the dataset of electricity with high voltage was selected for the energy consumption in this LCA.



Inputs

Flow	Category	Amount	Unit
acetic acid, without water, in 98% s...	201:Manufacture of basic c...	117.35580	kg
benzoyl peroxide		47.33750	kg
electricity, high voltage	351:Electric power generati...	168.00000	MJ
ethylene	192:Manufacture of refined...	54.82420	kg
methanol	201:Manufacture of basic c...	269.25590	kg
oxygen, liquid	201:Manufacture of basic c...	31.26580	kg
palladium (II) chloride		16.64670	kg
sodium hydroxide, without water, in...	201:Manufacture of basic c...	12.50620	kg
sodium sulfate, anhydrite	201:Manufacture of basic c...	277.51200	kg
sulfuric acid	201:Manufacture of basic c...	1.91660	kg
tap water	360:Water collection, treat...	205.24850	kg
transport, freight, lorry, unspecified	492:Other land transport/4...	1696.50000	kg*km
transport, freight, sea, container ship	501:Sea and coastal water ...	6319.00000	kg*km

Figure 3.4: Inputs of Polyvinyl Alcohol (PVA) (GreenDelta, 2006)



Flow	Category	Amount	Unit
Polyvinyl Alcohol (PVA)		**1000.00000**	**kg**

Figure 3.5: Outputs of Polyvinyl Alcohol (PVA) (GreenDelta, 2006)

3.3.2.1 Raw Materials and Processes

In this project, the DL-lactic acid was main raw material to produce the PLA after the hydrolysing of lactonitrile using chemical synthesis. To do the PLA synthesis, the method chosen was through the ring opening polymerization (ROP). In this process, there are two steps being taken, the lactic acid ($C_3H_6O_3$) was depolymerized to form the lactide ($C_3H_5O_3$) then polymerized into PLA ($(C_3H_4O_2)_n$ as shown in the process below. During the process of depolymerization, the catalyst used was zinc oxide (ZnO) to form the lactide while the tin octoate ($Sn(Oct)_2$)/$C_{16}H_{30}O_4Sn$ was used as the catalyst for the process of ROP.

$$C_3H_6O_3 + ZnO \xrightarrow{Depolymerization} C_3H_5O_3 + Sn(Oct)_2 \xrightarrow{ROP} (C_3H_4O_2)_n$$

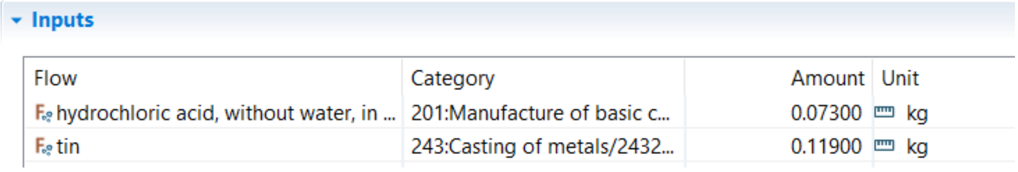
Due to the limitation of dataset of tin octoate in Ecoinvent 3.8, the dataset of tin octoate was generated in openLCA by adding the tin protoxide (SnO) and isocaprylic acid ($C_8H_{16}O_2$) (GreenDelta, 2006; Wernet et al., 2016). Based on Pan et al. (2011), the chemical equation of the formation of tin protoxide and tin octoate was shown as below.

$$Sn + 2HCI \rightarrow SnCl_2 + H_2$$

$$SnCl_2 + 2NaHCO_3 \rightarrow SnO + 2NaCl + H_2O + 2CO_2$$

$$SnO + 2C_7H_{15}COOH \rightarrow (C - H_{15}COO)_2Sn + H_2O$$

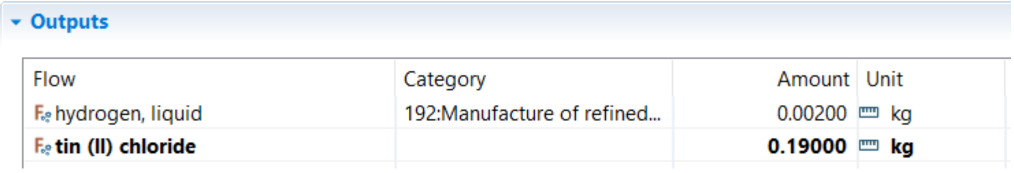
Figure 3.6 and Figure 3.7 shown the formation of the tin (II) chloride ($SnCl_2$) by following in the first equation using openLCA (GreenDelta, 2006). The inputs were including hydrochloric acid (HCI) and tin (Sn) and the outputs were including the hydrogen (H) and tin (II) chloride.



Inputs

Flow	Category	Amount	Unit
hydrochloric acid, without water, in ...	201:Manufacture of basic c...	0.07300	kg
tin	243:Casting of metals/2432...	0.11900	kg

Figure 3.6: Inputs of Tin (II) Chloride ($SnCl_2$) (GreenDelta, 2006)

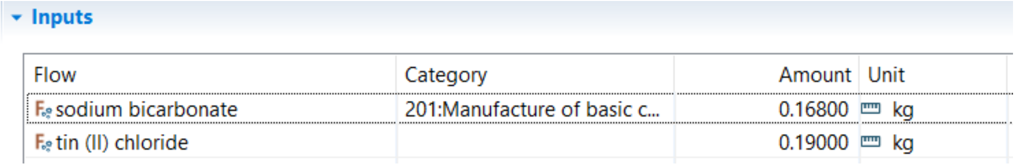


Outputs

Flow	Category	Amount	Unit
hydrogen, liquid	192:Manufacture of refined...	0.00200	kg
tin (II) chloride		**0.19000**	**kg**

Figure 3.7: Outputs of Tin (II) Chloride ($SnCl_2$) (GreenDelta, 2006)

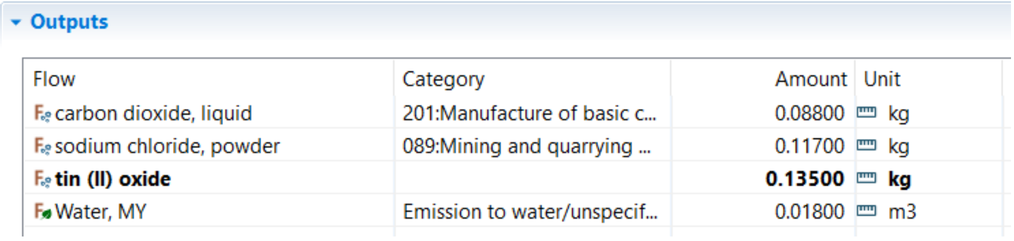
Figure 3.8 and Figure 3.9 shown the formation of the tin (II) oxide (SnO) by following on the second equation using openLCA (GreenDelta, 2006). The inputs to form tin (II) oxide were including sodium bicarbonate ($NaHCO_3$) and tin (II) chloride while for the outputs were including sodium chloride (NaCl), water (H_2O) and carbon dioxide (CO_2) and tin (II) oxide.



Inputs

Flow	Category	Amount	Unit
sodium bicarbonate	201:Manufacture of basic c...	0.16800	kg
tin (II) chloride		0.19000	kg

Figure 3.8: Inputs of Tin (II) Oxide (SnO) (GreenDelta, 2006)

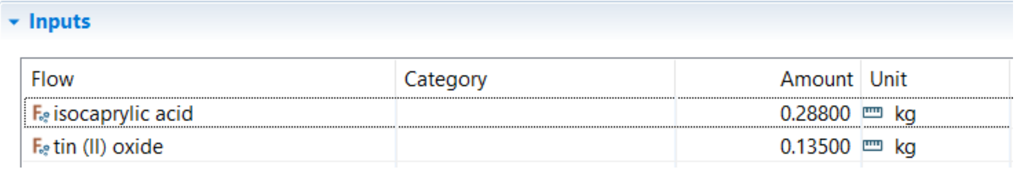


Outputs

Flow	Category	Amount	Unit
carbon dioxide, liquid	201:Manufacture of basic c...	0.08800	kg
sodium chloride, powder	089:Mining and quarrying ...	0.11700	kg
tin (II) oxide		**0.13500**	**kg**
Water, MY	Emission to water/unspecif...	0.01800	m3

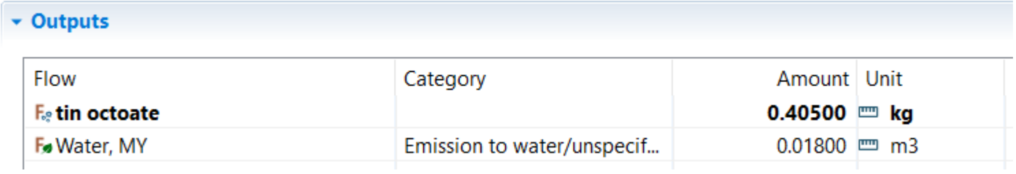
Figure 3.9: Outputs of Tin (II) Oxide (SnO) (GreenDelta, 2006)

Lastly, to form the tin octoate using openLCA, the inputs which were tin (II) oxide and isocaprylic acid were inserted as shown in Figure 3.10, and the outputs which were in the form of tin octoate ($C_{16}H_{30}O_4Sn$) and water (H_2O) were inserted as shown in Figure 3.11 by following the third equation (GreenDelta, 2006).



Flow	Category	Amount	Unit
isocaprylic acid		0.28800	kg
tin (II) oxide		0.13500	kg

Figure 3.10: Inputs of Tin Octoate ($Sn(Oct)_2$) (GreenDelta, 2006)



Flow	Category	Amount	Unit
tin octoate		**0.40500**	**kg**
Water, MY	Emission to water/unspecif...	0.01800	m3

Figure 3.11: Outputs of Tin Octoate ($Sn(Oct)_2$) (GreenDelta, 2006)

Figure 3.12 shows the flow diagram to produce the PLA in this methodology. To conduct the life cycle of PLA in this project, the dataset for DL-lactic acid and ZnO were directly taken from the Ecoinvent 3.8 (Wernet et al., 2016). Meanwhile, the datasets for $Sn(Oct)_2$, $SnCl_2$ and SnO were newly created in openLCA (GreenDelta, 2006).

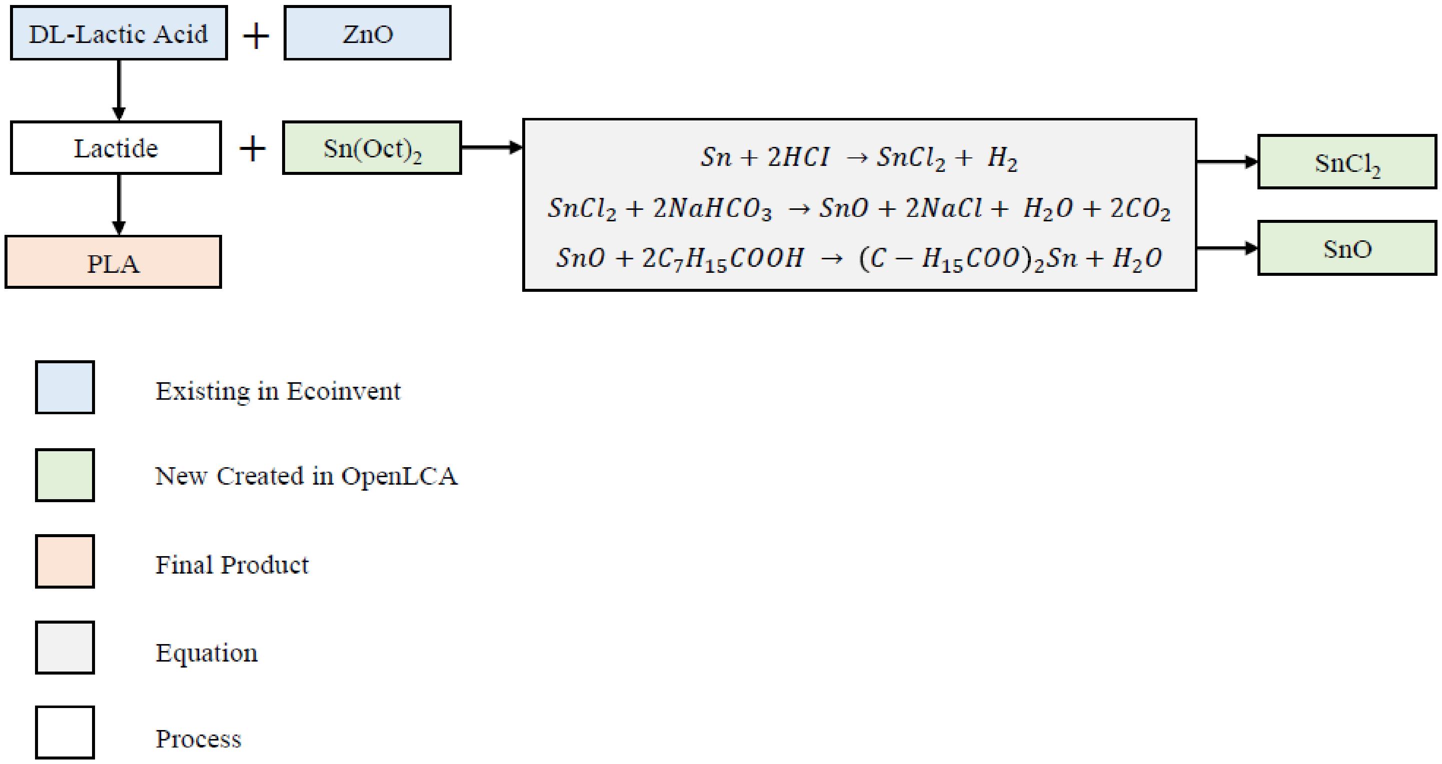


Figure 3.12: Flow diagram to Produce PLA

Next, to produce the PVA, ethylene was the main raw material selected in this project due to the easy accessibility of this material in Malaysia. There were three stages for the process to form the PVA from ethylene. The process from the ethylene (C_2H_4) to vinyl acetate ($C_4H_6O_2$) was the first stage. From the vinyl acetate to polyvinyl acetate ($(C_4H_6O_2)_n$ was the second stage. Then, the third stage was from the polyvinyl acetate to PVA (C_2H_4O).

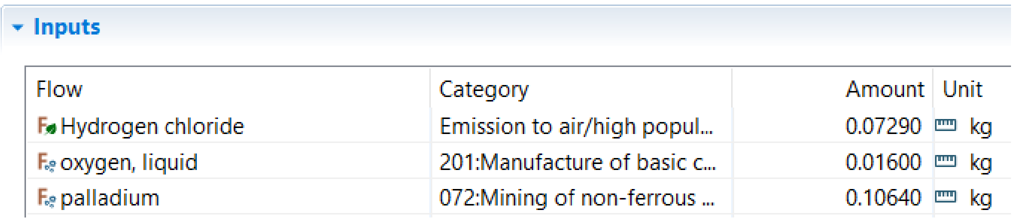
In the first stage, from ethylene, by adding the acetic acid ($C_2H_4O_2$) and oxygen (O_2) to form the vinyl acetate and water (H_2O). Based on Contreras et al. (2008), the chemical equation to form the vinyl acetate was shown as below.

$$C_2H_4 + C_2H_4O_2 + \frac{1}{2}O_2 \xrightarrow{Palladium\ Catalyst} C_4H_6O_2 + H_2O$$

In this stage, palladium-based catalyst was selected as the catalyst to transfer the ethylene to vinyl acetate. Palladium based catalyst has been proved to be the best option for this process and has been applied in this industry for the last thirty years (Contreras et al., 2008). The commonly used palladium catalyst, which is the palladium (II) chloride ($PdCl_2$) was the catalyst selected for this process in this project (Copelin and Falls, 1971). Due to the limitation of dataset of palladium (II) chloride in Ecoinvent 3.8, the dataset of palladium (II) chloride was generated in openLCA by adding the palladium (Pd), hydrogen chloride (HCl) and oxygen (O_2) (GreenDelta, 2006; Wernet et al., 2016). Based on Chemicalbook (2019), the chemical equation of the formation of palladium (II) chloride was shown as below.

$$Pd + 2HCl + \frac{1}{2}O_2 \rightarrow PdCl_2 + H_2O$$

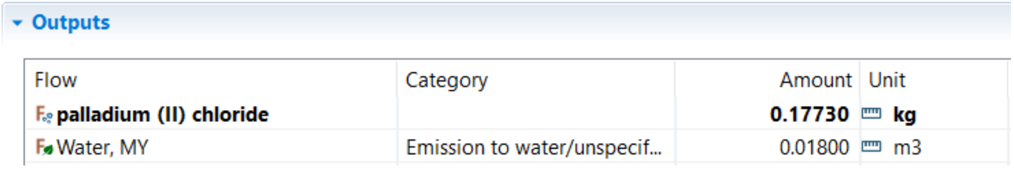
Figure 3.13 showed the inputs of palladium (II) chloride in openLCA which including the palladium, hydrogen chloride and oxygen (GreenDelta, 2006). Figure 3.14 shows the outputs which including palladium (II) chloride and water (H_2O).



Inputs

Flow	Category	Amount	Unit
Hydrogen chloride	Emission to air/high popul...	0.07290	kg
oxygen, liquid	201:Manufacture of basic c...	0.01600	kg
palladium	072:Mining of non-ferrous ...	0.10640	kg

Figure 3.13: Inputs of Palladium Chloride ($PdCl_2$) (GreenDelta, 2006)



Outputs

Flow	Category	Amount	Unit
palladium (II) chloride		**0.17730**	**kg**
Water, MY	Emission to water/unspecif...	0.01800	m3

Figure 3.14: Outputs of Palladium Chloride ($PdCl_2$) (GreenDelta, 2006)

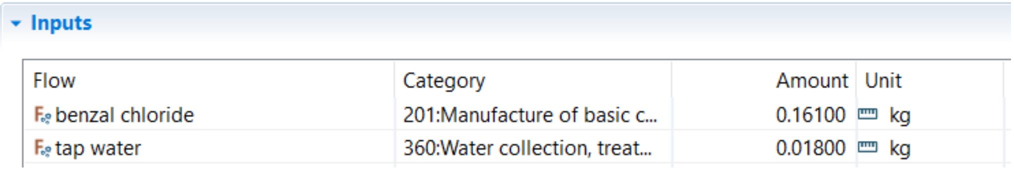
Coming to the second stage, it was the process from vinyl acetate ($C_4H_6O_2$), go through the free radical vinyl polymerization, to form the polyvinyl acetate $(C_4H_6O_2)_n$ (Britannica, 2020). The suitable initiator for the free radical vinyl polymerization process were including 2,2'-azo-bis-isobutyronitrile (AIBN), benzoyl peroxide and lauroyl peroxide (Yousef, 2016). Due to the limitation of the dataset in Ecoinvent 3.8, the benzoyl peroxide ($BPOC_{14}H_{10}O_4$) was selected as the initiator for this process in this project (Wernet et al., 2016).

Benzoyl peroxide was produced by the reaction of benzoyl chloride (C_7H_5ClO) with hydrogen peroxide (H_2O_2). In Ecoinvent 3.8, there was lack of dataset for the benzoyl chloride, yet the reaction of benzotrichchloride ($C_7H_5Cl_3$) with water (H_2O) produced the benzoyl chloride (Wernet et al., 2016). Benzotrichchloride is not listed in Ecoinvent 3.8, but benzal chloride ($C_7H_6Cl_2$) is, and benzal chloride is considered a reasonable proxy for benzotrichchloride (Wernet et al., 2016; Hill and Norton, 2019). The chemical equation to form the benzoyl chloride and benzoyl peroxide was shown as below.

$$C_6H_5CCl_3 + H_2O \rightarrow C_6H_5COCl + 2HCl$$

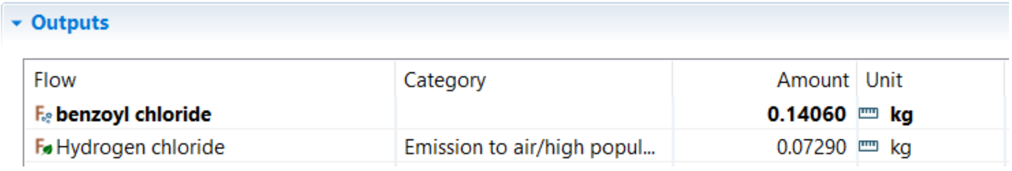
$$2C_6H_5COCl + H_2O_2 + 2NaOH \rightarrow (C_6H_5CO)_2O_2 + 2NaCl + 2H_2O$$

Figure 3.15 shows the inputs of benzoyl chloride in openLCA which including the benzal chloride and water (GreenDelta, 2006). Figure 3.16 shows the outputs which including benzoyl chloride and hydrogen chloride.



Flow	Category	Amount	Unit
benzal chloride	201:Manufacture of basic c...	0.16100	kg
tap water	360:Water collection, treat...	0.01800	kg

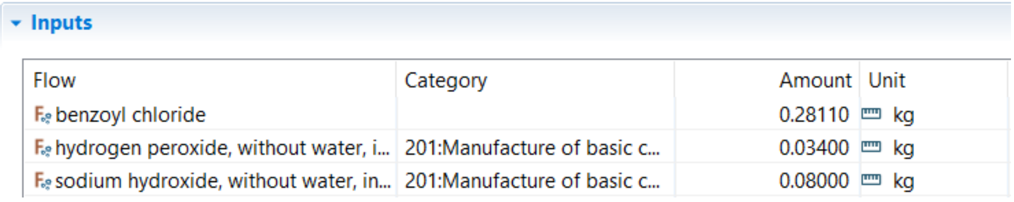
Figure 3.15: Inputs of Benzoyl Chloride (C_7H_5ClO) (GreenDelta, 2006)



Flow	Category	Amount	Unit
benzoyl chloride		**0.14060**	**kg**
Hydrogen chloride	Emission to air/high popul...	0.07290	kg

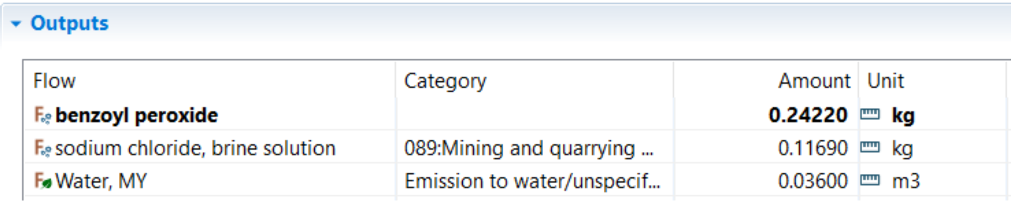
Figure 3.16: Outputs of Benzoyl Chloride (C_7H_5ClO) (GreenDelta, 2006)

Figure 3.17 shows the inputs of benzoyl peroxide in openLCA which including the benzoyl chloride, hydrogen peroxide and sodium hydroxide (NaOH) (GreenDelta, 2006). Figure 3.18 shows the outputs which including benzoyl peroxide, sodium chloride (NaCl) and water.



Flow	Category	Amount	Unit
benzoyl chloride		0.28110	kg
hydrogen peroxide, without water, i...	201:Manufacture of basic c...	0.03400	kg
sodium hydroxide, without water, in...	201:Manufacture of basic c...	0.08000	kg

Figure 3.17: Inputs of Benzoyl Peroxide ($C_{14}H_{10}O_4$) (GreenDelta, 2006)



Flow	Category	Amount	Unit
benzoyl peroxide		**0.24220**	**kg**
sodium chloride, brine solution	089:Mining and quarrying ...	0.11690	kg
Water, MY	Emission to water/unspecif...	0.03600	m3

Figure 3.18: Outputs of Benzoyl Peroxide ($C_{14}H_{10}O_4$) (GreenDelta, 2006)

Then coming to the third stage, the PVA (C_2H_4O) was formed from the polyvinyl acetate through the alkaline hydrolysis which was usually used as an industrial scale. The alkaline catalyst in alkaline hydrolysis may be employed in alcoholysis reaction. To coagulate the emulsion polyvinyl acetate into solid polyvinyl acetate, the sodium sulphate salt (Na_2SO_4), water (H_2O), methanol (CH_3OH) and sulfuric acid (H_2SO_4) were needed for the process. Then, the methanol and sodium hydroxide (NaOH) were needed for the alcoholysis process to form the PVA (Cecelia and Saad, 2008).

Figure 3.19 shows the flow diagram to produce the PVA in this methodology. To conduct the life cycle of PVA in this project, the dataset for ethylene, acetic acid, O_2, Na_2SO_4, H_2O, CH_3OH, H_2SO_4 and NaOH were directly taken from the Ecoinvent 3.8 (Wernet et al., 2016). Meanwhile, the datasets for PdCl2, benzoyl peroxide and benzoyl chloride were newly created in openLCA (GreenDelta, 2006).

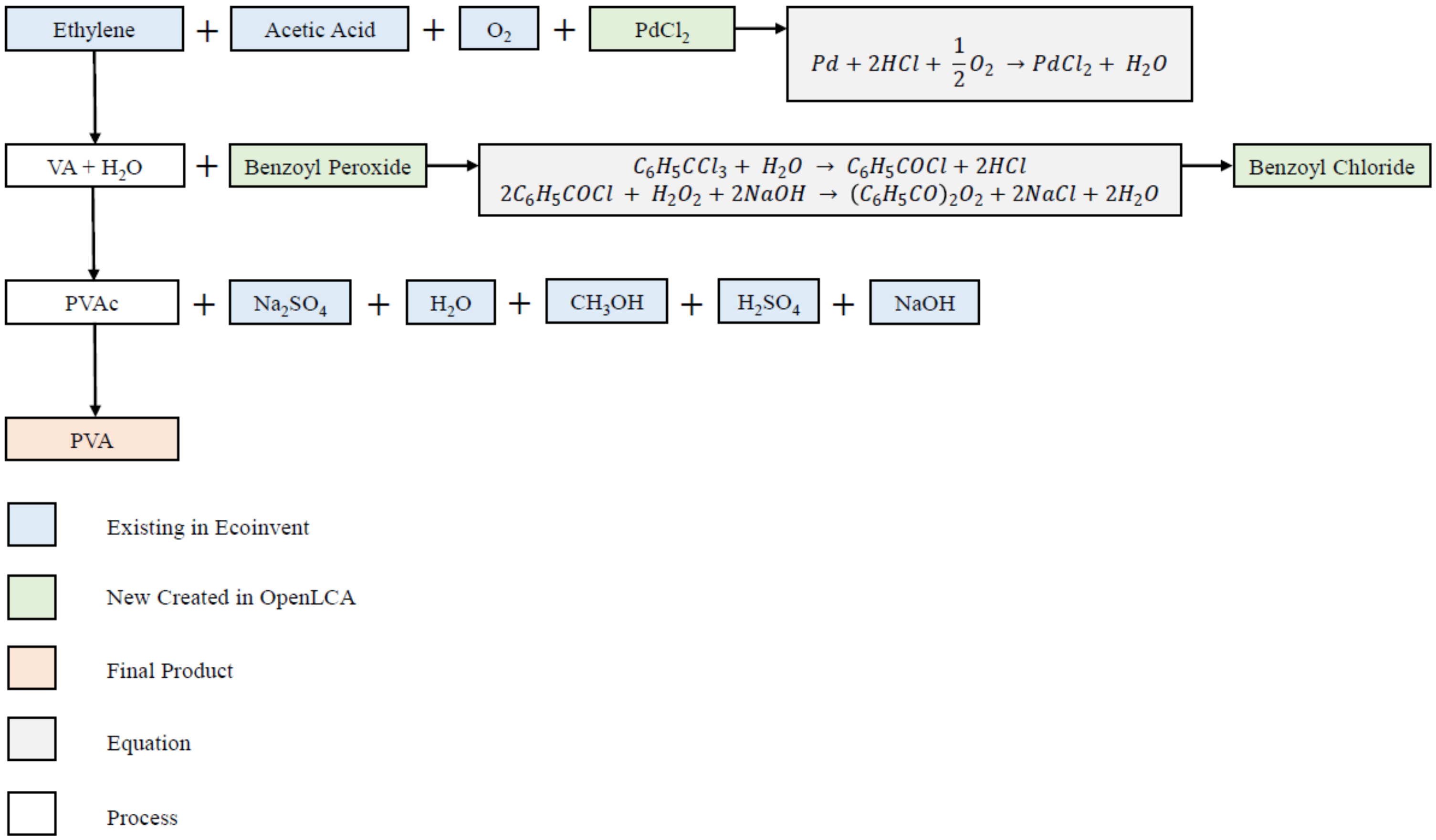


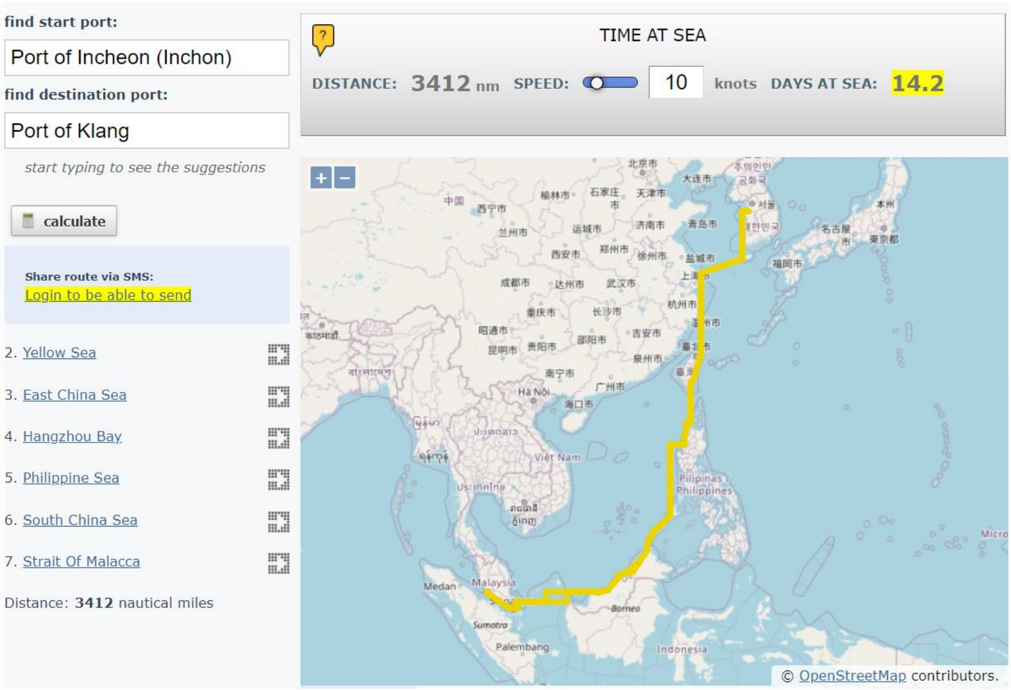
Figure 3.19: Flow diagram to Produce PVA

3.3.2.2 Transportation

In this project, the raw material for PLA which is the DL-lactic acid, was set to purchase from Sigma-Aldrich which their nearest warehouse is located at Gangnam-gu, Seoul to the location set in this project, Shah Alam, Selangor. During the process of depolymerization, the catalyst used which is zinc oxide to form the lactide and the tin octoate for the process of ROP were also set to purchase from Sigma-Aldrich in this project.

For the PVA, the palladium (II) chloride and benzoyl peroxide awere also set to purchase from Sigma-Aldrich, while the other materials are available in Malaysia, and set to purchase in Malaysia. The ethylene and methanol were set to purchase from Petronas Chemicals Olefins Sdn Bhd, acetic acid was set to purchase from INEOUS PCG Acetyls Sdn Bhd, oxygen was set to purchase from Iwatani Malaysia Sdn Bhd, sodium sulfate was set to purchase from Classic Chemicals Sdn Bhd, sulfuric acid was set to purchase from See Sen Chemical Berhad and the sodium hydroxide was set to purchase from Malay-Sino Chemical Industries Sdn Bhd.

To consider the transportation of these chemicals in bulking, the method of shipment chosen were using lorry for the road transport and using lorry for the land transport. For the raw materials set to purchase from Sigma-Aldrich, the chemicals were transported from Gangnam-gu, Seoul to the seaport at Incheon, Seoul with the distance of 37.7km. Then using sea transport which is container ship for the oversea shipment from Incheon, Seoul to Port Klang, Selangor with the distance of 3412nm as shown in Figure 3.20 and using lorry to ship the chemicals from Port Klang, Selangor to Shah Alam, Selangor with the distance of 17.6km.



find start port:
Port of Incheon (Inchon)
find destination port:
Port of Klang
start typing to see the suggestions

Share route via SMS:
Login to be able to send

2. Yellow Sea
3. East China Sea
4. Hangzhou Bay
5. Philippine Sea
6. South China Sea
7. Strait Of Malacca

Distance: **3412** nautical miles

TIME AT SEA

DISTANCE: 3412 nm SPEED: 10 knots DAYS AT SEA: 14.2

© OpenStreetMap contributors.

Figure 3.20: Distance for oversea shipment from Incheon, Seoul to Port Klang, Selangor

Table 3.1 shows the manufacturer, the factory’s location, the transport method, and the distance travelled for each material to the location set in this project.

Table 3.1: Details of the transportation for the raw materials

Biodegradable Polymer	**Material**	**Manufacturer**	**Factory's Location**	**Transport Method**	**Distance (km)**
Polylactic Acid (PLA)	DL-Lactic Acid	Sigma-Aldrich Inc.	Gangnam-gu, Seoul	Lorry	55.3
	Zinc Oxide			Container Ship	6319
	Tin Octoate				
Polyvinyl Alcohol (PVA)	Palladium (II) Chloride	Sigma-Aldrich Inc.	Gangnam-gu, Seoul	Lorry	55.3
	Benzoyl Peroxide			Container Ship	6319
	Ethylene	PETRONAS Chemicals Olefins Sdn Bhd	Kertih, Terengganu	Lorry	361
	Methanol				
	Acetic Acid	INEOUS PCG Acetyls Sdn Bhd	Kertih, Terengganu	Lorry	361
	Oxygen	Iwatani Malaysia Sdn Bhd	Senai, Johor	Lorry	328
	Sodium Sulfate	Classic Chemicals Sdn Bhd	Shah Alam, Selangor	Lorry	7.2
	Sulfuric Acid	See Sen Chemical Berhad	Pasar Gudang, Johor	Lorry	378
	Sodium Hydroxide	Malay-Sino Chemical Industries Sdn Bhd	Lahat, Ipoh, Perak	Lorry	206

3.3.2.3 Energy Consumption

The energy consumption to produce the PLA from lactic acid was found in 9600 MJ/ton (Zhao et al., 2018). Meanwhile, the energy consumption to produce the PVA from ethylene was found in 168 MJ/ton which 81% of the energy was consumed during the vinyl acetate production (Anthony et al., 2017).

3.3.2.4 Dataset in Ecoinvent 3.8

The compilation of the dataset used in this project was listed in this section. All the datasets were taken from the same database which is Ecoinvent 3.8 (Wernet et al., 2016). Therefore, some of the datasets were repeatedly used for PLA and PVA. The dataset for the transportation for the lorry and container ship, the energy consumption, and the sodium chloride for the PLA and PVA were same.

The dataset of lactic acid, zinc oxide, sodium bicarbonate, carbon dioxide, hydrochloric acid, tin, and hydrogen were used to produce PLA. The dataset of ethylene, acetic acid, oxygen, sodium sulphate, water, methanol, sulfuric acid, sodium hydroxide, palladium, hydrogen peroxide and benzoyl chloride were used to produce PVA. Table 3.2 shows the dataset information from Ecoinvent 3.8 (Wernet et al., 2016).

Table 3.2: Dataset Information from Ecoinvent 3.8 (Wernet et al., 2016)

Inputs/Outputs	Relation	Dataset	Dataset Description
Transport, Lorry	(PLA) and (PVA)	market for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Consequential, U - ROW	• This dataset is limited to the movement of goods. • The vehicle is diesel-powered and provides a fleet average for various lorry classes as well as EURO classes. • This service aggregates transportation data calculated using an average load factor, including empty return trips.
Transport, Container Ship	(PLA) and (PVA)	transport, freight, sea, container ship | transport, freight, sea, container ship | Consequential, U - GLO	• The dataset encompasses the entire transportation life cycle, from the design and construction of the container ship to the transportation of bulk freight and the construction of the port.
Energy Consumption	(PLA) and (PVA)	electricity production, oil | electricity, high voltage | Consequential, U - MY	• This dataset depicts the generation of high voltage electricity at a grid-connected 500 MW oil power plant in Malaysia in 2012. • Weighting was made with electricity production data in those countries based on IEA/OECD 2010.

Table 3.2: (Continued)

Lactic Acid	(PLA)	lactic acid production | lactic acid | Consequential, U – ROW	• The process "lactic acid, at plant, GLO" is modelled to produce lactic acid from acetaldehyde. • The technology used for this dataset is hydrolysis of lactonitrile.
Zinc Oxide	(PLA)	zinc oxide production | zinc oxide | Consequential, U – ROW	• This dataset represents the production of 1 kg of solid zinc oxide powder. • This dataset represents the production of zinc oxide out of secondary zinc materials by means of the indirect way.
Sodium Bicarbonate	(PLA) SnO	sodium bicarbonate, to generic market for neutralising agent | sodium bicarbonate | Consequential, U – GLO	• The technology used in this dataset is soda production, solvay process.
Carbon Dioxide	(PLA) SnO	carbon dioxide production, liquid | carbon dioxide, liquid | Consequential, U – ROW	• The technology used in this dataset involves extracting carbon dioxide from waste gas streams from various manufacturing processes using a 15-20% monoethanolamine (MEA) solution, followed by purification and liquefaction, all of which are powered by electricity.

Table 3.2: (Continued)

Sodium Chloride	(PLA) SnO, (PVA) Benzoyl Peroxide	sodium chloride production, powder | sodium chloride, powder | Consequential, U - ROW	• Data from a single European solution mining site were used to approximate the European mix of 41% solution mining and 59% rock salt mining. • The data is assumed to be representative of the global production. • Certain values are derived from data from a large chemical factory in Germany.
Hydrochloric Acid	(PLA) $SnCl_2$	hydrochloric acid production, from the reaction of hydrogen with chlorine | hydrochloric acid, without water, in 30% solution state | Consequential, U - ROW	• This dataset represents the production of 1 kg of hydrochloric acid from chlorine and hydrogen combustion.
Tin	(PLA) $SnCl_2$	tin production | tin | Consequential, U - ROW	• The Ausmelt Furnace's technology for smelting tin concentrates is based on a patent developed by Australia's Commonwealth Scientific and Industrial Research Organization CSIRO.

Table 3.2: (Continued)

Hydrogen	(PLA) $SnCl_2$	hydrogen cracking, APME | hydrogen, liquid | Consequential, U - ROW	• Data are derived from the European plastics industry's Eco-profiles (PlasticsEurope). • The technology used in this dataset is the production during cracking of naphtha.
Ethylene	(PVA)	ethylene production, average | ethylene | Consequential, U - ROW	• Data are derived from the European plastics industry's Eco-profiles (PlasticsEurope). • The technology used in this dataset is through the product out of steam cracking of naphtha.
Acetic Acid	(PVA)	acetic acid production, product in 98% solution state | acetic acid, without water, in 98% solution state | Consequential, U - ROW	• The process is analogous to the Celanese process (which is an optimised version of the Monsanto process), in which methanol reacts with carbon monoxide through a rhodium catalyst. • It is assumed that 50% of the off gas is burned as fuel, resulting in lower VOC emissions and increased CO_2 emissions.

Table 3.2: (Continued)

Oxygen	(PVA) $PdCl_2$	air separation, cryogenic | oxygen, liquid | Consequential, U - ROW	• Air is primarily composed of nitrogen and oxygen, but it also contains trace amounts of water vapour, argon, carbon dioxide, and other gases in trace amounts (e.g., noble gases). • Cryogenic air separation is the process of purifying and liquefying various components of air, most notably oxygen, nitrogen, and argon.
Sodium Sulfate	(PVA)	sodium sulfate production, from natural sources | sodium sulfate, anhydrite | Consequential, U - ROW	• This dataset simulates the exploitation of sodium sulphate in its anhydrous state. • The processes by which sodium sulphate is produced from natural resources, such as basins where water evaporates naturally during hot weather. • The precipitated sodium sulphate minerals are then removed from these basins for further treatment.

Table 3.2: (Continued)

Water	(PVA) Benzoyl Chloride	tap water production, conventional treatment | tap water | Consequential, U - ROW	• The conventional method of treatment entails coagulation and decantation, as well as filtration and disinfection. • Additional treatment methods such as oxidation (ultraviolet radiation, ozone) and pH and alkalinity adjustment may be used in some plants.
Methanol	(PVA)	methanol production | methanol | Consequential, U - GLO	• This dataset represents the production of methanol using the steam reforming process. • The dataset includes the consumption of raw materials and energy, estimated catalyst use, emissions to air and water from the process, as well as the infrastructure use. • The use of CO2 is not included and the hydrogen that is produced during the process is assumed to be burned in the furnace.
Sulfuric Acid	(PVA)	sulfuric acid production | sulfuric acid | Consequential, U - ROW	• This dataset is a weighted average from the respective regional datasets.

Table 3.2: (Continued)

Sodium Hydroxide	(PVA) Benzoyl Peroxide	sodium hydroxide to generic market for neutralising agent | sodium hydroxide, without water, in 50% solution state | Consequential, U - GLO	• The technology used in this dataset is based on technology validity of datasets producing sodium hydroxide in chlor-alkali electrolysis.
Palladium	(PVA) $PdCl_2$	market for palladium | palladium | Consequential, U - GLO	• The data used is mainly based on a LCA study for auto catalysts in Germany.
Hydrogen Peroxide	(PVA) Benzoyl Peroxide	hydrogen peroxide production, product in 50% solution state | hydrogen peroxide, without water, in 50% solution state | Consequential, U - ROW	• The autooxidation (AO) or anthraquinone process is the most frequently used method for producing hydrogen peroxide.
Benzal Chloride	(PVA) Benzoyl Chloride	benzal chloride production | benzal chloride | Consequential, U - ROW	• Stoechiometric calculations are used to model raw materials. • Energy consumption is estimated using data from the literature.

3.3.3 Life Cycle Impact Assessment (LCIA)

In LCIA, the further examination of the potential environmental impacts from the LCI result was conducted in this section. In this methodology, the analysis of environmental impacts was including the midpoint and endpoint methods and evaluated by using the ReCiPe 2016 (H) approach. Same, the LCIA of this assessment was conducted using the openLCA with the datasets found at Ecoinvent 3.8 (GreenDelta, 2006; Wernet et al., 2016).

During the LCA analysis, the impact categories in the openLCA was chosen to determine the technique used to evaluate the environmental impacts. Then the LCI results will be arranged into their relevant impact categories at the classification stage. After that, the scores of each environmental impact were generated, the higher the score of the environmental impact, the greater the emission in that category. In addition, the relative weight between the previous phase and the environmental impacts were also generated.

There is total 13 indicators generated using the Midpoint ReCiPe 2016 (H) approach. The indicators for the midpoint method were including Toxicity Potential (TP), Photochemical Oxidant Formation Potential (OFP), Particulate Matter Formation Potential (PMFP), Fossil Fuel Potential (FFP), Freshwater Eutrophication Potential (FEP), Global Warming Potential (GWP), Ionizing Radiation Potential (IRP), Agricultural Land Occupation Potential (LOP), Marine Eutrophication Potential (MEP), Surplus Ore Potential (SOP), Ozone Depletion Potential (ODP), Terrestrial Acidification Potential (TAP) and Water Consumption Potential (WCP).

There are only three indicators generated using the Endpoint ReCiPe 2016 (H) approach. The indicators for the endpoint method are including Human Health (HH), Resource Depletion (RA) and Ecosystem (ED).

3.3.4 Life Cycle Interpretation

The components of the environmental impacts of each indicator were interpreted in detail in this section. The value of the environmental impacts in each indicator were generated to analyse the reason that caused the higher or lower of the environmental impact in those indicators.

There were 18 environmental impacts that categorised to the midpoint indicators. The human carcinogenic toxicity, human non-carcinogenic toxicity, freshwater ecotoxicity, marine ecotoxicity and terrestrial ecotoxicity were categorised under the TP indicator with the unit of kg 1,4-DCB. The ozone formation human health and ozone formation terrestrial ecosystems were categorised under the OFP indicators with the unit of kg Nox eq. The fine particulate matter formation with the unit of kg PM2.5 eq was under the PMFP indicator. The fossil resource scarcity with the unit of kg oil eq was under the FFP indicator. The freshwater eutrophication with the unit of kg P eq was under the FEP indicator. The global warming with the unit of kg CO_2 eq was under the GWP indicator. The ionizing radiation with the unit of kBq Co-60 eq was under the IRP indicator. The land use with the unit of m^2a crop eq was under the LOP indicator. The marine eutrophication with the unit of kg N eq was under the MEP indicator. The mineral resource scarcity with the unit of kg Cu eq was under the SOP indicator. The stratospheric ozone depletion with the unit of kg CFC11 eq was under the ODP indicator. The terrestrial acidification with the unit of kg SO_2 eq was under the TAP indicator. The water consumption with the unit of m^3 was under the WCP indicator.

For the endpoint method, there were 8 environmental impacts under the HH indicator with the unit of DALY. The environmental impacts were fine particulate matter formation, global warming related to human health, human carcinogenic toxicity, human non-carcinogenic toxicity, ionizing radiation, ozone formation related to human health, stratospheric ozone depletion and water consumption related to human health. The 2 environmental impacts which are fossil resource scarcity and mineral resource scarcity were under the RA indicators with the unit of USD2013. There were 12 environmental impacts under the ED indicators with the unit of species.yr. The environmental impacts were including freshwater ecotoxicity, freshwater eutrophication, global warming related to freshwater ecosystems, global warming related to terrestrial ecosystems, land use, marine ecotoxicity, marine eutrophication, ozone formation related to terrestrial ecosystems, terrestrial acidification, terrestrial ecotoxicity, water consumption related to aquatic ecosystems and water consumption related to terrestrial ecosystem.

Table 3.3 and Table 3.4 show the midpoint and endpoint indicators and the related environmental impacts.

Table 3.3: Midpoint Indicators and Related Environmental Impacts (GreenDelta, 2006)

Midpoint Indicator	**Environmental Impact**
Toxicity Potential (TP)	Human carcinogenic toxicity (kg 1,4-DCB)
	Human non-carcinogenic toxicity (kg 1,4-DCB)
	Freshwater ecotoxicity (kg 1,4-DCB)
	Marine ecotoxicity (kg 1,4-DCB)
	Terrestrial ecotoxicity (kg 1,4-DCB)
Photochemical Oxidant Formation Potential (OFP)	Ozone formation, Human health (kg Nox eq)
	Ozone formation, Terrestrial ecosystems (kg Nox eq)
Particulate Matter Formation Potential (PMFP)	Fine particulate matter formation (kg PM2.5 eq)
Fossil Fuel Potential (FFP)	Fossil resource scarcity (kg oil eq)
Freshwater Eutrophication Potential (FEP)	Freshwater eutrophication (kg P eq)
Global Warming Potential (GWP)	Global warming (kg CO2 eq)
Ionizing Radiation Potential (IRP)	Ionizing radiation (kBq Co-60 eq)
Agricultural Land Occupation Potential (LOP)	Land use (m2a crop eq)
Marine Eutrophication Potential (MEP)	Marine eutrophication (kg N eq)
Surplus Ore Potential (SOP)	Mineral resource scarcity (kg Cu eq)

Table 3.3: (Continued)

Ozone Depletion Potential (ODP)	Stratospheric ozone depletion (kg CFC11 eq)
Terrestrial Acidification Potential (TAP)	Terrestrial acidification (kg SO2 eq)
Water Consumption Potential (WCP)	Water consumption (m3)

Table 3.4: Endpoint Indicators and Related Environmental Impact (GreenDelta, 2006)

Endpoint Indicator	**Environmental Impact**
Human Health (HH), DALY	Fine particulate matter formation
	Global warming, Human health
	Human carcinogenic toxicity
	Human non-carcinogenic toxicity
	Ionizing radiation
	Ozone formation, Human health
	Stratospheric ozone depletion
	Water consumption, Human health
Resource Depletion (RA), USD2013	Fossil resource scarcity
	Mineral resource scarcity

Table 3.4: (Continued)

Ecosystem (ED), species.yr	Freshwater ecotoxicity
	Freshwater eutrophication
	Global warming, Freshwater ecosystems
	Global warming, Terrestrial ecosystems
	Land use
	Marine ecotoxicity
	Marine eutrophication
	Ozone formation, Terrestrial ecosystems
	Terrestrial acidification
	Terrestrial ecotoxicity
	Water consumption, Aquatic ecosystems
	Water consumption, Terrestrial ecosystem

3.4 Summary

Throughout this chapter, the methodology to conduct the LCA for PLA and PVA were recorded. The goal and scopes for the LCA were set at the beginning stage to have a parameter to conduct the LCA. Then, coming to the longest part in this methodology, the LCI. In LCI, the inputs such as raw materials, energy consumption and the transportation for PLA and PVA were included. During the process to do the LCI, it was found the limitations of datasets for certain inputs such as $Sn(Oct)_2$, $SnCl_2$ and SnO for PLA and PdCl2, benzoyl peroxide and benzoyl chloride for PVA in Ecoinvent 3.8 (Wernet et al., 2016). Therefore, these datasets have to be created in openLCA (GreenDelta, 2006). After that, there were 13 midpoint impact categories and 3 endpoint impact categories generated throughout the analysis, stated in the LCIA section. Lastly, the total of 18 environmental impacts were generated under the midpoint impact categories and 22 environmental impacts under endpoint impact categories were generated to interpret environmental issues in detail, and to indicate which process that led to the environmental issue.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, the results generated from the life cycle assessment (LCA) in the previous chapter was tabulated, analysed and discussed. The top 3 indicators for the polylactic acid (PLA) and polyvinyl alcohol (PVA), the environmental impact that affect the result, and the input data that caused the environmental impact is discussed in this section.

4.2 Polylactic Acid (PLA)

In this section, the PLA midpoint (H) 2016 and endpoint (H) 2016 results provided with the value that generated from the LCA was tabulated in Table 4.1 and Table 4.2. The top 3 highest value of midpoint indicator and the top 1 highest value of endpoint indicator is discussed in this section.

4.2.1 PLA Midpoint (H) 2016

The positive value generated indicates that the net consequence of the process is environmentally harmful. Therefore, from the value showing in Table 4.1 has indicated that the total processes to manufacturer the PLA in Malaysia are not friendly to the environment. The top 3 highest value of the midpoint indicators show in Table 4.1 are Toxicity Potential (TP) with the total value of 4.15E+04 kg1,4-DCB, Global Warming Potential (GWP) with the value of 9.94E+03 kg CO_2 eq and the Fossil Fuel Potential (FFP) with the value of 3.22E+03 kg oil eq. From the TP indicator, the highest value of the environmental impact is caused by the terrestrial ecotoxicity with the value of 3.34E+04 kg 1,4-DCB.

The toxicity potential (TP) which including the environmental impact of human toxicity, freshwater aquatic ecotoxicity, marine ecotoxicity, and terrestrial ecotoxicity, expressed in kg 1,4-dichlorobenzene-equivalents (1,4DCB-eq), was utilised as a characterisation factor at the midpoint level. In the midpoint calculations, the chemical 1,4-dichlorobenzene (1,4-DCB) was used as a reference substance, with the calculated potential impact of the chemical being divided by the potential impact of 1,4-DCB emitted to urban air for human toxicity, fresh water for freshwater ecotoxicity, seawater for marine ecotoxicity, and industrial soil for terrestrial ecotoxicity (ReCiPe 2016, 2017).

Terrestrial ecosystem in another name is called as land ecosystem. The 5 major terrestrial ecosystems are including the forest, desert, taiga, grassland and tundra (Bruce Smith, 2019). Terrestrial ecotoxicity is stand for the environmental pollutants that affect land-dependent organisms and their environment. There are three elements required to affect the terrestrial ecotoxicity which are (1) a source, (2) a receptor and (3) an exposure pathway. Pollutants reach the terrestrial ecosystem in a variety of ways, including direct application, diffuse source emissions, and long-range transit. Microbes in the soil, invertebrates, plants, amphibians, reptiles, birds, and mammals all act as terrestrial receptors. Pollutants can reach terrestrial organisms by cutaneous, oral, inhalation, and food-chain exposure. Even though plants and animals can develop tolerance to some environmental pollutants over time and adapt to them, the terrestrial ecotoxicity discussed risk assessment by combining exposure and effects data to estimate the likelihood of adverse effects on individual organisms, populations, or communities (Fairbrother, 2005).

Global Warming Potential (GWP) is a widely used midpoint characterisation factor for climate change. The GWP quantifies the additional radiative forcing integrated for 20, 100 or 1,000 years, caused by the emission of 1 kilogramme of GHG in comparison to the additional radiative forcing integrated over the same time horizon generated by the release of 1 kg of CO_2. The Fossil Fuel Potential (FFP) of the fossil resource (kg oil-eq/unit of resource) is defined as the ratio between the energy content of the fossil resource and the energy content of crude oil as the midpoint indicator for fossil resource use. The fossil fuel potential (FFP) is calculated using the higher heating values (HHV) of crude oil, natural gas, hard coal, brown coal, and peat (ReCiPe 2016, 2017).

Table 4.1: PLA Midpoint (H) 2016 Result (GreenDelta, 2006)

Indicator	**Environmental Impact**	**Total Value**
TP	Human carcinogenic toxicity (kg 1,4-DCB)	2.49E+02
	Human non-carcinogenic toxicity (kg 1,4-DCB)	2.13E+02
	Freshwater ecotoxicity (kg 1,4-DCB)	7.31E+03
	Marine ecotoxicity (kg 1,4-DCB)	3.35E+02
	Terrestrial ecotoxicity (kg 1,4-DCB)	3.34E+04
OFP	Ozone formation, Human health (kg Nox eq)	2.05E+01
	Ozone formation, Terrestrial ecosystems (kg Nox eq)	2.12E+01
PMFP	Fine particulate matter formation (kg PM2.5 eq)	1.47E+01
FFP	Fossil resource scarcity (kg oil eq)	3.22E+03
FEP	Freshwater eutrophication (kg P eq)	1.58E+00
GWP	Global warming (kg CO_2 eq)	9.94E+03
IRP	Ionizing radiation (kBq Co-60 eq)	2.82E+02
LOP	Land use (m^2a crop eq)	5.82E+01
MEP	Marine eutrophication (kg N eq)	3.84E-01
SOP	Mineral resource scarcity (kg Cu eq)	5.60E+01
ODP	Stratospheric ozone depletion (kg CFC11 eq)	3.86E-03
TAP	Terrestrial acidification (kg SO_2 eq)	3.36E+01
WCP	Water consumption (m^3)	8.74E+01
	Total	5.52E+04

In Figure 4.1 shows the relationship between the input data of PLA in the life cycle inventory (LCI) and the environmental impacts generated from LCA. The data for the TP indicator used in this figure was taken only from the terrestrial ecotoxicity. To do so, it is to evaluate what are the main components that caused the high terrestrial ecotoxicity value in the processes.

From the Figure 4.1, it can be clearly observed that the main components to cause the environmental impact for the TP indicator, GWP indicator and FFP indicator is from the production of lactic acid. The impact from the production of lactic acid contributed under the TP indicator is 67.10 %, 75.15 % for the GWP indicator and 75.70 % for the FFP indicator.

Energy consumption as the second higher environmental impact contributor is hardly to be unseen from the Figure 4.1. The impact from the energy consumption category contributed under the TP indicator is 30.35 %, 26.56 % for the GWP indicator and 23.72 % for the FFP indicator.

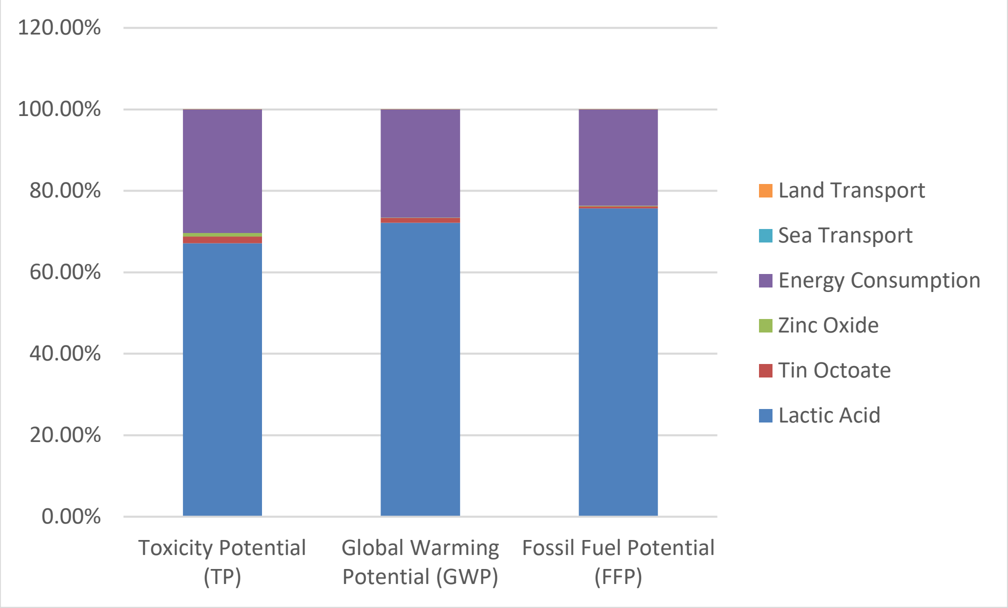


Figure 4.1: Relationship between Input Data and PLA Top 3 Midpoint Indicators

The lactic acid which in this project was produced through the chemical synthesis by using the technology of the hydrolysis of lactonitrile. According to Komesu et al. (2017), using lactonitrile as the raw material is the most technically and economically feasible chemical synthesis production method. However, chemical production is costly and reliant on by-products from other industries that are sourced from fossil fuels. Additionally, chemical synthesis produces a racemic mixture of lactic acid (DL-lactic acid) and for any particular use, only one of the lactic acid isomers is wanted. Therefore, the steps to produce the lactic acid isomers must keep repeating to get the desired amount of the product. Thus, it caused the higher cost, higher energy consumption and higher environmental impact for the raw materials and manufacturing process using the chemical synthesis.

4.2.2 PLA Endpoint (H) 2016

Table 4.2 shows the total value of the endpoint indicators of PLA. The highest positive value of the endpoint indicator of PLA is human health (HH) with the value of 3.09E+06 DALY. Resource depletion (RA) with the unit of USD2013 gained the second higher positive value which is 1.19E+03. Further, the ecosystem (ED) with the negative value of -1.87E+14 species.yr indicated the friendly environmental impact in this category from the process to produce the PLA in Malaysia.

Table 4.2: PLA Endpoint (H) 2016 (GreenDelta, 2006)

Indicator	Total Value
HH (DALY)	3.09E+06
RA (USD2013)	1.19E+03
ED (species.yr)	-1.87E+14

HH indicator stand for the human health damage, and DALY in its full name is called disability adjusted life year. The DALY is a well-established term in medicine and has been incorporated into several well-known endpoint impact assessment methodologies, including ReCiPe and Impact2002+. It is used to measure the burden of human disease caused by environmental contamination and to assign it to the product or service's life cycle. DALYs quantify the difference between an ideal world in which everyone lives to the standard life expectancy in perfect health and the reality. The measure is calculated as the sum of years of life lost (YLL) owing to premature death and years of life lost due to disability (YLD) while living with the disease or its consequences.

Table 4.3 shows the water consumption, human health covered the greatest environmental impact in the HH indicator. Table 4.4 shows the inputs that caused the greater impact on water consumption, human health is from the tin octoate. According to World Health Organization (2005), tin may be transported in water, and it is sparingly soluble in water. Human health affected by the tin compound are through the inhalation like breathing in, dermal exposure like skin contacts and through oral like eating or drinking (Atsdr, 2005).

Table 4.3: Environmental Impact under PLA Endpoint (H) 2016 Human Health Indicator (GreenDelta, 2006)

Environmental Impact	Total Value
Fine particulate matter formation	9.23E-03
Global warming, Human health	9.23E-03
Human carcinogenic toxicity	7.06E-04
Human non-carcinogenic toxicity	1.67E-03
Ionizing radiation	2.40E-06
Ozone formation, Human health	1.87E-05
Stratospheric ozone depletion	2.04E-06
Water consumption, Human health	3.09E+06

Table 4.4: Relationship between PLA Inputs and Water Consumption, Human Health (GreenDelta, 2006)

Inputs	Total Value
Lactic Acid	1.90E-04
Tin Octoate	3.09E+06
Zinc Oxide	-6.89E-08
Energy Consumption	7.67E-06
Sea Transport	9.70E-11
Land Transport	3.37E-11

4.3 Polyvinyl Alcohol (PVA)

In this section, the PVA midpoint (H) 2016 and endpoint (H) 2016 results provided with the value that generated from the LCA was tabulated in Table 4.5 and Table 4.6. The top 3 highest value of midpoint indicator and the top 1 highest value of endpoint indicator is discussed in this section.

4.3.1 PVA Midpoint (H) 2016

The negative value generated indicates that the net consequence of the process is environmentally friendly. Therefore, from the value showing in Table 4.5 has indicated that the total processes to manufacturer the PVA in Malaysia are friendly to the environment. The top 3 highest negative value of the midpoint indicators are same with PLA which are showing in Table 4.5. The indicators are Toxicity Potential (TP) with the total value of -4.19E+08 kg1,4-DCB, Global Warming Potential (GWP) with the value of -1.07E+06 kg CO2 eq and the Fossil Fuel Potential (FFP) with the value of -2.55E+05 kg oil eq. From the TP indicator, the highest value of the environmental impact is caused by the terrestrial ecotoxicity with the value of -3.76E+08 kg 1,4-DCB.

Table 4.5: PVA Midpoint (H) 2016 Result (GreenDelta, 2006)

Indicator	Environmental Impact	Total Value
TP	Human carcinogenic toxicity (kg 1,4-DCB)	-3.68E+05
	Human non-carcinogenic toxicity (kg 1,4-DCB)	-3.83E+07
	Freshwater ecotoxicity (kg 1,4-DCB)	-1.60E+06
	Marine ecotoxicity (kg 1,4-DCB)	-2.17E+06
	Terrestrial ecotoxicity (kg 1,4-DCB)	-3.76E+08
OFP	Ozone formation, Human health (kg Nox eq)	-1.54E+04
	Ozone formation, Terrestrial ecosystems (kg Nox eq)	-1.57E+04
PMFP	Fine particulate matter formation (kg PM2.5 eq)	1.33E+05
FFP	Fossil resource scarcity (kg oil eq)	-2.55E+05
FEP	Freshwater eutrophication (kg P eq)	-2.45E+03
GWP	Global warming (kg CO_2 eq)	-1.07E+06
IRP	Ionizing radiation (kBq Co-60 eq)	-8.72E+03

Table 4.5: (Continued)

LOP	Land use (m^2a crop eq)	5.90E+04
MEP	Marine eutrophication (kg N eq)	1.76E+06
SOP	Mineral resource scarcity (kg Cu eq)	1.74E+05
ODP	Stratospheric ozone depletion (kg CFC11 eq)	-1.29E+00
TAP	Terrestrial acidification (kg SO_2 eq)	4.59E+05
WCP	Water consumption (m^3)	-1.17E+04
	Total	-4.18E+08

In Figure 4.2 shows the relationship between the input data of PVA in the life cycle inventory (LCI) and the friendly environmental impacts generated from LCA. The data for the TP indicator used in this figure was taken only from the terrestrial ecotoxicity. To do so, it was to evaluate what are the main components that caused the high terrestrial ecotoxicity value in the processes.

From the Figure 4.2, it can be clearly observed that the main components to cause the friendly environmental impact for the TP indicator, GWP indicator and FFP indicator is from the production of palladium (II) chloride. The impact from the palladium (II) chloride contributed under the TP indicator, the GWP indicator and the FFP indicator are almost 100 %.

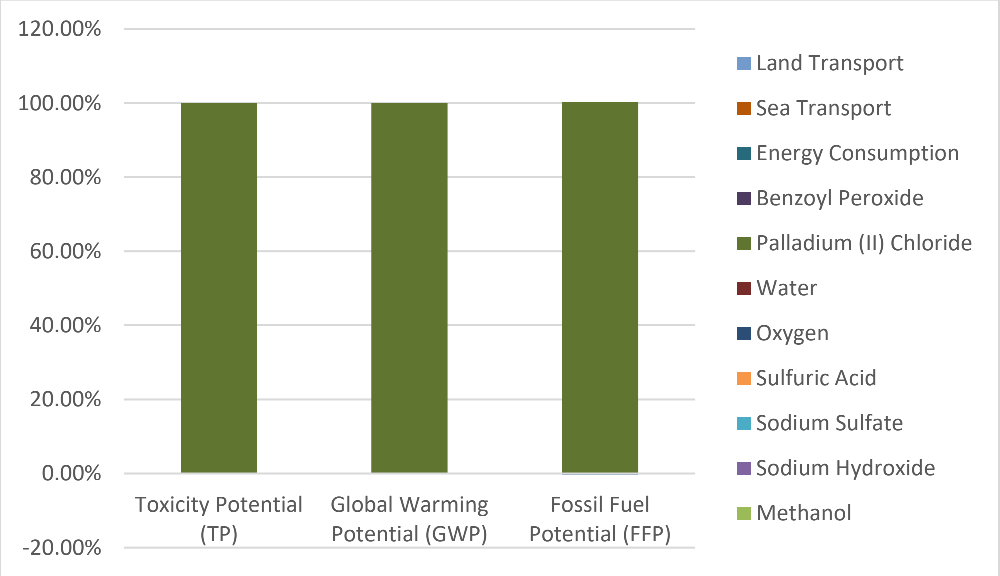


Figure 4.2: Relationship between Input Data and PVA Top 3 Midpoint Indicators

The palladium (II) chloride is one of the palladium catalyst which it is considered as an activated carbon-supported catalyst that is friendly to the environment (Sarioğlan, 2013). One of the most significant advantages of using activated carbon is that it can be reactivated or regenerated, which means that the adsorbed components can be desorbed from the activated carbon, resulting in fresh activated carbon that can be reused (Alex and Carrie, 2021). Due to this characteristic of the activated carbon-supported catalyst, the palladium (II) chloride is not only environmental sustainable, but offer better economic benefit to the processes.

4.3.2 PVA Endpoint (H) 2016

Table 4.6 shows the total value of the endpoint indicators of PVA. The highest negative value of the endpoint indicator of PVA is human health (HH) with the value of -9.90E+04 DALY. Resource depletion (RA) with the unit of USD2013 gained the second higher negative value which is -6.16E+02. Further, the ecosystem (ED) with the positive value of 8.54E-02 species.yr indicated the friendly environmental impact in this category from the process to produce the PVA in Malaysia.

Table 4.6: PVA Endpoint (H) 2016 (GreenDelta, 2006)

Indicator	Total Value
HH (DALY)	-9.90E+04
RA (USD2013)	-6.16E+02
ED (species.yr)	8.54E-02

Table 4.7 shows the global warming, human health covered the greatest friendly environmental impact in the HH indicator. Table 4.8 shows the element that caused the greater impact on global warming, human health is from the palladium (II) chloride. Like explained in the midpoint section, palladium (II) chloride is environmentally sustainable catalyst due to the activated carbon characteristic. The recovery of the palladium catalyst from the spent catalyst mixed with the hydrochloric acid and hydrogen peroxide has improved the diffusion rate of the hydrogen and provided a high energy efficiency characteristic to the process (Sarioğlan, 2013). Plus, hydrogen

peroxide is found to use as the air pollution controller from the by adsorb the polluted gas into liquid and prevent it from emitting to the environment (Deo, 1988).

Table 4.7: Environmental Impact under PVA Endpoint (H) 2016 Human Health Indicator (GreenDelta, 2006)

Environmental Impact	**Total Value**
Fine particulate matter formation	8.33E+01
Global warming, Human health	-9.91E+04
Human carcinogenic toxicity	-1.22E+00
Human non-carcinogenic toxicity	-8.72E+00
Ionizing radiation	-7.40E-05
Ozone formation, Human health	-1.40E-02
Stratospheric ozone depletion	-6.90E-04
Water consumption, Human health	-2.59E-02

Table 4.8: Relationship between PVA Inputs and Global Warming, Human Health (GreenDelta, 2006)

Inputs	**Total Value**
Ethylene	7.69E-05
Acetic Acid	2.10E-04
Methanol	2.70E-04
Sodium Hydroxide	1.64E-05
Sodium Sulphate	4.26E-05
Sulfuric Acid	-5.41E-07
Oxygen	5.92E-05
Water	7.55E-08
Palladium (II) Chloride	-9.91E+04
Benzoyl Peroxide	1.80E-04
Energy Consumption	5.15E-05
Sea Transport	5.57E-08
Land Transport	2.17E-07

4.4 Summary

Throughout this chapter, the environmental impacts along with their values were generated throughout the analysis from openLCA (GreenDelta, 2006). The top 3 midpoint indicators to produce the PLA and PVA in Malaysia were Toxicity Potential (TP), Global Warming Potential (GWP) and Fossil Fuel Potential (FFP) and the top 1 endpoint indicator to produce PLA and PVA was Human Health (HH). Though the top 3 midpoint indicators and top 1 endpoint indicator were same for PLA and PVA, the sign of the values are different. The total midpoint value generated for the production PLA was positive which indicates the net consequence was environmentally harmful. For the PVA, the total midpoint value generated for the production of PVA was negative which indicates the net consequence was environmentally friendly.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this project, two types of biodegradable polymer which is polylactic acid (PLA) and polyvinyl alcohol (PVA) were selected as the product to conduct the investigation. To investigate the availability of these two biodegradable polymers in Malaysia, the analysis of the environmental impact to produce these biodegradable polymers in Malaysia was conducted through the life cycle assessment (LCA).

While conducting the life cycle inventory (LCI) for PLA and PVA, the raw materials and the production method used are including the consideration of the easy accessibility in Malaysia. Therefore, the raw material for PLA and PVA are produced from crude oil which the PLA is from the lactonitrile and the PVA is from the ethylene.

The previous chapter shows the total midpoint result for PLA is 5.52E+04 which is a positive value. It means the net consequences of the process or the selected method to manufacturer the PLA in Malaysia is harmful to the environment. The reasons to cause this result are come from different aspects. First, the method chosen to produce the lactic acid is through the chemical synthesis which will cause the higher consumption of the energy due to the minor portion of lactic acid produced throughout one process. Further, the power generations used in Malaysia are not from the renewable or clean sources. Then, the raw material for the PLA through the chemical synthesis used is mainly from the petrochemical. Even though Malaysia is one of the crude oil production countries, but the overall processes to refine the crude oil is bad to the environment. Lastly, no manufacturer is found in Malaysia, that is produce neither the raw material to produce PLA, which is lactonitrile, nor the hydrogen cyanide. Therefore, the raw materials in this project are set to purchase from other country.

Coming to the endpoint result for PLA, the impact for the human health to produce the PLA in Malaysia is in positive value with the value of

3.09E+06 DALY which means it can damage the human health by using the production method selected in this project. Then, the impact on the resource depletion with the positive value of 1.19E+03 USD2013 stand for the production method using in this project is not economically friendly. Lastly, the impact on the ecosystem indicator by produce the PLA in Malaysia is the only indicator in negative value with the value of -1.87E+14 species.yr. Even though the net consequences of the environmental impact to produce the PLA in Malaysia is not friendly, but it is still providing the good impact to the ecosystem in Malaysia.

Thus, the availability to produce the PLA in Malaysia is not optimistic compared to PVA, therefore the production of PLA in Malaysia is inopportune. PLA as the biodegradable polymer provided with the better strength compared to the other types of biodegradable polymer, it is relatively suitable to replace the non-biodegradable conventional polymer. However, the technology and the availability of the raw materials to produce the PLA in Malaysia has to be strengthened to make the processes more environmentally friendly.

Coming to the PVA, the midpoint result shows in the previous chapter is -4.18E+08 which is the negative value. It means that the net consequences of the production method to produce the PVA in this project is environmentally friendly. The main reason to cause this result is because of the palladium (II) chloride that act as the activated carbon-supported catalyst that can be recovered after used. Anyway, the raw materials to produce the PVA in this project are mostly available in Malaysia. Plus, the energy consumption for the process to produce the PVA is relatively low compared to PLA.

The endpoint result of the PVA shows in the previous chapter, for the impact of the human health is in the negative value which is -9.90E+04 DALY. It means the production method selected to produce the PVA in Malaysia is benefit to the human health. For the impact of resource depletion, the value generated is also in negative value which is -6.16E+02 USD2013. It may because of the raw materials are available in Malaysia and makes the production economically friendly. However, once there are production processes, there are pollutions generated. The impact of the ecosystem for the production of PVA is in the relatively small positive value of 8.54E-02 species.yr which is considered as the production of PVA has bringing some bad impact to the ecosystem.

To be conclude, the availability of the production of PVA in Malaysia is better and the production is recommended. In reality, it was found around one to two factories that are manufactured the PVA in Malaysia even though the information for those companies and the production method they are using to produce their PVA is limited.

5.2 Limitations of Study

In this project, the life cycle assessment (LCA) is limited by using the cradle-to-gate manner. Which means the processes only covered from the raw material extraction until the production of the PLA and PVA including the transportations and energy consumption. The transportation assumptions used in this study may differ from the actual distance travelled, as the routes of different hauling trucks may not be the same. Additionally, the fuel consumption and the vehicle’s emissions for the transportations are critical to be assumed. Therefore, these may affect the accuracy for the transportation of the LCA analysis.

Furthermore, the limitation of the datasets in Ecoinvent is one of the challenges to conduct the LCA analysis in this project. Especially for the local dataset, only the electricity and tap water dataset used are stated from Malaysia, others are taken from the datasets from global or the rest of world. Further, some of the material or the catalyst used in this LCA are newly created due to the lack of dataset for these components. These datasets are created without the consideration of the transportation used and the energy consumption, therefore it may cause the inaccuracy of the analysis in this project.

Moreover, the existing of the biodegradable polymers are not likely to the non-biodegradable polymers which having more than 100 years of the history. It is relatively hard to get the completed journal articles provided with all the raw materials used and its amount to produce the PLA and PVA.

Especially for the PLA, there is only 5 % to 10 % of the manufacturers are using the chemical synthesis to produce the lactic acid (Jamshidian et al., 2010). Mix and match the raw materials from different sources of journal articles without the experiment, it may affect the accuracy of the production method used for the PLA and PVA in this project.

5.3 Recommendations

Throughout this project, the main reason to cause the environmentally harmful to produce the PLA in Malaysia is using the chemical synthesis to produce the lactic acid. Therefore, it is recommended to use the biological synthesis to produce the lactic acid to reduce the bad environmental impact exists in this project. In addition, the raw material to produce the PLA through the biological synthesis is recommended to use sugar as the raw material can be imported from our neighbour country, Thailand. Therefore, the energy consumption and the emission from the transportation can be reduced.

Further, it is suggested to conduct some experiments or surveys to increase the accuracy of the LCA analysis. For instance, more data collection should be done for local production for each raw materials of PVA as the raw materials are set to purhase in Malaysia, but the datasets using in the LCA analysis are from global and the rest of world. Moreover, the data collected from the surveys or the experiments can be used as the life cycle inventory (LCI) for the project to analyse the environmental impacts throughout the processes.

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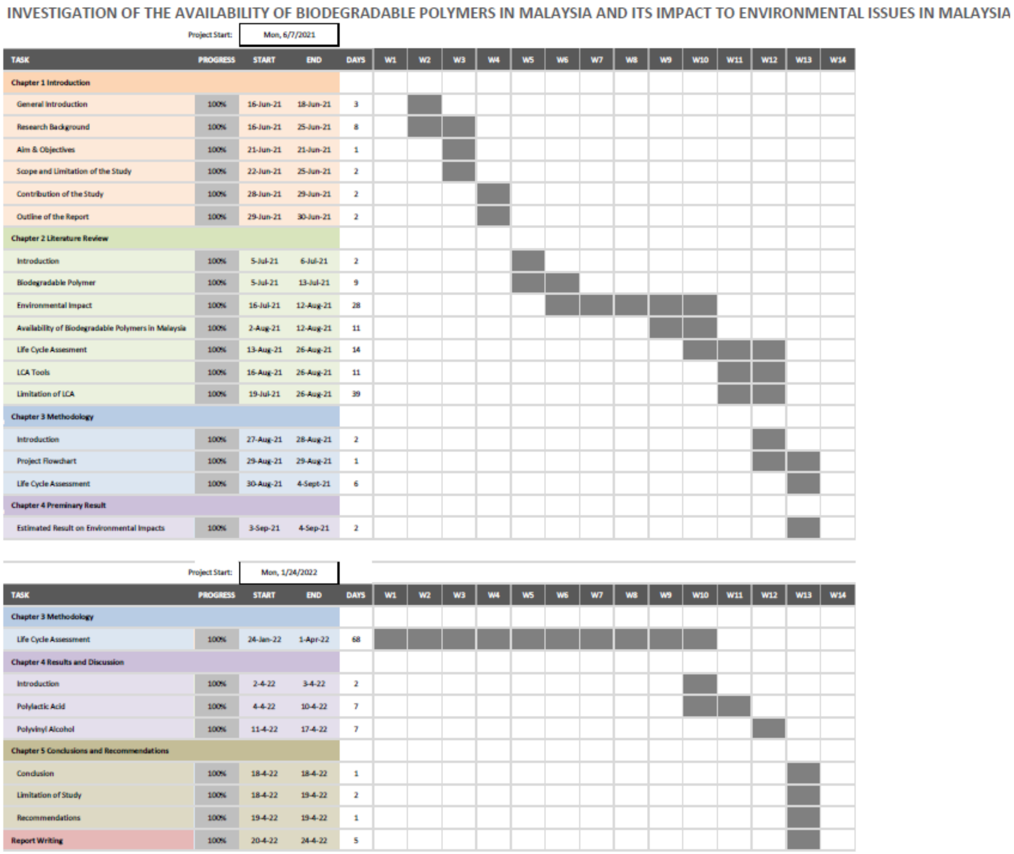
APPENDICES

Appendix A: Gantt Chart



INVESTIGATION OF THE AVAILABILITY OF BIODEGRADABLE POLYMERS IN MALAYSIA AND ITS IMPACT TO ENVIRONMENTAL ISSUES IN MALAYSIA

Project Start: Mon, 6/7/2021

TASK	PROGRESS	START	END	DAYS	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
Chapter 1 Introduction																		
General Introduction	100%	16-Jun-21	18-Jun-21	3		■												
Research Background	100%	16-Jun-21	25-Jun-21	8		■	■											
Aim & Objectives	100%	21-Jun-21	21-Jun-21	1			■											
Scope and Limitation of the Study	100%	22-Jun-21	25-Jun-21	2			■											
Contribution of the Study	100%	28-Jun-21	29-Jun-21	2				■										
Outline of the Report	100%	29-Jun-21	30-Jun-21	2				■										
Chapter 2 Literature Review																		
Introduction	100%	5-Jul-21	6-Jul-21	2					■									
Biodegradable Polymer	100%	5-Jul-21	13-Jul-21	9					■	■								
Environmental Impact	100%	16-Jul-21	12-Aug-21	28						■	■	■	■	■				
Availability of Biodegradable Polymers in Malaysia	100%	2-Aug-21	12-Aug-21	11									■	■				
Life Cycle Assesment	100%	13-Aug-21	26-Aug-21	14										■	■	■		
LCA Tools	100%	16-Aug-21	26-Aug-21	11											■	■		
Limitation of LCA	100%	19-Jul-21	26-Aug-21	39											■	■		
Chapter 3 Methodology																		
Introduction	100%	27-Aug-21	28-Aug-21	2												■		
Project Flowchart	100%	29-Aug-21	29-Aug-21	1												■	■	
Life Cycle Assessment	100%	30-Aug-21	4-Sept-21	6													■	
Chapter 4 Preminary Result																		
Estimated Result on Environmental Impacts	100%	3-Sep-21	4-Sep-21	2													■	

Project Start: Mon, 1/24/2022

TASK	PROGRESS	START	END	DAYS	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
Chapter 3 Methodology																		
Life Cycle Assessment	100%	24-Jan-22	1-Apr-22	68	■	■	■	■	■	■	■	■	■	■				
Chapter 4 Results and Discussion																		
Introduction	100%	2-4-22	3-4-22	2										■				
Polylactic Acid	100%	4-4-22	10-4-22	7										■	■			
Polyvinyl Alcohol	100%	11-4-22	17-4-22	7												■		
Chapter 5 Conclusions and Recommendations																		
Conclusion	100%	18-4-22	18-4-22	1													■	
Limitation of Study	100%	18-4-22	19-4-22	2													■	
Recommendations	100%	19-4-22	19-4-22	1													■	
Report Writing	100%	20-4-22	24-4-22	5													■	