Master Thesis

Insights from Life Cycle Assessment literature: Is Polylactic Acid (PLA) really sustainable compared to fossil-based alternatives?

Xue Leping

Master Student, Environmental Science and Engineering,

EPFL Advisors:

Prof. Dr. Philippe Thalmann

EMPA Advisors:

Claudia Som

Tijana Ivanović

Abstract

The growth of the plastics industry has brought about environmental problems that cannot be ignored, and bio-based plastics are considered to be one of the promising solutions that have received increasing attention in recent years. PLA is the emerging bio-based plastic of this century. Due to its excellent performance and relatively inexpensive production cost, it has become one of the most popular biodegradable plastics and is often seen as an alternative to petroleum-based plastics. While PLA has been perceived as a new type of biodegradable plastic that is much more environmentally friendly than fossil-based plastics like PET.

In this project, a total of 26 peer-reviewed papers on LCA related to PLA products since 2003 were reviewed by means of meta-analysis. In all these papers, the environmental performance of PLA is compared with that of fossil-based polymers using LCA. The reasons for the differences in the results of different studies are also analyzed and summarized from the perspectives of data source, scope, feedstock, geography, and impact categories, respectively.

It was founded that most of these LCA studies of PLA were conducted based on the life cycle inventory data of PLA products from two of the most famous PLA manufacturers, NatureWorks and Total Corbion. The choice of data source for LCA studies is often determined by the feedstock of the studied object, with most studies using corn as the feedstock preferring data from NatureWorks, while data from Total Corbion are more appropriate for LCA studies with sugarcane-based PLA. Sugarcane-based PLA has better environmental performance than corn-based, mainly in terms of land and water use. Due to advances in production technology, especially in the lactic acid production chain, the environmental performance of PLA is gradually getting better over time. Compared to other options, when cradle to gate is chosen as the study scope, the environmental performance of PLA is better, and the theory of carbon credit can explain this phenomenon well. Among all waste management scenarios, industrial incineration with energy recovery system is currently the most popular and the best environmental performance because recovered energy will be calculated as a negative carbon credit. Throughout all the reviewed studies, PLA performs worse than traditional fossil-based plastics in almost all kinds of environmental impact categories except for greenhouse and non-renewable energy.

In conclusion, PLA is currently not a more environmentally friendly alternative to fossil-based plastics. However, new feedstock is constantly being updated as technology evolves, and the latest technology being developed involves the use of methanotrophic bacteria and cyanobacteria to produce lactic acid directly from methane or carbon dioxide, which will greatly improve the environmental performance of PLA. Replacing the energy supply for PLA production system from fossil to green energy sources will also have a significant impact on improving the eco-profile of PLA. With the development of a decarbonized economy and the depletion of fossil resources, PLA will have a brighter future.

Keywords: polylactic acid (PLA), bioplastic; bio-based plastic; life cycle assessment (LCA); polyethylene terephthalate (PET)

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Looking back on my two years of study at EPFL, I have been puzzled and anxious, but more than that, I am thankful and content.

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Despite how little time two years is, I have learned so much in that time. All those who have been supportive and assisted me are in my best wishes for everything.

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List of Abbreviations

Abbreviation	Definition
LCA	Life cycle analysis
PLA	Polylactic acid
PLLA	Poly-L-lactic acid
PE	Polyethylene
PP	Polypropylene
PS	Polystyrene
PET	Polyethylene terephthalate
PTT	Polytrimethylene terephthalate
TPC-ET	Thermoplastic Copolyester Elastomer
PHA	Polyhydroxyalkanoates
PBS	Polybutylene succinate
APET	Amorphous Polyethylene Terephthalate
PBAT	Polybutylene adipate terephthalate
TPS	Thermoplastic Starch
HDPE	High-density polyethylene
LDPE	Low-density polyethylene
XPS	Extruded polystyrene
EU	European Union
USDA	the United States Department of Agriculture
CIEL	Center for International Environmental Law
GB/T 41010-2021	Chinese National Standard
ISO	International Organization for Standardization

LCI	**Life cycle inventory**
LCIA	**Life cycle inventory analysis**
EOL	**End of life**
NPK ratios	**The percentage the product contains by volume of nitrogen (N), phosphorus (P), and potassium (K)**
ROP	**Ring-opening polymerization**
GWP	**Global warming potential**
GHG	**Green house gas**
FU	**Function Unit**
BD	**Biodegradation**
AP	**Aquatic acidification**
NREU	**Non-renewable energy use**

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1. Introduction

Human society has advanced enormously since the industrial revolution, and the countless new materials and technological advancements have made people's lives more comfortable and enjoyable. Plastic began to permeate people's daily lives in the mid-nineteenth century. Plastic is a special type of polymer with a large molecular weight. The most common plastic polymers such as polyethylene, the feedstock of plastic bags, and polyethylene terephthalate, which is used to produce bottles, are derived from petroleum hydrocarbons. Due to its cheapness, lightness, safety, and other advantages, in just a few decades, it has become the mainstream of the packaging industry. Currently, one hundred plastic bottles are purchased globally every minute, and up to five trillion plastic bags are used annually. And the annual global production of plastic has reached 380 million tons in 2015 and will grow exponentially in the future [1].

The largest market for plastics is the packaging industry, and these plastics are generally disposable, accounting for more than one-third of the plastic produced each year, 98 percent of which is made from fossil fuels [2] [3]. In most cases, fossil-based plastic and plastic products are stable polymer structures, which is why they can accumulate in the environment (if littered), or at landfills (if not incinerated). As a result, plastic waste imposes a near-permanent burden on the natural environment. Since 1950, 55% of all plastic waste worldwide has been landfilled directly or discarded into the environment [4]. This plastic waste is scattered all over the globe and places a tremendous burden on the ecosystem.

When plastic is discarded into the environment, plastic additives, such as stabilizers, harmful colorants, plasticizers, and heavy metals, gradually leach out and eventually penetrate into the various aspects of the environment [6]. Besides, the plastics industry produces large amounts of greenhouse gases. Statistically, the level of greenhouse gas emissions associated with the production, use, and disposal of conventional fossil-fueled plastics is expected to grow to 19% of the global carbon budget by 2040 [5]. In addition, plastic waste debris pose a huge threat to the marine ecosystem [8]. It is estimated that there are approximately at least 14 million tons of plastic waste in the global oceans every year [7]. Over 260 species of marine life, such as sea turtles, invertebrates, seabirds, fish, and marine mammals, have been ingested or entangled in plastic debris, rendering them unable to survive until they die [8], [9]. It is also notable that plastic waste will slowly break down into micro-plastics with very small particle diameters, which will enter the bodies of living organisms, including humans, through natural cycles, and pose a potential threat to human survival and health [10]. According to Wilcox et al., plastic particles were found in the stomachs of almost 90% of seabirds [11].

In view of the development of decarbonization and also the pressures placed on the global environment by plastic, such as climate warming, environmental pollution, depletion of non-renewable resources and biological threats, in recent years, researchers around the world have been exploring various ways to alleviate the environmental pressure caused by traditional plastics, such as finding new alternatives to produce plastics, reuse, recycling, and developing new technologies for plastic waste management. It was at this point that bioplastic came into the public consciousness as a new type of excellent alternative to traditional plastics[6] [7].

As shown in Figure 1, bioplastics are broadly classified as bio-based and/or biodegradable [8]. Bio-based plastics are produced from natural and renewable organic materials, like corn, soybean, and vegetable oils. Biodegradable plastics could be decomposed by living organisms, like microbes [9]. Not all bio-based materials are biodegradable, and likewise, not all biodegradable materials are necessarily bio-based. A material is considered biobased when its source is a renewable organism and considered biodegradable when it is broken down and used as a source of energy by microorganisms and under appropriate environmental conditions [10], [11]. The key factor in determining whether a plastic is bio-based is the bio-content, which is the amount of carbon in the polymer that comes directly from bio-based raw materials. Only when the bio-based carbon content is 100% is the polymer considered fully bio-based, otherwise it is partially bio-based [12].

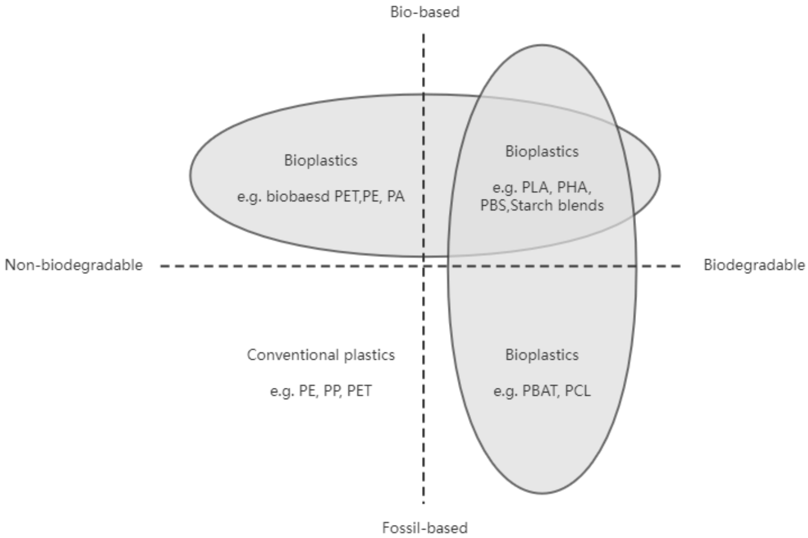

Figure 1： Material classification system based on their biodegradability and bio-based content (adapted from European Bioplastics [118])

Whether it is bio-based and whether it is biodegradable has a significant impact on bioplastic's environmental performance. Bio-based biodegradable plastics are often considered to have a lower carbon footprint than fossil-based plastics [13], [14]. It was proven in a previous study that with the increase of the bio-content, the life-cycle impact of bioplastics product on three types of water impacts, including water scarcity, water pollutants, and water resources, increases dramatically. Other environmental impact categories, like acidification, eutrophication, pesticide emission, and land use have shown the similar trend [12]. In addition, the main challenge for plastics is waste management [15]. Biodegradable plastic can be degraded by microorganisms and absorbed by the environment within a few months, and effectively reduce the amount of waste produced. While non-biodegradable plastics can cause a variety of environmental and ecological problems when spilled into the environment, so biodegradable plastics will have a more positive impact on the environmental threads in this regard [15]. The rise of bioplastics industry is predestined. From a social science perspective, economies represented by the European Union (EU) have been pursuing decarbonization in recent years to move away from fossil fuel use and to sustain economic development. Decarbonization is seen as an opportunity to mitigate the tension between capital accumulation and the demands of climate change mitigation. The ability to decarbonize will depend on its ability to direct investments toward low-energy and low-carbon energy sources. Therefore, globally, the development of the bio-based materials industry has been encouraged and supported by strong government policies.

To better guide and encourage the development of the bioplastics industry, governments in various regions around the world have formulated corresponding policies. As one of the world's largest emitters of greenhouse gases, the EU's historical cumulative greenhouse gas emissions account for about 25% of the world total, but the EU has always been a staunch defender and complier of the Paris Agreement and one of the first economies in the world to propose the carbon neutral plan and decarbonization. The EU has built a comprehensive carbon neutral policy framework, including the deployment of focused emission reduction measures in key sectors, supporting scientific and technological R&D projects, and the adoption of diverse fiscal and financial safeguards (seen in Appendix A2.1). As one of the possible solutions to reduce the carbon footprint of the plastic industry, the rise of bioplastics has also seen a lot of effort put into it. The EU enacted the European Green Deal in 2019, which regulates the policy framework for the sourcing, labelling and use of bioplastics [16]. Besides, the EU launched the European Bioeconomy Strategy back in 2012 to encourage EU countries to transition to a bioeconomy and to support the development of the bioplastics industry [17]. In addition, the EU has invested heavily in research and development for bioplastics. The EU has already allocated €250 million for such work through the recently launched Horizon 2020 program, with a further cap of €100 million in 2020 [18]. Compared to Europe, the bioplastics market in China started late, but as there have been many previous experiences from other areas, the relevant policy departments in China have introduced many special policies and regulations on bioplastics in recent years, specifying many standards such as biodegradation rates, labeling requirements and testing methods for bioplastics, and emphasizing the construction of bioplastics recycling projects in the "14th Five-Year Plan of Action for the Control of Plastic Pollution" in 2021.

Bioplastics are being given more and more attention in recent years from the perspectives of energy security and environmental friendliness. They are also being used in a variety of industries as an alternative to traditional plastic, like PET, especially in the packaging industry because a biodegradable package greatly reduces the environmental impact from the much waste due to the short life of a package[15]. About 2.42 million tons of bioplastics will be produced globally in 2021, of which the packaging industry will use 1.15 million tons or

48% of the total[19]. These bioplastics are utilized in the outer packaging of cosmetics and food products. Bioplastics are doing exceptionally well in the food packaging industry. In particular, bioplastics have outperformed traditional packaging when it comes to extending the shelf life of food. However, according to statistics, the global PET market size is up to 80.9 million tons in 2021 [20], more than half of this production is used in the packaging industry[21]. Therefore, there is a huge scope for the development of bio-based materials in order to transform the traditional fossil-based economic model into a bio-based economy.

Bioplastics are often considered a green alternative to fossil-based plastics. In reality, however, the development of biobased plastics has been fraught with challenges and questions. First, the sustainability of the feedstock for bio-based plastics is uncertain. When former agricultural land and forests are used to grow industrial crops, the resulting land use changes may have a negative impact on climate change and may also pose a threat to the food supply [22]. Secondly, the degradation rate of bioplastics is uncertain and unstable, and there is a lack of clear and scientific labeling and certification systems [23]. In addition, from a market perspective, traditional fossil-based plastics are far less expensive to produce and process than bio-based plastics. In general, the production cost of bioplastics is 20-80% higher than that of conventional plastics [24]. This is mainly due to the fact that most of the processes related to bioplastics are still in the development stage and therefore have not yet achieved mass production [25].

Compared with other biopolymers, polylactic acid (PLA) is considered to be one of the most commercially promising bioplastics available today, which is not only bio-based but also biodegradable under industrial composting conditions[26]. As the name implies, PLA is a hydrophobic polymer synthesized from lactic acid. It can be prepared by direct condensation of lactic acid or ring-opening polymerization of lactide. And indeed, it should be noted that nowadays, the PLA commercialized for commodity applications is made from ring-opening polymerization of lactide, a dimer of lactic acid. Therefore, a more precise term for this biopolymer should be polylactide rather than polylactic acid [27].

PLA has many excellent properties, such as excellent mechanical properties, renewability, biodegradability, and non-toxicity [28]. Especially compared with other biodegradable polymers, PLA has lower production cost [29] and a better thermal processability [30]. Polylactic acid is proving to be a viable alternative to fossil-based plastics for many applications. For example, because of its great mechanical strength, it can be used in place of PET and PS in various applications, such as plastic packaging or automotive parts [31]. Because of its biocompatibility, it could also be used to make medical devices. It can then be used in 3D printing due to its outstanding thermomechanical characteristics. It could potentially be utilized as a substitute for fossil-based fibers in apparel and other applications [30], [32]. The global market size of PLA is 566.74 million dollars in 2021 and is expected to grow at a compound annual growth rate of over 26.6% from 2022 to 2030[33].

Based on the bright commercial promise of PLA, there has been much scientific research and analysis into the various aspects of PLA. To evaluate the environmental performance of PLA, life cycle assessment is introduced, which is a method for systematically analyzing the environmental impact associated with all the stages of the life cycle of a product or service. Typically, the use of LCA begins with a Goal and scope definition, followed by an inventory analysis, then a selection of environmental impact categories to be assessed, and finally ends with an interpretation. LCA emphasizes a comprehensive understanding of the environmental impact of the material transformation process, which includes not only the emission of various wastes, but also the consumption of materials and energy and the damaging effects on the environment. It could help to prevent the transfer of environmental problems and facilitates pollution prevention through whole process control.

The study of LCA for PLA can be traced back to a study conducted by Vink and his team [34] for NatureWorks' product Ingeo. Since then, LCA has become one of the most commonly used tools for analyzing the environmental performance of PLAs. Many LCA studies for PLA are seeking to compare the environmental impact of bioplastics and traditional fossil-based plastics throughout their life cycle to determine which one has better environmental performance. From the published LCA studies on PLA, it was found that the methodology, scope, object, and impact categories used in different studies were different, and thus the results varied. Some studies demonstrate that PLA is a more environmentally friendly plastic product [35], while others demonstrate that PLA has better environmental impacts than fossil plastics only in terms of fossil fuel consumption and climate change [36], [37].

This project will provide a systematic response to these previous studies on PLA and will hopefully lead to a more scientifically sound conclusion of whether PLA has a better environmental performance than fossil-based polymers.

2. Life cycle of PLA

The life cycle of PLA generally has 7-8 stages: (1) Cultivation and transportation of feedstocks like corn or sugarcane; (2) conversion from raw materials to glucose; (3) fermentation of sugar to lactic acid; (4) conversion from lactic acid to lactide; (5) polymerization of lactide into high molecular weight PLA; (6) production of PLA products from PLA polymers, such as for example single-use packaging;(7) consumption and use of PLA products, and (8) End of Life of PLA products.

The first six stages will be presented in detail as production processes of PLA in the next subchapter. The EOL stage of PLA is subject to large uncertainties. The efficiency of biodegradability of PLA is uncertain when the environment is uncertain [38], which will affect the global warming gas emission from the EOL stage of PLA directly. Therefore, PLA will exhibit different environmental impacts under different EOL senarios. The possible EOL options will be described in detail in the next subchapter.

The consumption part of PLA is always neglected because of the uncertainty and complexity, and it has no impact on the final result.

2.1 Production processes of PLA

Cargill Dow is the biggest PLA producer in the world, producing a PLA polymer product named Natureworks^{TM} Ingeo with following the steps shown in Figure 2. In this section, this product will be used as a representative to elaborate on the steps of PLA production process in detail.

Each section of the production of PLA will be described in detail as following.

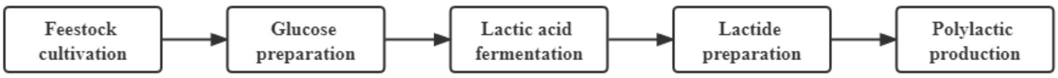

Figure 2: The schematic of production process of PLA (adapted from Vink, 2015 [54])

2.1.1 Feedstock Cultivation

The cultivation and production of raw materials is the beginning of the life cycle of PLA. At this stage, the plant converts solar energy into biomass energy through photosynthesis and stores it. The chemical equation for photosynthesis is:

$$nH_2O + nCO_2 \xrightarrow{light} (CH_2O)_n + nO_2$$

This chemical equilibrium equation is the theoretical basis for the better performance of bioplastics than fossil-based plastics in terms of carbon credit. The most common method used in calculating the carbon credit of PLA is The European Commission's Lead Market Initiative， when the studied scope is from cradle to factory gate, the total carbon emissions from the life cycle of PLA, the CO2 absorbed during feedstock cultivation will be counted as a negative number [39].

In addition to solar energy, the inputs associated with this stage include seeds, fertilizers, energy (electricity and fuel oil) for stages such as farm maintenance and sowing and harvesting, irrigation water for farming, chemicals for weed control and pest control, and inputs for land.

2.1.2 Glucose production

After harvesting, the crop will be transported to a processing plant where it is broken down to form glucose.

For corn and cassava, both crops are converted to raw sugar by enzymatic hydrolysis of starch into glucose. First, the corn kernels or cassava blocks are transported to a starch production plant where they undergo several transformations to separate the germ, fiber, gluten, and finally starch, which is then stabilized and stored. Next the prepared starch is transported to a glucose manufacturing plant for enzymatic hydrolysis, where the glycosidic bonds in the starch are selectively cleaved by enzymes to produce glucose monomers [40].

Sugarcane, as a sugary raw material, can be directly processed and glucose extracted from it. Generally, it is necessary to crush the sugarcane first, then heat and filter the juice obtained, and then produce raw sugar crystals [41].

2.1.3 Lactic acid production

Lactic acid is a pale-yellow odorless liquid that is the simplest hydroxycarboxylic acid. The quality of monomeric lactic acid is a key parameter affecting the performance of the final polylactide (PLA) product.

The specific reaction equation for lactic acid fermentation is as follows.

$$C_6H_{12}O_6 + 2ADP + 2Pi \rightarrow 2CH_3CH(OH)COOH + 2ATP$$

In order to maintain a stable external environment at 35-45°C and pH 5-6.5, the fermentation process often requires the addition of a moderate amount of alkali [42].

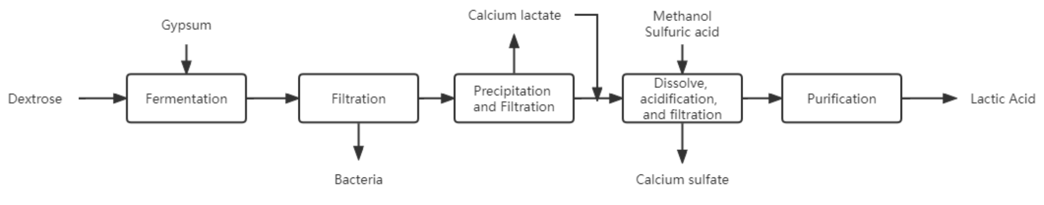

Figure 3: The production process of lactic acid (adapted from Vink et al, 2015[54].)

As shown in Figure 3, there are several phases to produce lactic acid and during these stages, purification is a very important part of the production process of lactic acid that affects the quality of the product. The cost of lactic acid separation and purification accounts for almost 50% of the overall lactic acid fermentation production cost [43]. Some of the most common separation and purification techniques include precipitation, filtration, acidification, carbon adsorption, evaporation and crystallization [44].

2.1.4 Lactide production

Water is removed from lactic acid ($CH_3CHOHCOOH$) by using an acid catalyst to form lactide ($C_6H_8O_4$), as shown in the following chemical equation:

$$2CH_3CHOHCOOH \rightarrow C_6H_8O_4 + 2H_2O$$

Cyclic lactide are available in three possible forms: D,D-lactide, L,L-lactide, and meso-lactide. The greater sensitivity of the meso-lactide to the ROP reaction relative to the first two lactides means that fewer catalysts and lower processing temperatures can be used. The lactide mixture is then purified by vacuum distillation and melt crystallization.

2.1.5 Polylactide production

There are two mainstream processes for producing PLA. The first one is direct polycondensation of lactic acid, by which, generally, only low to medium molecular weight polymers are produced and a relatively large reactor and a complex process are required.

Compared to the previous method, the second method, ring-opening polymerization by cyclic dimer, is more popular to obtain high molecular weight polymers. The lactide obtained in the previous step completes the ring-opening polymerization under vacuum or inert gas environment through the coordination insertion mechanism for metal complexes or activation of monomers by organic/cationic initiators [45]. In general, the previous mechanisms are more widely accepted because these metal catalysts can participate in human metabolism and are considered to be non-toxic [46].

2.2 End of Life of PLA

Although PLA is theoretically biodegradable, because of its uncertainty, waste management is necessary and always not allowed to be discarded or self-composting. The degradation rate of PLA is very slow in the natural environment [47] In general, the following EOL pathways are possible: landfilling, industrial composting, industrial incineration, mechanical recycling, chemical recycling, etc [48]. In different EOL scenarios, PLA undergoes different degrees of biodegradation and forms end products like, water, carbon dioxide and other greenhouse gases. When the study scope of LCA of PLA is from cradle to grave, this part of outputs will be taken into account for the greenhouse gas emission scenarios in the whole life cycle of PLA [31], [48]–[50].

Landfills are considered to be the most cost-effective way to dispose of municipal solid waste [51]. When PLA is disposed in **landfills**, only about 1% will degrade over a 100-year life cycle. From this point of view, landfill disposal is an environmentally friendly way of disposal [47]. However, if a longer time dimension is considered, this EOL option leads to the largest impact of PLA on global warming. It also means that PLA waste will continue to pile up in landfill [47].

Biodegradation is the natural way of recycling and PLA is biodegradable under industrial composting conditions. **Industrial composting**, on the other hand, would be considered the worst EOL option because of the large amount of greenhouse gases released by composting [48]. Also, the energy produced by PLA during composting will not be recovered.

As a kind of chemically stable polymers, the only way to permanently eliminate PLA is through destructive thermal treatments such as incineration or pyrolysis [2]. As the most popular method of PLA waste treatment, **industrial incineration** will not only reduce the volume of waste, but also recover energy from the waste, which can offset some of the greenhouse effect. Compared to other treatment options, although combustion greenhouse gases may pose a new environmental threat, heat treatment is particularly advantageous in the category of agricultural land use and cost [48].

Mechanical recycling refers to the recycling, sorting, regrinding and reprocessing of PLA waste. According to a previous study, 1 kg of PLA recyclate is equivalent to 0.54 kg of origin PLA. The carbon credit of the recyclate exceeds the negative credit generated during the recycling process [48]. It is considered the most environmentally friendly treatment in many studies, but the operating costs are relatively high. In addition, PLA is still a new type of plastic, and the volume of PLA waste is relatively small, thus, mechanical recycling is currently performed using manual labor, and a commercial operation model has not yet been developed [48].

Chemical recycling of PLA is the hydrolysis of PLA waste at high temperature to lactic acid, which can be re-polymerized into PLA with the same properties as the original materia. The conversion efficiency of PLA to usable lactide is 90%, so 1 ton of PLA waste can produce 900 kg of PLA [48]. Similar to mechanical recycling, carbon credit for the replacement of virgin PLA outweighs any potential environmental harm brought on by chemical recycling, which means it is environment friendly. However, chemical recovery is relatively expensive and complex, and is still at the laboratory stage.

3. Research questions, hypothesis and Goal

As discussed in the above chapter, in the eyes of many, PLA is perceived as the most promising alternative of traditional plastic to alleviate many environmental problems such as resource sustainability, global warming and environmental pollution caused by plastic waste. However, by reviewing the past literature, it is difficult to determine whether PLA is more environmentally friendly compared to traditional fossil-based plastics. Therefore, this project will assume that PLA is a sustainable alternative to fossil-based plastics based on past research. In order to verify whether this hypothesis is valid or not, this study needs to accomplish the following objectives:

1. Mapping the basis of LCA data sources of PLA: e.g., how many and what type (origin, transparency, completeness, and timeliness) of LCA data sets are available for PLA?
2. Sorting out the possible raw materials of PLA.
3. Examine the effects of PLA feedstock, choice of scope, and choice of LCA data source on the judgment of whether PLA environmental performance is better than conventional plastics.

To accomplish the above objectives, this project needs to answer the following questions.

1. What are the raw materials now used to produce PLA?
2. Are there different production processes for PLA?
3. Which polymers (and in which applications) can be replaced by PLA according to the desired properties?
4. What are the most relevant variables affecting the environmental performance of PLA (e.g., type of feedstock)?
5. What role does carbon crediting play in LCA studies of PLA and how does it affect LCA results?
6. Whether and to what extent the choice of scope of LCA affects the results of environmental impact analysis of PLA.

4. Methods

To accomplish the above objectives, an exhaustive reviewing and analysis of a large body of literature was required to identify and organize the findings of each literature on LCA for PLA. Therefore, the selection of literature was critical to this study.

In order to conduct a comprehensive review of the available literature on LCA for PLA, the keywords "PLA" and "LCA" were searched through both Google scholar and Web of Sciences. As such a search generates a lot of literature hits, a further filtering was necessary.

Distinguish the literature into studies containing primary and secondary data based on the source of the research data. Primary papers are based on the first-hand information from factory production in the field, like Vink's work in 2007 [52], 2010 [53], 2015 [54], all of which were corporate science and technology reports that have not been peer-reviewed. Noteworthy, ecoinvent dataset is also primary data. Secondary papers were based on primary data of scientific importance and reliability, and the data are processed or supplemented with the actual situation of the research subject to draw the required conclusions. All the studied secondary papers clarified their data sources and every of them were peer-reviewed.

In addition, it should be noted that the selected literature must be studied with 100% PLA polymers or PLA products. PLA composites will not be considered in this project, so the results of comparison could be more clearly. Besides, the selected literature must have a complete LCA analysis process for PLA. The scope of the selected literature must start from the feedstock cultivation of PLA, and studies that only perform LCA analysis on one part of the PLA life cycle will not be selected for the study.

Next, the theory of meta-analysis will be conducted in this project to evaluated the difference among those published LCA studies, including objectives, functional units, scope, feedstock and geography, data sources, impact categories, and final results. In this study, these findings were grouped in the table named "*The results of life cycle impact assessment in the selected literature and parameters of literatures"* (see in Appendix)

Next, a gap analysis was conducted. Based on the results of the literature review, the differences between the different literatures will be compared initially summarized. And the causes leading to gap will be further explored to find some conclusions. And then more LCA studies will be considered.

The following aspects will be considered:

1. The scope of LCA.

   Generally, according to the endpoints of the study, the LCA of PLA can be divided into two broad categories: from cradle to gate and from cradle to grave. Studies from cradle to gate could be subdivided into from cradle to factory gate and from cradle to consumer gate. Studies from cradle to grave can be considered as the combination of from cradle to consumer gate and the end-of-life section.

2. Feedstock.

   In this study, the details of the cradle in each LCA study will be also focused. The raw materials for PLA are generally crops with high sugar content such as corn and sugarcane. Different raw materials will lead to different life cycle trajectories, such as the different carbon emissions during crop growth and the different impact of pesticides and fertilizers required for crop cultivation on the natural environment.

3. Geography.

   Geographic location has a large impact on the life cycle of PLA, which is mainly expressed through the environmental impact of the transportation process between different links. In addition, geographic location also determines the environment in which crops are grown, so there may be differences in resource inputs.

4. Data source.

   Identify the data sources used in different literature and collate the differences between different data sources across the lifecycle of PLA. Analyze how and how much these data differences affect the results of the lifecycle evaluation.

5. Impact categories

   To present the environmental performance of PLA more visually, the results of the inventory analysis will be converted into contributions to the relevant impact categories. And the evaluation of PLA may be different for different environmental categories. For this purpose, the differences in the comparative results of the environmental performance of PLA and traditional fossil-based plastics in terms of different impact categories must be analyzed. Thus further identify where PLA performs better and where it performs worse relative to traditional fossil-based plastics in terms of environmental impacts over the entire life cycle, and validate the environmental hotspots over the life cycle of PLA.

5. Results

A total of 26 research papers analyzing and evaluating the life cycle of PLA were reviewed to answer the research questions, whether PLA has a better environmental performance than traditional fossil-based plastic or not. The timing of these publications is shown in Figure 4, with 1-2 LCA research papers on PLA being published each year since 2009. It is noteworthy that the number of published literature is significantly higher in 2021 than in other years.

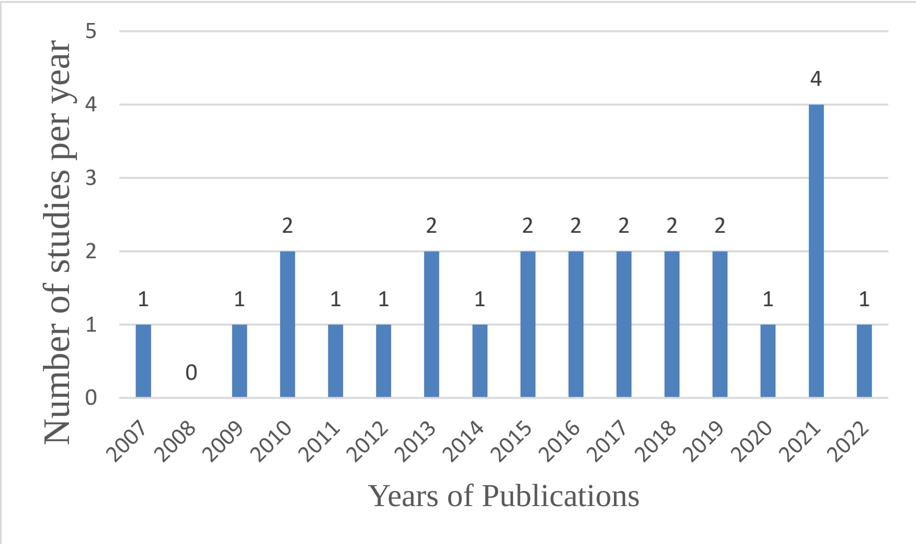

Figure 4: Years of Publication

As shown in Figure 4, most of the papers were published in recent years, so that the accuracy of the information and findings is guaranteed. These LCA papers are divided into 2 categories according to the scope of the study: 1) from cradle to gate and 2) from cradle to grave, including all life cycle sections of PLA.

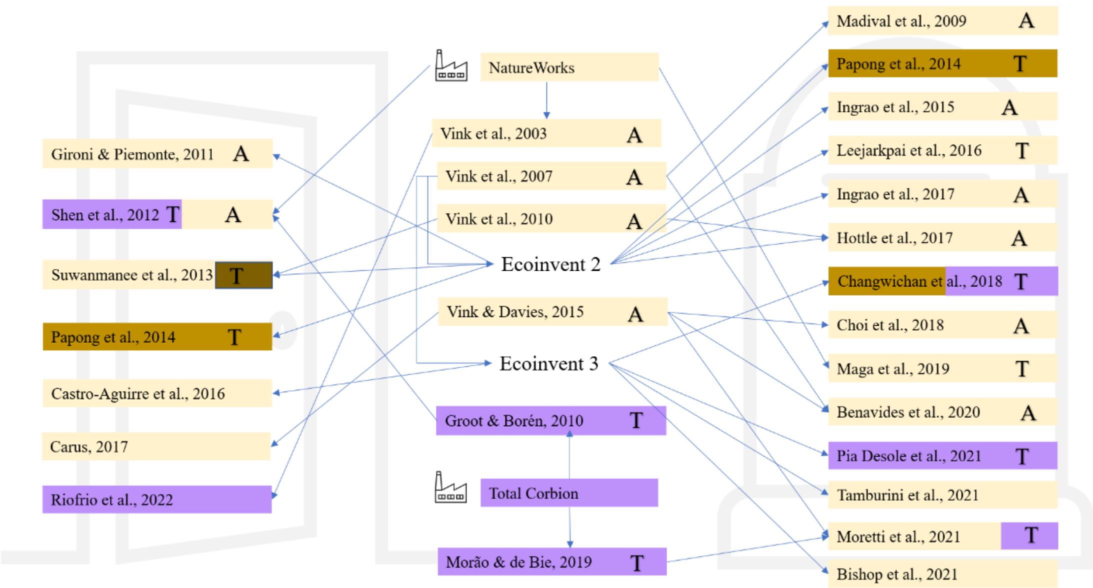

Figure 5: Results of literature reviewing

In Figure 5, publications of the left have the cradle-to-gate scope and those of the right are cradle-to-grave. Purple signifies sugarcane, yellow stands for corn and brown refer to cassava as feedstock. The arrows point to the sources of LCA data for PLA. The letters show different origins of feedstocks, for example, A means America and T means Thailand. In the figure above, some studies point to multiple data sources because they use combined data sources, such as PLA production data from Natureworks, and data of corn cultivation and Eol section of PLA from ecoinvent database.

As can be seen from the figure above, most of the studies were conducted with corn as feedstock, and the origin of corn was mostly the United States. There are 60 percent of reviewing publications whose studied scope is cradle to grave. However, during reviewing, it was found that, because of ignoring of consumption stages, these studies generally divided from cradle to gate and Eol into two parts to calculate and compare them separately.

5.1 Data sources

In reviewing the literature, it was found that when conducting LCA on PLA or fossil-based plastic, the various studies' choices of data sources are not dispersed.

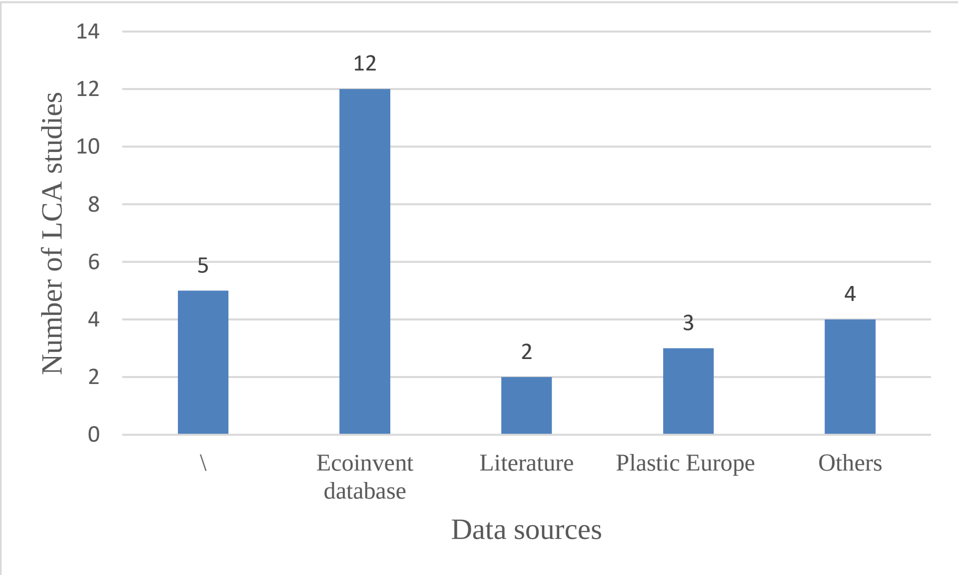

Figure 6: Data Sources of LCA of fossil-based plastics

Not all the reviewed studies compared LCA results for PLA and for fossil-based plastics. Among the 26 reviewed papers, there were 5 studies without comparing LCA results of PLA with LCA results of fossil plastics, which was shown as “\” in the above figure. About half of the total LCA studies for fossil-based polymers were based on ecoinvent database. Plastic Europe provided data support for 3 studies. There were 2 studies that conducted life cycle assessment based on the results of previous literature. The rest of the literature is based on other databases or did not specify the data sources for LCA of fossil-based plastics within the article.

The source of most of the LCA of PLA research data can be traced back to two of the world's best-known PLA producers: NatureWorks (U.S.) and Total Corbion (Netherlands). NatureWorks' manufacturing facilities are primarily established in North America and the Asia Pacific region, and Total Corbion's facilities are concentrated in the Asia Pacific region. Besides, as reported by Corbion, they are planning to open new PLA manufacturing facilities in Europe.

The earliest research on life cycle assessment of PLA dates back to a study conducted by Vink et al. in 2003 on NatureWorks' product Ingeo. As the first study to make PLA eco-profiles available to the general public, the team referenced the format of the eco-profiles for traditional petrochemical plastics published by the European Plastics Manufacturers Association, using the same methodology, software, and core database, and presented the analysis in the same format. This allowed for a more direct comparison of the differences between the eco-profiles for PLA and traditional fossil-based plastics.

Thereafter, in 2007, Vink et al. conducted another life cycle assessment for NatureWorks' new product, Ingeo 2005. In this study, the global warming potential of 1 kg of Ingeo polymer is 2.023 kg of carbon dioxide equivalent [52]. In 2010, the ecological profile of Ingeo 2009 CIT was made publicly available in the same format. The results of life cycle assessment of this product showed that the value of GWP is 1.24 kg of carbon dioxide equivalent. In 2015, Vink et al. conducted another life cycle assessment for the newest product, Ingeo 2014, and the GWP index is 0.62 kg of carbon dioxide equivalent. Compared to previous studies, this study also analyzed other environmental indicators besides energy and GWP.

It is obvious that with the development of time, the carbon footprint of PLA resin reported by Vink[34], [52], [54] also decreased. NatureWorks gave a clear explanation that at the end of 2008, a new way of producing lactic acid was introduced and led to the manufacture of Ingeo 2009, which was subsequently replaced by Ingeo 2014 as the first improvement. The production data remained unchanged during this period, but the latest LCA database was used in the 2015 study, which led to the difference in results.

In these above studies, all data are derived from NatureWorks' primary plant data and field research. More specifically, the data for the Feedstock cultivation phase was derived from local average corn growth data. Other production data, such as glucose production, lactic acid production, lactide production, and finally polymer production, were obtained from NatureWorks plants.

In the reviewed literature, the earliest LCA study based on Corbion's plant data is from Groot & Borén, 2010[55]. At that time, this PLA manufacturer was known as Purac, and in 2017, officially changed its name to Corbion, and became a globally known manufacturer of lactic acid. A portion of the lactic acid manufactured by Corbion is shipped to Total Corbion PLA, which is the PLA manufacturer, where the lactic acid is synthesized into PLA. In 2019, Corbion supported Morão & de Bie, 2019[56] in conducting an LCA of PLA product named Luminy produced at the Total Corbion PLA manufacturing plant in Thailand. In this study, the PLA production data was derived exclusively from operational or design data from Total Corbion's plant, and other supporting data, such as sugarcane cultivation processes required for the sugarcane growing process, were obtained from Agri-footprint V2.0.

The ecoinvent database is indispensable for almost all of the LCA research literature on PLA. A query of the ecoinvent database revealed that the source of PLA production data for ecoinvent V2 was NatureWorks, which is also known as the data made public in Vink et, al., 2007[52], and the location of data adaptation was modified from the U.S. to global by the internal model of ecoinvent. In 2013, ecoinvent launched the third version of its database. However, according to ecoinvent, there is no data updates regarding of PLA production. Therefore, it can be assumed that the research literature using the ecoinvent database is also based on the NatureWorks plant data in 2007. Furthermore, in addition to the production data of PLA, ecoinvent also provides other supporting data, such as inputs and outputs during transportation, data on the cultivation of different crops in different countries, etc.

The data sources were clearly stated in all the reviewed publications. There were five papers using production data from Total Corbion PLA, and the feedstock in these publications was always sugarcane cultivated in Thailand. There was only one study using primary data from field research and using the ecoinvent database as a supplement, whose feedstock was cassava from Thailand. While the rest of the studies used data from the ecoinvent database or Vink's publications, which can be considered that they were all based on NatureWorks' production data. It can be said that the feedstock of the PLA product under study determines the choice of database.

By comparing the two papers based on different original plants data and their LCA results, it was found that, in Morao, 2019[56], Total Corbion's PLA products have less global warming potential and non-renewable resource impact and higher renewable energy consumption than NatureWorks' Ingeo.

In addition, all the five studies based on Total Corbion production data concluded that PLA performs better in terms of GWP, and energy consumption compared to traditional fossil plastics. However, in the NatureWorks-based studies, there were differences in the conclusions. For example, Castro[57] and Elena[58] concluded that PLA has a higher GWP than PET, while other studies held the opposite opinion. However, it is difficult to prove that Total Corbion's production data has a better environmental performance than NatureWorks' data. This is because there are more critical influences, such as the fact that researchers often add or use a lot of local data to supplement or replace the original database in order to accommodate local studies. Therefore, further analysis of other variables is needed.

5.2 Feedstock and geography

In the analysis of the data sources of LCA of PLA, it was found that the choice of data source was highly dependent on the feedstock. For example, when the feedstock is sugarcane from Thailand, the data source generally uses the production data from Total Corbion PLA, and when the feedstock is corn, the data source can generally be traced back to the production data from NatureWorks. Therefore, the choice of feedstock is very important for the life cycle assessment of PLA.

Most biobased plastics are currently manufactured using starch as a feedstock (about 80% of current biobased plastics) [59]. The main sources of this starch are currently corn, potatoes, and cassava. Other potential sources include bamboo yams, barley, some species of vines, millet, oats, rice, sago, sorghum, sweet potatoes, taro, and wheat. There are also renewable plant materials such as lignocellulose (bagasse, wood chips, willow branches) and seaweed that can be used to produce biopolymers. However, the conversion cost of such raw materials is high, so they are not yet available on a commercial scale. According to Natureworks, they are working on technology to convert methane or carbon dioxide directly into lactic acid [60].

As a typical bio-based plastic, different with traditional fossil plastics that use non-renewable energy sources such as petroleum as feedstock, corn, sugarcane and cassava are the most common feedstock used to produce PLA, as shown in Figure 5. The main producers of these three crops are the United States [54] and Thailand [56]. The inputs required to grow and harvest different crops in different regions also vary. From the life cycle of PLA, it could be noticed that after the carbohydrates in the feedstock have been extracted and converted into glucose, the choice of the original feedstock no longer affects the following steps. So, it could be concluded that the difference in feedstock affects the LCIA results mainly occurs in the growing, harvesting, and processing stages.

Corn is undoubtedly the most popular feedstock for the preparation of PLA, since it is the world's most productive and important food crop and has a competitive cost, Besides, the maturity of intensive farming systems for industrial corn is very high and it could grow on a large scale in almost every part of the world.

Corn cultivation in the United States is generally high in scale and mechanization. The United States is the world's largest producer of corn, with approximately 348 million tonnes of corn produced in 2019, accounting for approximately 31.3% of total global corn production [61]. Of this, approximately one-third is used as feed for livestock, one-third is used to make ethanol, and the remainder is used to produce food, industrial products or for export. The United States has a high rate of fertilizer application for corn production, so the manufacture and use of fertilizers and agrochemicals contribute most to the environmental impact of the corn production process. And according to the work of Vink, the contribution of these agricultural equipment to environmental impact can be negligible.

For **corn cultivation in Thailand**, it is less mechanized than in the United States and sometimes relies on human harvesting. And Thai farmers will use open burning after the harvesting process to prepare the land for the next planting activity [62]. So, the cultivation process of corn in Thailand includes land preparation, planting, weeding, farming, harvesting, milling and post harvesting [63].

Cassava cultivation in Thailand involves the following steps: land preparation, planting, crop maintenance (fertilization, weed control), and harvesting. In these processes, the input elements mainly include diesel fuel (for mechanical operation and transportation), fertilizers, herbicides (cassava growers in Thailand generally choose paraquat and glyphosate as common herbicides), water for irrigation, solar energy [64]–[66]**.**

Sugarcane cultivation in Thailand generally consists of land preparation, planting, maintenance and harvesting stages. The land preparation stage is fully mechanized with 2-3 tillage before the middle. Planting is mechanized in most areas, but there are still areas where sugarcane is planted manually. The chemical fertilizers used in sugarcane cultivation vary across Thailand, generally with NPK ratios of 16:8:8 and 15:15:15, with some areas using both chemical and biological fertilizers. Most Thai sugarcane farms rely on rainwater as a source of irrigation water. Thai sugarcane is harvested once a year, and in the majority of cases the harvest is done by hand. After the harvest stage, Thai farmers burn the sugarcane residue (leaves and roots) on site for the next cultivation [67].

During the literature review, it is found that was a small number of studies that directly compared the differences in life-cycle environmental impacts of PLA products using different crops as feedstock. However, as different crops require different inputs of energy and fertilizer at different stages of cultivation, and the processing methods are also various, the resulting environmental impacts in terms of ecotoxicity, acidification, eutrophication, climate change, water use, and land use vary. According to a previous study, corn cultivation requires more than 10 times more fertilizer inputs than sugarcane cultivation, so corn has a much higher GWP than sugarcane [68].

In addition, the environmental and economic impact of crop production depends to a large extent on the geography, especially since different regions have different water sources and varying precipitation conditions, and therefore depend on irrigation to a different extent[69]. Besides, geography can have an impact on transportation, in addition to the resource inputs required for crop growth. For some papers, the contribution of transportation to the life cycle environmental impact is found to be non-negligible.

5.3 Scope and its impact on climate change results

The scope of inquiry for a PLA life cycle assessment often includes from cradle to gate and from cradle to grave. The choice of scope can have a great influence on the LCA results of PLA [50]. When the scope is from cradle to grave, CO_2 will be released into the atmosphere at the end of the life of the PLA product, which will lead to a higher global warming potential result of LCA calculation. While when the scope is from cradle to gate, it means that the CO_2 absorbed from the environment by feedstocks will be stored in the PLA product, which will lead to a significant decrease in the global warming potential index. For studies with the scope from the cradle to the gate, as shown in Figure 7 below, it is necessary to distinguish whether the specific scope is from the cradle to the factory gate or from the cradle to the consumer gate.

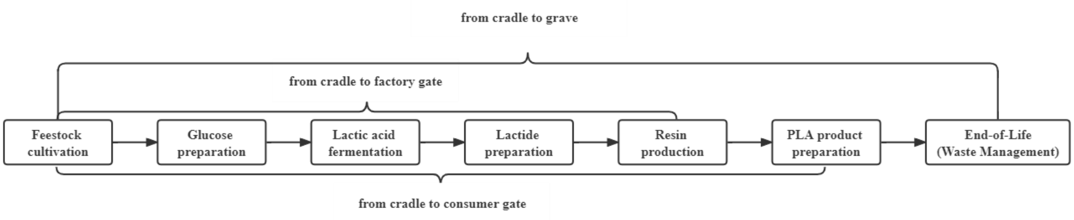

Figure 7: Different scopes of LCA of PLA.

In this section, the extent to which the global warming potential of PLA varies across the different scopes studied will be compared. This is because it was discovered throughout the literature review that global warming potential, the environmental impact category that has received the most attention in these past studies, while other environmental impact categories have been largely ignored [70]. It is possible to visualize the impact of the choice of scope on the results by examining the variation of this indicator.

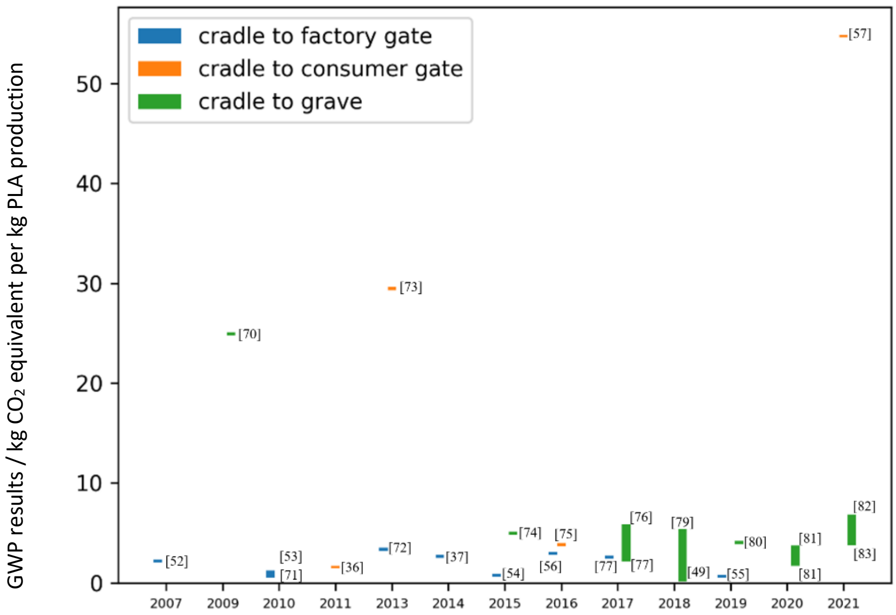

Figure 8: Reported LCA ranges of GWP for PLA with different scopes from the reviewed studies. (Outliers have been excluded from the chart for visualization purposes)

Since in previous studies, the results of GWP were generally calculated as kg CO_2 equivalent per function unit, and the function unit was always different for each study, it was difficult to visually compare the differences between the results of different studies. Therefore, in this project, those raw results were converted to kg CO_2 equivalent per kg PLA production, where if the scope of the study is from cradle to factory gate, then PLA production here is PLA resin, otherwise it is PLA products such as PLA packaging foils. The result of the conversion is shown in the following tables (Table 1 - 3). In these tables, the results on the green background are the raw data directly from the papers, while the results on the original background are the calculated data in this project. Besides, in those tables, the performance of PLA and other materials in this indicator is compared, that is, the material located to the left of the lesser sign performs better. For details on the original data see Table A3 *The results of life cycle impact assessment in the selected literature and parameters of literature* in Appendix.

Figure 8 shows the range of the values of GWP results of each reviewed paper. The horizontal axis is the years of publications, and the vertical coordinate is the transformed value of GWP results reported in these studies. The source of each data is clearly labeled in the figure. The different scopes are distinguished by different colors. From the above figure, it can be found that the range of these results does not differ much when the scope of the study is cradle to factory gate. In contrast, when the study range is cradle to grave, different studies in the same year show more different results. In addition, there are three outliers in the graph, the specific reasons for which will be analyzed in the next text.

In the early days of LCA analysis of PLA, scope from cradle to gate scopes was preferable, while nowadays the end-of-life link of PLA is increasingly taken into account. Similarly, climate change-related indexes were devoted much attention in the early days, and other metrics were studied sparingly. But nowadays, studies consider a more comprehensive environmental impact.

In some of these 26 studies, the results could not be converted to the required units (kg CO_2 equivalent per kg PLA production) according to the above-mentioned calculation process, so in the following analysis, the specific values of GWP in these studies are also not being considered, only the comparative results of the LCA of PLA and fossil-based plastics will be focused. As can be seen from the above figure, after removing the outliers, the GWP values reported in these studies still have non-negligible differences, especially when the studied scope is cradle to grave. The reasons for the differences will be analyzed next according to the different study scopes.

Firstly, as to the papers with cradle to factory gate scope, Vink's team have been doing several LCA studies of PLA from cradle to factory gate based on the PLA product named Ingeo produced by Natureworks, which is one of the most famous PLA producers all over the world. Vink's study is very meaningful for PLA-related studies, and almost all other studies with corn as the feedstock will use Vink's latest study data as one of the data sources [54]. Vink's studies not only clarify the detailed process and data of Ingeo production, but also publishes the material flow data during the life cycle of Ingeo.

Table 1: GWP results and comparison in different literatures with cradle to factory gate scope
*PLLA: Poly-L-lactic acid, PET: Polyethylene terephthalate, PS: Polystyrene, TPS: Thermoplastic Starch, HDPE: High-density polyethylene, PP: Polypropylene, LDPE: Low-density polyethylene

Reference	Feedstock	Scope	Results (kg CO_2 eq/kg PLA)	Comparison (< means better performance)
Vink et al., 2007 [52]	Corn in America	cradle to factory gate	2.023	\
Vink et al., 2010 [53]	Corn in America	cradle to factory gate	1.24	\
Groot & Borén, 2010 [55]	Sugarcane in Thailand	cradle to factory gate	0.50-0.80	PLLA<PET<PS
Shen et al., 2012 [35]	Corn in America	cradle to factory gate	1.3	PLA<PET
	Sugarcane in Thailand		0.5	PLA<PET
Hottle et al., 2017 [71]	Corn	cradle to factory gate	3.2	TPS<HDPE<PP<LDPE<PET<PLA<PS
Vink & Davies, 2015 [54]	Corn in America	cradle to factory gate	0.62	\
Castro-Aguirre et al., 2016 [57]	Corn	cradle to factory gate	2.79	LLDPE<HDPE<PP<LDPE<PET<PLA<PS
Morão & de Bie, 2019 [56]	Sugarcane in Thailand	cradle to factory gate	0.5	\
Papong et al., 2014 [37]	Cassava in Thailand	cradle to factory gate	2.48	PLA<PET
Carus, 2017 [72]	Corn	cradle to factory gate	2.44	PE<PLA
Riofrio et al., 2022[73]	Sugarcane in Ecuador	cradle to factory gate	\	HDPE<PP<PET<PLA

In other studies, with cradle to factory gate scope [37], [57], [72] , PLA generally performs better than alternative polymers in GWP terms. However, in the paper by Hottle et al., PLA only outperformed PS and causes a stronger greenhouse effect than all other materials studied which other materials, including TPS, PP, HDPE LDPE, and PET. This is because Hottle et al. use only empirical data from the ecoinvent database and therefore set up the scenarios with longer transport distances than the other papers.

Besides, the results of works from Vink [52]–[54], Groot[55] and [56], are significantly lower than others work. One possible reason is that the data sources in the researches from Vink and Morão are the famous leaders in the global market of PLA, like Natureworks and Total Corbion. Those famous producers would prefer renewable energy to power the production of PLA. In Groot's study [55], the remaining biomass was burned as one of the energy sources, thus reducing the fossil energy demand in the production process. In other sources, the database of ecoinvent is generally used directly, without considering alternative energy sources, and thus the GWP values are relatively high.

There are 5 papers whose scope is determined as from cradle to consumer gate and generally have an additional product manufacturing section after cradle to factory gate, like shown in Figure 7 [36], [58], [74], [75] [73]. In those reviewed papers, the function units were generally PLA packaging, such as PLA boxes and bottles. Again, PLA continued to perform better than fossil-based materials, like PET[36], PS [75], LDPE [73], in GWP impact.

Table 2: GWP results and comparison in different literatures with cradle to consumer gate scope

Reference	Feedstock	Scope	Results (kg CO_2 eq/kg PLA)	Comparison (< means better performance)
Gironi & Piemonte, 2011 [36]	Corn in America	cradle to consumer gate	1.41	PLA<PET
Suwanmanee et al., 2013 [75]	Corn and cassava in Thailand	cradle to consumer gate	29.3	PS<PLA<PLA/starch
Leejarkpai et al., 2016 [74]	Corn in Thailand	cradle to consumer gate	3.673	\
Tamburini et al., 2021 [58]	Corn	cradle to consumer gate	54.6	PET<PLA
Riofrio et al., 2022 [73]	Sugarcane in Ecuador	cradle to consumer gate	\	LDPE<PLA

In addition, it is interesting to note that the choice of scopes has become more from cradle to grave over time. There were 10 of the 25 papers whose studied scopes were only from cradle to gate. Among them, except for the LCA studies done by Erwin T.H. Vink and Ana Morão, which only focus on NatureWorks and Total Corbion PLA products, respectively, there were 5 of the remaining 7 papers were published in 2010-2013. This is a side-effect of the continued tightening of global waste management policies, which makes the impact of the EOL section on the LCA of PLA product increasingly important.

Table 3: GWP results and comparison in different literatures with cradle to grave scope

PBAT: Polybutylene adipate terephthalate, PHA: Polyhydroxyalkanoates, PBS: Polybutylene succinate, APET: Amorphous Polyethylene Terephthalate, RPET: Recycled Polyethylene Terephthalate, SPLA: Sugarcane-based Polylactic acid, CPLA: Cassava-based Polylactic acid, XPS: Extruded polystyrene,

<table>
<tr><th>Reference</th><th>Feedstock</th><th>Scope</th><th colspan="2">Results (kg CO_2 eq/kg PLA)</th><th>Comparison (< means better performance)</th></tr>
<tr><td rowspan="2">Papong et al., 2014 [37]</td><td rowspan="2">Cassava in Thailand</td><td>cradle to grave+100% landfill</td><td colspan="2">7.93-8.85</td><td>PET<PLA</td></tr>
<tr><td>cradle to grave+100% incineration</td><td colspan="2">2.64-3.56</td><td>PLA<PET</td></tr>
<tr><td>Madival et al., 2009 [76]</td><td>Corn in America</td><td>cradle to grave</td><td colspan="2">24.8</td><td>PS<PLA<PET</td></tr>
<tr><td>Ingrao et al., 2015 [77]</td><td>Corn in America</td><td>cradle to grave</td><td colspan="2">4.826</td><td>\</td></tr>
<tr><td>Ingrao et al., 2017 [78]</td><td>Corn in America</td><td>cradle to grave</td><td colspan="2">5.85</td><td>\</td></tr>
<tr><td>Carus, 2017 [72]</td><td>Corn</td><td>cradle to grave + incineration</td><td colspan="2">2.09</td><td>PLA<PE</td></tr>
<tr><td rowspan="2">Choi et al., 2018 [79]</td><td rowspan="2">Corn in America</td><td>cradle to grave+100% incineration</td><td colspan="2">5.38</td><td>PLA<LDPE< PLA/PBAT</td></tr>
<tr><td>cradle to grave+100% landfill</td><td colspan="2">2.24</td><td>PLA<LDPE< PLA/PBAT</td></tr>
<tr><td rowspan="5">Changwichan et al., 2018 [49]</td><td rowspan="5">Cassava or Sugarcane</td><td rowspan="2">cradle to grave+ 70% Landfill +30% Composting</td><td>SPLA</td><td>CPLA</td><td rowspan="5">PBS<PHA<SPLA<CPLA</td></tr>
<tr><td>3.13</td><td>3.41</td></tr>
<tr><td>cradle to grave+ 100% Composting</td><td>2.70</td><td>2.98</td></tr>
<tr><td>cradle to grave+ 100% Recycling</td><td>0.11</td><td>0.28</td></tr>
<tr><td>cradle to grave+ 100% Incineration</td><td>2.84</td><td>3.13</td></tr>
<tr><td>Maga et al., 2019 [80]</td><td>Corn</td><td>cradle to grave</td><td colspan="2">3.89</td><td>PP<PLA<RPET<XPS<APET</td></tr>
<tr><td rowspan="3">Benavides et al., 2020 [81]</td><td rowspan="3">Corn in America</td><td>cradle to grave (Landfill+ 0%BD)</td><td colspan="2">1.7</td><td rowspan="3">Bio-PE<PLA landfill with 0% biodegradable (BD)<HDPE<LDPE< PLA composting with 60% BD<PLA Landfill with 60% BD</td></tr>
<tr><td>cradle to grave (Landfill+ 60%BD)</td><td colspan="2">3.7</td></tr>
<tr><td>cradle to grave (Composting+ 60%BD)</td><td colspan="2">3.3</td></tr>
</table>

Bishop et al., 2021 [82]	Corn	cradle to grave	6.83	\
Moretti et al., 2021 [83]	Corn in America Sugarcane in Thailand	cradle to grave	3.8	PP<PLA<PET

As discussed previously, as the only difference to cradle to consumer gate scope, the EOL section will be taken into account when the study is extended to from cradle to grave.

When the EOL section is not specified, as studies [76], [80], [83] show, PLA consistently performs better than PET, but worse than materials like PP [77], [83] or PS [76].

When the EOL section is specified, conclusions differ with different EOL scenarios. When energy recovery is not considered, PLA will have a higher value of GWP than PET [76] [37], and the values of GWP of PLA decreased with the decrease of the degree of biodegradation [76]. When energy recovery is considered, the recovered energy is credited to the PLA's life cycle inventory as a negative carbon credit, and therefore exhibits a significantly lower GWP value and shows that PLA performs better than PET [37], [60].

It is not difficult to find that different EOL options are an important reason for the large disparity in GWP results in different studies.

Through the analysis in this chapter, the results of GWP show two tendencies in the time dimension and the scope dimension. The GWP of PLA shows a decreasing trend as the time of literature publication increases. For example, Vink's three works ranged from 2.023 kg CO_2 eq/kg PLA in 2007 to 1.24 kg CO_2 eq/kg PLA in 2010 to 0.62 kg CO_2 eq/kg PLA in 2015. As an important data source for many subsequent LCA of PLA, Vink's conclusion will have implications for other studies. Besides, in the scope dimension, the mean value of the results of these studies was 1.77 kg CO_2 eq/kg PLA when the study scope was from cradle to factory gate, while the mean value of the results of the researches was 2.54 kg CO_2 eq/kg PLA when the study scope was from cradle to consumer gate, and similarly, when the study range was from cradle to grave, the mean value of the study works was 4.5 kg CO_2 eq/kg PLA. In addition, in studies specifying different EOL scenarios, it was found that different EOL choices had different impacts on the results. The greenhouse gas emissions will increase with the increasement of biodegradability of PLA.

The concept of carbon credit could be introduced to explain this phenomenon to some extent. There are two main approaches to calculating the carbon credit in PLA: 1. Carbon is considered to be CO2 neutral and excluded from the inventory analysis, or, 2. Carbon is accounted for as carbon storage. In theory, carbon storage is considered reversible in most cases and will inevitably increase carbon emissions in the future, but it does delay carbon emissions and offset current anthropogenic carbon emissions.

According to the European Commission's Leading Market Initiative, when the scope of study is from cradle to gate, biogenic carbon in PLA should be excluded from the total carbon calculation. The carbon absorbed by photosynthesis from the atmosphere during the cultivation of feedstocks and the input energy and other materials consumer in the process of production of PLA is sequestered in PLA pellets or products as carbon atoms. When LCA was taken, carbon storage appears to have reduced outputs, which result in the better performance of LCA of PLA.

When the scope of study is from cradle to grave, industrial incineration allows some of the released carbon to be converted into usable energy, which to some extent offsets some of the carbon emissions. Whereas when PLA was completely landfilled with no biodegradation, the carbon remains sequestered in the PLA product, and when biodegradation occurs, the carbon is gradually released into the environment. Thus, the GWP results of PLA from industrial incineration should be higher than those only stays in the consumer gate, and likewise higher than PLA landfilled without biodegradation, but should be lower than PLA which was landfilled with biodegradation. These results provide some evidence that the choice of scope has an impact on the results of the life cycle analysis.

Overall, the results calculated in each paper were different. However, concentrating on the values of GWP would make the comparison more obvious. In general, the GWP is lower when the scope is from cradle to factory gate relative to from cradle to consumer gate. The results of several papers with the study scope from cradle to grave were generally somewhat larger than those with the study scope from cradle to factory gate. The effect of the EOL sector is always significant.

However, not all the reviewed literature was analyzed in this section. Because some literature does not have clear data calculations, it is not possible to compare the analysis with other literature. There is also some literature that focuses only on the LCA of the EOL section, which are also not meaningful for comparative analysis in this section.

5.4 Impact categories other than climate change

In reviewing the literature, it was found that as more and more attention has been devoted to PLA, the variety of environmental impact categories selected for LCA studies on PLA has increased. The average number of environmental impact categories studied in these reviewed papers was close to 8 as shown in Figure 9.

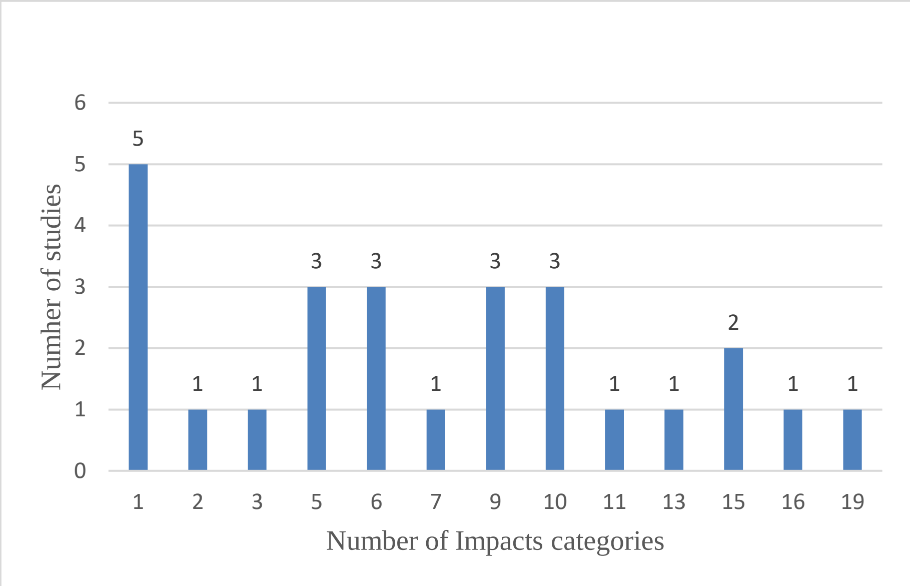

Figure 9: Number of impact categories (The horizontal axis indicates the number of impact categories in these LCA studies, and the vertical axis means the times of the studies with the corresponding number of impact categories)

All of the reviewed studies considered global warming potential, and five studies assess only this one environmental impact. In addition, the most common impact categories are acidification potential (studied for 17 times), eutrophication (studied for 24 times), toxicity (studied for 18 times), ozone depletion (studied for 11 times), photochemical ozone formation (studied for 7 times), resources depletion (studied for 21 times), water depletion (studied for 8 times), and land use and change (studied for 12 times).

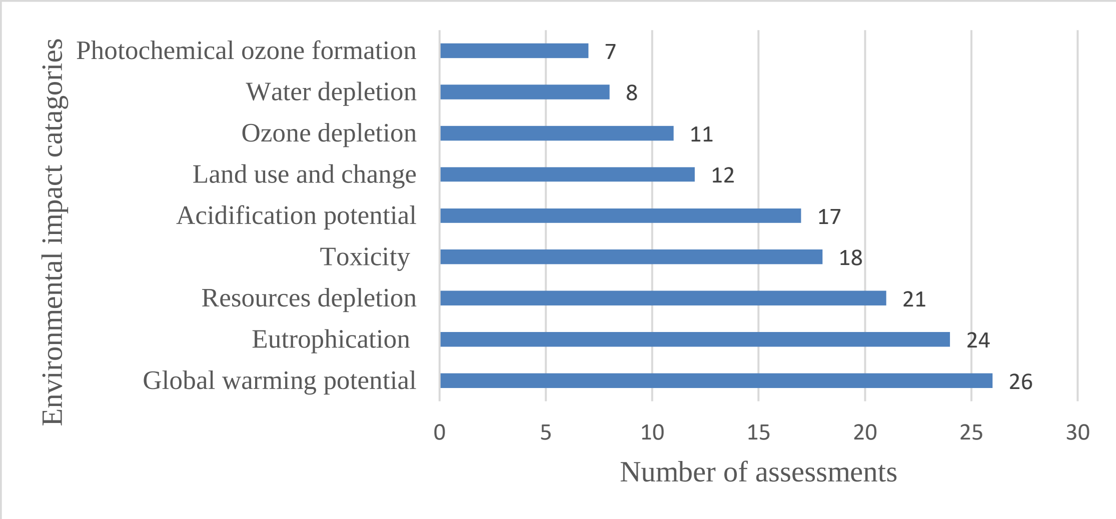

Figure 10: Number of assessments of different impact categories

It is worth noting that the eutrophication counted here includes freshwater eutrophication, marine eutrophication, and terrestrial eutrophication potential. The indicator of toxicity includes human eutrophication and ecotoxicity potential. Resources depletion is divided into renewable energy depletion and non-renewable energy depletion.

In some studies, the study method was not explicitly stated. However, in the remaining studies, IMPACT 2002+ was the most commonly used study method, followed by CML 2001, and ILCD 2011+ has been the more popular analysis method in recent years. Those LCA method also affect the environmental impact of polymers in different geographical locations and compare different LCA methods allows to examine the environmental impact of polymers in different regions [84]. Figure 11 showed the frequency of different LCA analysis methods in this project.

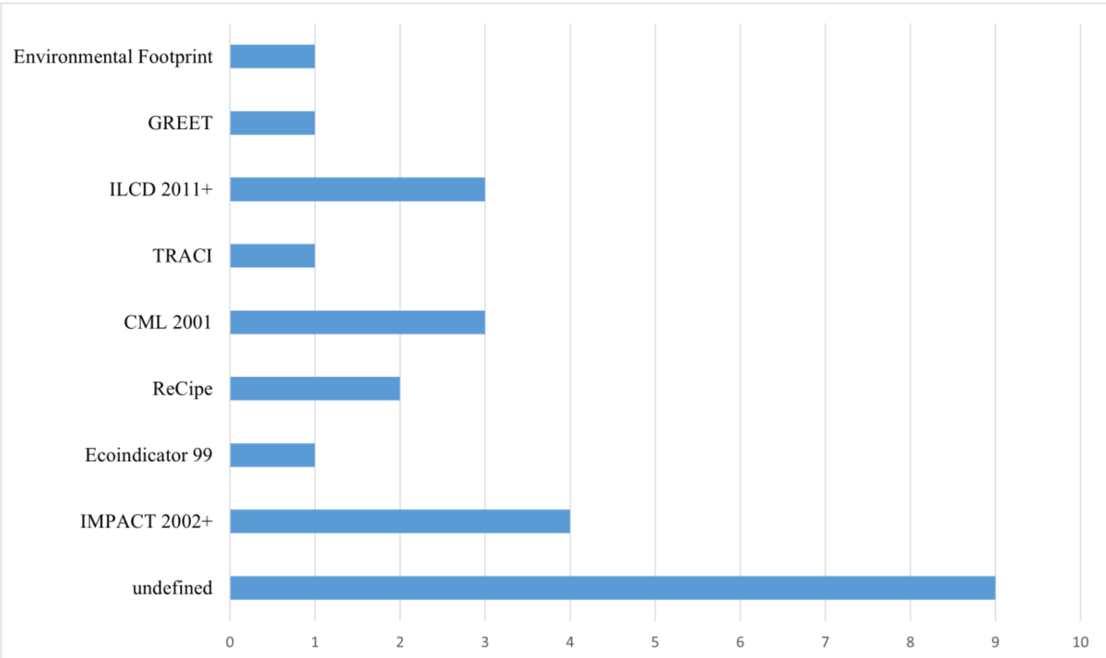

Figure 11: Life cycle assessment methods used in reviewed publications

During the previous analysis, GWP was the impact category that received the most attention, and as PLA has received more and more attention, the number of environmental impact categories evaluated in the LCA of PLA has increased. In reviewing the literature, it was found that for some environmental impact categories, PLA performs better than fossil-based plastics, while for other environmental impact categories, PLA has a worse environmental performance.

In almost all the reviewed studies, PLA performed worse than any other polymers in water-related impact categories, including aquatic acidification, eutrophication, and water depletion. There was only one paper showing a totally different result with other studies [73]. The same anomaly is also manifested in the toxicity indicators. It is important to distinguish between ecotoxicity and human toxicity. In general, PLA performs worse both in terms of eco-toxicity and human toxicity compared to traditional fossil-based plastics [58], [71], [85]. Whereas the results reported by Ariel in 2022 [73] demonstrated that PLA performed better in human toxicity. There is no comparison about these differences and reasonable explanations in this paper. However, a closer look at this literature reveals that the PLA in this study was imported, not locally produced, and the authors only calculated the ecological impact on the local area, so the results of this paper differ from the conclusions of other studies in many of the results of the impact analysis.[76]

For ozone depletion, PLA performed worse than other polymers in most studies but reported better than PET by Madival in 2009[76]. It was explained that transportation of the resins and containers of PET contributed more to ozone depletion by Madival [58], [76].

When compared in terms of resources consumption, PLA always performed better than fossil-based polymers in non-renewable resources while worse in renewable resources. In addition, land use and land change are the only impact category where PLA performed relatively poorly in all studies.

5.5 Uncertainty assessment

Uncertainty assessment does not affect the calculation results but affects the reliability of LCA results. The sources of uncertainty in LCA studies often include models, scenarios, and parameters, data sources [86]. Quantitative uncertainty assessment is often lacking in the most of the reviewed LCA studies, and this means that the confidence level of these LCA results is also unreliable.

In the reviewed literature, only 2 studies performed uncertainty analysis [78], [82], and both chose Monte Carlo simulation for 1000 iterations to analyze parameter uncertainty, which are the most commonly used analysis method and source of uncertainty in LCA studies. These two papers adopted consequential life-cycle assessment [82] and attributional life-cycle assessment [78], respectively. In both two studies, the test results for uncertainty were within the confidence interval [78], [82].

6. Discussion

This project analyzes the environmental performance and sustainability of PLA from the perspective of LCA research by reviewing a total of 26 peer-reviewed academic papers. The reasons for the differences in the results of different studies were analyzed and summarized from the perspectives of data source, study scope, feedstock, geography, and impact categories, respectively. Through the analysis in the previous sections, it is evident that these factors have more or less an impact on the results of the comparative analysis of the environmental performance of PLA and fossil-based plastics over their life cycle, and that these factors are interlinked.

6.1 The differences from different parameters

First, LCA studies of PLA are generally based on the two most original plant data: NatureWorks (corn-based) and Total Corbion (sugarcane based). The choice of data source depends on the type of raw material. When using corn-based PLA products as research and analysis subjects, the data source is generally taken directly from NatureWorks academic reports [34], [52]–[54], or from the ecoinvent general database, which is also based on NatureWorks factory data, with some adjustments and changes based on local conditions. And when sugarcane-based PLA products were chosen as the object of study and analysis, the choice of data source varies in this reviewed literature because of the lack of early representative LCA studies for Total Corbion's product Purac. Some are based on the original factories production data and field study [34], [52], [53], [56], [87], some are based on these previous publications [35], [83], and others are based on the ecoinvent database. When the studied object is cassava-based, the data source is generally from the latest ecoinvent database. And data from ecoinvent for sugarcane-based and cassava-based PLA is adjusted from the life cycle inventory of corn-based PLA in ecoinvent general database. The degree of matching between data sources and the feedstock of the study subjects will largely influence the final analysis results. In Riofrio et al., 2022 [73], the feedstock was sugarcane, but the findings of Vink in 2003 (The eco-profile of Ingeo 2003)[34] was set as the data source. The results of this research hold opposite points with almost all other studies in almost all environmental categories.

The results of the LCA of PLA also differed based on the different dates of the reported data. Specifically, before 2010, the LCA studies based on NatureWorks product Ingeo showed less required energy and fewer byproducts than those based on the Purac from Total Corbion in the same period. While by comparing the results of another LCA study of a brand-new PLA performed by Total Corbion in 2019 [56] with the LCA study of Ingeo 2014 reported in Vink & Davies, 2015 [54], it was found that Total Corbion's PLA had better environmental performance. Moreover, with the development of technology, the production process of PLA has been continuously refined and improved, so the environmental impact assessment results of PLA have become better and better.

The effect of different feedstocks on LCA assessment results depends mainly on the inputs and outputs of the feedstock cultivation section. Nowadays, corn, sugarcane and cassava are the three most common feedstocks for PLA production. Corn is grown on a large scale within the United States, while sugarcane and cassava are suitable for hotter climates such as Thailand and Brazil. There are different growing habits in different growing regions. For example, crops in the U.S. are produced with more pesticide and fertilizer inputs, which will result in different LCA results. The process of feedstock cultivation contributes a lot to the entire life cycle of PLA. Feedstock cultivation involves land use change (LUC), and whether or not LUC is considered can make a significant difference to the results. From the results of the analysis, the sugarcane-based PLA products performed the best in the global warming potential indicator. In addition, when comparing these studies, it was found that PLA generally performed better than PET on the GWP indicator when corn was grown in the United States and Thailand. Therefore, geographic location can also have an impact on the results. Firstly, geographic location can affect transportation and thus change the PLA life cycle inventory input data, but differences in transportation distance have not been taken into account in most studies. Second, differences in geographic location can lead to climatic differences, especially in precipitation, and thus can have some impact on water-related metrics.

The scope of the study has the most significant impact on the LCA results of PLA. There is a significant difference between inputs and outputs when the studied life cycle scope is different. From the comparison of the analysis results of global warming potential, PLA performs better when the studied scope is from cradle to factory gate (PLA pellets) than when the scope is from cradle to consumer gate (different PLA products). In addition, during reviewing, it was found that the choice of scope also tends to change from cradle to gate to cradle to grave in the time dimension. When the scope is cradle to gate, the carbon dioxide absorbed through photosynthesis during feedstock cultivation will be stored in PLA waste as organic carbon, so the carbon footprint of PLA is low considering the biogenic carbon benefits. As the only difference between cradle to consumer gate and cradle to grave, the option of EOL may negate these benefits and have a great impact on the LCA results of PLA. The environmental performance of PLA is better when energy recovery is considered, whereas when energy recovery is not considered, the fossil-based plastics can be considered as not undergoing any degradation in the EOL session due to their very stable chemical properties, and thus the GWP performance of PLA is worse than that of fossil-based materials such as PET in this case.

As the number of impact categories studied by LCA of PLA is increasing over time, it is necessary to identify the impact categories that are most relevant to each part of the PLA life cycle. Firstly, feedstock cultivation has a direct impact on water and land related impact categories, while resin production has the greatest contribution to global warming potential. Since PLA feedstock is a renewable biomass resource, non-renewable resource depletion always performs better than fossil-based plastics, and renewable resource depletion performs worse relatively. When comes to other environmental impact categories, PLA performs PLA performs worse than fossil-based plastics in most environmental impact categories due to the complex feedstock cultivation. Cultivation needs a lot of water and land, so PLA performs worse on these indices. The input of fertilizers and pesticides contributes to the higher toxicity and ozone depletion.

In general, the differences in each of these factors contribute to some extent to the differences in the LCA results for PLA. Among them, the choice of study scope, especially the different EOL scenarios, has the most significant impact on the global warming potential indicator in the PLA life cycle. When comparing PLA to other fossil-based plastics, different researchers, based on different situations, have conducted LCA studies of PLA and will come to different conclusions.

6.2 The interlink among those studied parameters

This project reviewed the data sources, feedstock, geography, scope, and impact categories of previous LCA studies of PLA and found that these factors also influence each other.

Geographic location will largely influence the feedstock type, with each region having a different preference, for example, the US prefers to grow corn, while Thailand prefers to grow sugarcane. The difference in feedstock also leads to a diverse choice of data sources. The LCA studies of corn-based PLA prefer original data from NatureWorks, while the LCA studies of sugarcane-based PLA prefer Total Corbion's data. The different varieties of feedstocks and different growing environments also lead to different environmental performance of PLA products based on different feedstocks.

6.3 Comparison with previous review work

Several researchers have already compared the results of LCA of bioplastics and fossil plastics but there were often different results being reported. Moreover, in the past literature reviews, the life cycles of different plastics have been presented substantially, and the cross-sectional comparison of different LCAs is lacking. Therefore, these reviews often conclude that bioplastics are better or worse compared to conventional plastics, but without a clear explanation from a research perspective [88], [89]. This project filled these gaps and gave a clear explanation for the diversity.

6.4 Limitations

In this project, the robustness of these LCA studies was examined. In addition, this project examined the data sources of these studies and validated the database preference and overlaps in data sources. The quality of LCA has not been given sufficient attention in past studies. In this project, several factors that affect the quality of LCA are identified and it is discussed how these factors affect the final results and how much they will affect the results. This project is an important reference for subsequent LCA studies on PLA.

However, this project also has some drawbacks. Due to the nature of the study, it can only be based on past research literature, and in many cases, the data in the literature are not standardized or perfect, which leads to a lack of credibility in the secondary calculations and comparisons. Besides, to verify how much the different feedstock will affect the LCA results of PLA, LCA should be conducted on different feedstock cultivation process.

Overall, PLA does have advantages over traditional fossil-based plastics in terms of climate change and energy consumption, but since PLA performs worse in the vast majority of other environmental impact categories, it is difficult to conclude that PLA is a more environmentally friendly material than traditional fossil-based plastics.

However, since PLA has shown a very clear trend of increasingly better environmental performance over time, it is worthwhile to believe that with the development of biotechnology and the utilization of green energy, PLA has a great potential to outperform fossil-based plastics in the future in other environmental performance categories [90] [91].

Besides, although there is no specific estimate of the potential market potential of PLA, it is indisputable that PLA is one of the most popular bio-based plastics, and the development of PLA will largely contribute to the development of bio- and decarbonization economy.

7. Conclusion and outlook

This project studied peer reviewed LCA research articles on PLA and found that most studies demonstrated no advantage of PLA over PET for most environmental impact categories. Whereas the conclusions of these studies did not remain consistent, this project analyzes the reasons for the discrepancy in results and summarizes several different influencing factors such as data source, feedstock, geographic location, scope, and impact category. This section is useful to help understand possible studies to improve the credibility and scientific validity of future LCA studies.

First, the current LCA research on PLA is mainly oriented towards two mainstream PLA products, Ingeo from NatureWorks and Purac from Total Corbion, and the LCA studies are largely based on the original eco-profile of these two products. There are also many studies that do not have an exact product under study and generally assume a PLA product, and such studies are often based on ecoinvent general database.

In addition, the difference in the results of the environmental impact assessment of PLA and the comparison with fossil-based plastics is related to the choice of data source, feedstock, geography, study scope, and impact category. Feedstock largely determines the choice of data source, and feedstock has very distinct geographical characteristics. For example, Thailand mainly produces sugarcane, while most of the corn comes from the United States. The environmental performance of sugarcane-based PLA is better than that of corn-based PLA.

The main reason for the poor environmental impact of PLA compared to traditional fossil-based plastics is that the production of crops has worse environmental performance than the extraction of petrochemical feedstocks. In addition, since fossil-based plastics do not biodegrade, the outputs are theoretically less relative to PLA over the entire life cycle.

When the scope of the study is from cradle to gate, the manufacturing process of PLA resin production is always considered to be the segment that contributes the most to the life cycle impact of PLA. And EOL options can largely affect the environmental performance of PLA, so improving the recycling rate and reuse of PLA, while employing an effective energy recovery mechanism when PLA is completely scrapped can improve the environmental performance results of PLA. To further improve the environmental performance of PLA, more efforts need to be invested in the manufacturing and waste management aspects of PLA.

Besides, the PLA-related database should be further improved. First, the reference factory data in the ecoinvent database are not from the latest NatureWorks report but are still based on the data published by Vink et al. in 2007[52], so there is a large time lag in the data. Although the newer data may make few differences on the future LCA studies, the timeliness illustrate a more efficient process. In addition, there is a lack of material database with cassava-based PLA products as the main subject of study, and this gap needs to be filled in the future research.

In addition, the impact of transportation is unclear in most studies, and it is suggested that subsequent studies could elaborate on transportation and its contribution to the overall life cycle analysis.

Lastly, it was noticed that the vast majority of LCA studies did not clarify the used LCA category and ignored uncertainty analysis, whereas comprehensive uncertainty analysis should be included in all published LCA studies unless it can be reasonably excluded in terms of the objectives and scope of the study. Therefore, in future studies, both the categories of LCA and uncertainty tests should be further refined for more rigorous conclusions.

Overall, it was strongly suggested that researchers should consider different research subjects in order to select the most practical research methods, the most effective research directions, and the most appropriate data sources for their studies, rather than defaulting to generic databases.

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Appendix

A1 Types and properties of common plastics

1. PET or PETE (polyethylene terephthalate).

   PET is a kind of polymer material formed from ethylene glycol and terephthalic acid at high temperatures and in a low vacuum environment [92]. Due to its very stable physical and chemical properties, light weight and high strength, PET is used in a wide range of applications such as food packaging, fiber manufacturing and engineering plastics [93]. Although PET is produced from oil and gas, it is still a very energy efficient material, with only about 0.7% of crude oil being used to produce PET each year. PET is also the most recycled plastic material in the world. The recycling rate for PET is 31% in the USA and 52% in Europe [92], with Switzerland having a recycling rate of around 75% [93].

2. PE (Polyethylene)

   PE is one of the most common plastics and the ethylene used is generally derived from petrochemicals or can be produced by dehydrating ethanol [94]. Ethylene is formed into different densities of polyethylene in different environments. HDPE (High Density Polyethylene) is formed at high temperatures and pressures, and LDPE (Low density polyethylene) at low temperatures and pressures[94]. Generally, polyethylene is less hard and rigid, but more ductile, more chemically stable and less biodegradable, but produces methane and ethylene when exposed to solar radiation [94]. There are, however, some subtle differences between different densities of polyethylene. HDPE, for example, is stiffer and opaquer than LDPE and can also withstand higher temperatures [95], [96].

3. PP (Polypropylene).

   Polypropylene is a thermoplastic polymer formed from propylene monomers and has a higher degree of hardness and heat resistance than polyethylene. Polypropylene also has very good thermoplasticity and chemical resistance. Due to these superior properties, polypropylene is the second largest commodity plastic market after polyethylene [97]. The main end-user of polypropylene is the packaging industry, which accounts for approximately 30% of the total, followed by electrical and equipment manufacturing, each accounting for 13%. The household appliances and automotive industries each account for 10%, followed by construction materials at 5% [98].

4. PS (Polystyrene).

   Polystyrene is made from styrene monomer. Polystyrene is transparent, hard but fragile. In general, polystyrene is chemically stable and resistant to water and many acids and bases but is easily eroded by mail. Polystyrene is often used in products where transparency is required, such as food packaging and laboratory apparatus. Polystyrene is usually injection molded, vacuum molded or extruded. Of these, extruded polystyrene (XPS) offers higher stiffness, lower thermal conductivity, and improved surface roughness.

5. TPS (Thermoplastic Starch)

Thermoplastic starch is usually made from natural starch. Starch-based polymers generally suffer from high moisture sensitivity and low mechanical strength, so plasticisers are generally added during the preparation process to break down the crystals of the starch granules and form a material that can be injection or blow moulded. There are a wide range of applications for packaging of products with extended shelf life [99].

A2 Bioplastics related policies in European Union, America and China

A2.1 European Union

Europe has been a pioneer in the bioplastics industry. The European Union (EU) has been committed to promoting bioplastics as a means of facilitating Europe's transition to a circular economy. Over the past 10 years, the EU has introduced a number of policies to ensure that the European bioplastics market can flourish.

In 2012, the EU adopted the European Bioeconomy Strategy, which aims to address the production of renewable bioresources and their conversion into important products and bioenergy [100].

In December 2015, the European Commission published its Circular Economy Proposal [101], an action plan in which the EU recognizes "the advantages of bio-based materials due to their renewable, biodegradable and compostable nature." In January 2018, the European Commission published the "European Plastics in the Circular Economy Strategy" newsletter [102]. Subsequently, the EU waste legislation was revamped to allow biodegradable and compostable packaging to be collected with biowaste and recycled in industrial composting and anaerobic digestion, and separate collection of biowaste is planned to be mandatory across Europe by 2023.

In 2019, the EU released the European Green Deal, announcing that a policy framework on the procurement, labeling and use of bioplastics will be introduced in a new circular economy initiative. However, there is still no EU law that applies comprehensively to bio-based, biodegradable and compostable plastics [103]

A2.2 America

In April 2012, the Obama administration issued the National Bioeconomy Blueprint, stating that it would promote domestic biomass research through the U.S. Department of Agriculture (USDA) to increase the availability of biobased products, including bioplastics.

Four months later, the U.S. government introduced the Qualifying Renewable Chemical Production Tax Credit Act, which provides a lower tax regime for manufacturers of renewable biobased products to incentivize the growth of the industry. The bill was officially introduced in June 2013 [104].

The USDA has always been a key driver of bioplastics R&D. In 2002, the USDA introduced the Bio-Preferred program under the U.S. Farm Bill, which has undergone several revisions and was reauthorized in 2018. The program serves as a market development program to increase the market acceptance of biobased products, thereby increasing sales of biobased products.

In addition, the U.S. government is committed to establishing a circular economy and has launched a number of programs to this end. These include the National Recycling Strategy, the Sustainable Materials Management Program, and others. These programs encourage the development of sustainable materials and focus on the recycling management of these materials. Yet this effort has struggled within the U.S. According to the literature, only California is currently attempting to enact laws to phase out conventional plastics, and this legislative effort is facing bureaucratic resistance.

A2.3 China

As a major producer and consumer of plastics in China, it is important to regulate the processing, production, marketing and application of bioplastics in a comprehensive manner to alleviate the existing environmental pressure in China. In 2008, the Chinese government has been implementing the "Plastic Restriction Order" and has achieved a series of results after that. In 2015, six years after the "Plastic Restriction Order", some local governments have proposed a more stringent "Plastic Ban Order". In 2017, the Chinese government has enacted a ban on waste imports, this move that has greatly reduced plastic waste in China, but has also prompted some other countries to find other solutions for their own plastic waste.

In 2020, China's National Development and Reform Commission, together with the Ministry of Ecology and Environment, issued the Opinions on Further Strengthening Plastic Pollution Control, which clearly put forward specific requirements for phased plastic restriction and encouraged the promotion and application of bioplastics. With the intensive introduction and gradual implementation of these policies, as well as the booming development of take-out and other industries, China's consumption of bioplastics has been rising year by year. Some data show that the average annual growth rate of China's biodegradable plastic consumption in the past five years is around 20%, and in 2019, China's biodegradable plastic consumption is about 260,000 tons.

However, as China's bioplastics market started late, laws and regulations for bioplastics are not perfect. Moreover, the environmental risks and management pressure of bioplastics are not clear in the global context, so in 2021, the Chinese government has issued several policies and laws and regulations on bioplastics.

At the beginning of 2021, the Chinese government announced the "14th Five-Year Plan of Action for Plastic Pollution Control", which clearly indicates that the development of the bioplastics industry in China is good, however, there are some problems such as low overall recycling rate, uneven development in urban and rural areas, insufficient scale and unscientific waste management. Therefore, the program puts forward a series of requirements for the above problems:

- Firstly, the scientific recycling and treatment of plastic waste will be accelerated as soon as possible.
- Secondly, because the waste generated in rural and urban areas has a large diversity, there should be different waste management means for different areas. For example, in urban areas, bioplastic recycling outlets should be promoted, specifically, waste separation and collection facilities and equipment should be reasonably laid out in populated areas, such as large communities, office buildings, shopping malls, hospitals and schools; While in rural areas, it is proposed that the recycling of agricultural films and packaging should be paid more attention and it will be encouraged that relevant organizations and enterprises to actively carry out recycling activities and publicity and education work.
- In addition, the government will actively support the construction of bioplastic recycling projects, while also improving relevant standards to increase the added value of bioplastics.
- Finally, the Chinese government will comprehensively promote the construction of industrial incineration facilities to minimize landfill disposal of waste, and at the same time strengthen the comprehensive improvement of existing landfills.

At the end of 2021, the Chinese government issued another national standard GB/T 41010-2021 "Biodegradable Plastics and Products Degradation Performance and Labeling Requirements". This document standardizes the terms and definitions of biodegradation and biodegradation rate, and stipulates the requirements of degradation performance, labeling requirements and inspection methods.

In this standard, biodegradation and biodegradation rates are defined as following respectively.
Biodegradation: a property of a material that is degraded due to biological activity, especially enzymes, so that it is gradually disintegrated by microorganisms or certain organisms as a nutrient source, resulting in a decrease in its relative molecular mass and mass loss, a decrease in physical properties, etc., and is eventually decomposed into compounds of simpler composition and mineralized inorganic salts of the elements contained, and biological dead bodies.

Biodegradation rate: In the aerobic biodegradation process, the organic carbon contained in the experimental material will be converted into carbon dioxide by microbial decomposition, and the percentage of carbon dioxide measured cumulatively during the experiment and the theoretical amount of carbon dioxide released from the material.

A3 The results of life cycle impact assessment in the selected literature and parameters of literatures

Reference	Scope	Function Unit	Feedstock and Geography	Data Source of LCA of PLA	Impact assessment mehods	Studied Impact	Results	Comparison	Uncertainty assessment	Data Source of LCA of fossil-based plastic
Vink et al., 2007	LCA, from cradle to gate	1 kg Ingeo biopolymer	Corn in the United States	First-hand data	Undefined	GHG emission	2.023 kg CO_2 eq	PLA<PET	\	\
Madival et al., 2009	LCA, from cradle to grave	1000 containers of capacity 0.4536 kg each for the packaging of strawberries	Corn in the United States	Literature, Ecoinvent (for PET&PS), NatureWorks (for PLA)	IMPACT 2002+	Global warming	735kg CO_2 (564kg for transportation)	PS<PLA<PET	\	Ecoinvent
						Aquatic acidification	5.66g SO_2 5.66/0.4536	PS<PET<PLA		
						Ozone layer depletion	9.15×10^{-5} kg CFC-11	PS<PLA<PET		
						Aquatic eutrophication	0.0886 kg PO_4	PS<PLA<PET		
						Toxicity	257,000kg TEG (TEG: (triethylene glycol)	PLA<PS<PET		
						Non-renewable	13,400 MJ	PLA<PS<PET		

		(29.6g/box)				energy				
						Land use	10.3	PS<PLA<PET		
Vink et al., 2010	LCA, from cradle to gate	1 kg Ingeo biopolymer	Corn in the United States	First-hand data	Undefined	GHG emission	1.24 kg CO_2 eq	PLA<PET	\	\
Groot & Borén, 2010	LCA, from cradle to gate	1 ton biopolymer	Sugarcane in Thailand	European Plastics Association Literatures	undefined	Global warming potential	500-800 kg CO_2 eq	PLLA<PET<PS	\	\
Gironi & Piemonte, 2011	LCA, from cradle to gate	12.2kg PLA bottels	Corn in the United States	Ecoinvent v.2.0	Ecoindicator 99	Global warming	17.202 kg CO_2 eq	PLA<PET	\	Buwal 250 libraries
						Non-renewable energy	924.882 MJ	PLA<PET		
						Renewable energy	389.668 MJ	PET<PLA		
						Acidification	171.044 g SO_2 eq	PET<PLA		
						Eutrophication potential	95.404 g PO 4 eq	PET<PLA		
Shen et al., 2012	LCA, from cradle to	1 kg of polymer granulates	PLA: 50% from corn in	Companies: NatureWorks	\	Non-renewable energy use (NREU) (Ingeo 2009)	42MJ/kg	Bio-based PET, PLA, recycled PET and recycled bio-based	\	Plastics Europe

	factory gate	, amorphous grade 1 kg of staple fiber 1 kg of bottles	America,50% from sugarcane from Thailand	LLC (maize-based). PURAC (sugarcane-based).		Greenhouse gas (GHG) emissions (Ingeo 2009)	1.3 kg CO_2 eq	PET < Petrochemical PET		
						Non-renewable energy use (NREU) (PURAC PLLA)	31MJ/kg	Man-made cellulose fibers produced in integrated plants < PLA, recycled PET, recycled bio-based PET < Petrochemical PET		
						Greenhouse gas (GHG) emissions (PURAC PLLA)	0.5 kg CO_2 eq			
Hottle et al., 2013	LCA, from cradle to gate	1 kg Ingeo resin	Corn	Ecoinvent v2.2 Vink (2007)	ReCipe	Global warming potential	3.2 kg CO_2 eq	TPS<HDPE<PP<LDPE<PET<PLA<PS	\	Ecoinvent v2.2
						Eutrophication	\	HDPE,LDPE,PP,PS<PET<TPS<PLA		
						Ecotoxicity	\	PP<TPA<HDPE<PS<LDPE<PET<PLA		
						Acidification	\	PP<HDPE<LDPE<TPS<PET<PS<PLA		
						Ozone depletion	\	PET<TPS<PLA		
						Smog Formation	\	HDPE<PP<LDPE<TPS<PLA<PET<PS		

						Human health - carcinogens	\	PP<HDPE<LDPE<TPS<PS<PLA<PET		
						Human health – non-carcinogens	\	HDPE,PP,LDPE,PS<PLA<PET<TPS		
						Human health - respiratory	\	PP<HDPE<LDPE<TPS<PLA<PS<PET		
Suwanmanee et al., 2013	LCA, from cradle to consumer gate	10,000 boxes weighing 597.6kg	Corn and cassava in Thailand	Ecoinvent 2.2 Vink, 2010	undefined	Global warming potential	1.75×10^{4} kg CO_2 eq	PS<PLA<PLA/starch	\	Ecoinvent 1.01
						Acidification	7.82 m^2 UES per FU	PS <PLA/starch<PLA		
						Photochemical ozone formation	6.71×10^{-3} person × ppm × h per FU	PS <PLA/starch<PLA		
Papong et al., 2014	LCA, from cradle to gate(GWP, FED, AP, EP, HTP); from cradle to grave(G	1000 units of 250-ml drinking water bottles	Cassava in Thailand	Ecoinvent; Firsthand data	CML 2001	Global warming potential	1.54-2.48 kg CO_2 eq;	PLA<PET	\	Ecoinvent (2008) Thai National Life Cycle Inventory Database
						Fossil energy demand	32.47 MJ	PLA<PET		
						Acidification potential	16.16g SO_2 eq	Cassava-based PLA < sugarcane-based PLA; PET < PLA		
						Eutrophication potential	9.22 g PO_4 eq	PET<PLA		
						Human toxicity	2.67 kg 1,4-DB eq	PLA<PET		

	WP)					potential				
Vink & Davies, 2015	LCA, from cradle to gate	1 kg Ingeo biopolymer	Corn in the United States	First-hand data	CML 2001	Global warming potential	0.62 kg CO_2 eq	\	\	\
						Primary energy of nonrenewable resources as HHV	40.05 MJ (HHV)			
						Primary energy of renewable resources	26.61 MJ			
						Acidification potential	7.26 g SO2 eq			
						Eutrophication potential	1.38 g PO4 eq			
						Photochemical ozone creation potential	0.60 g ethene eq			
						Ozone depletion potential	3.99×10^{-10} g CFC-11 eq			
Ingrao et al., 2015	LCA, from cradle to grave	a parcel containing 1 kg of trays	Corn in the United States	Ecoinvent 2.2	IMPACT 2002+	Climate footprint	4.826 kg CO_2 eq	The production of PLA pellet contributes most to GWP (61.26%)	\	Literature Ecoinvent

								Transportation from pellet to tray producer 14.33%		
								Power consumption 11.63%		
Leejarkpai et al., 2016	LCA, from cradle to grave	1,000 boxes with the carrying capacity of 100.0 g and the volume is 2.00×10^{-4} m^3 per box	Corn in Thailand	Ecoinvent 2.2 Suwanmanee et al. (2013a).	undefined	Global warming potential	219.5 kg CO2 equivalent per FU (from cradle to consumer gate)	PS<PLA’<PET<PLA’’	\	Suwanmanee et al., 2013a, Suwanmanee et al., 2013b[105]
							PLA in 100% landfill > PLA in 96% Landfill+4%Composting > PLA in 50% Landfill+50%Composting > PLA in 100%Composting	PS<PET<PLA		
Castro-Aguirre et al., 2016	LCA, from cradle to gate	1 kg PLA resin	Corn	Ecoinvent v3.2	ReCiPe (E)	Climate change	2.79 kg CO_2 eq	LLDPE<HDPE<PP<LDPE<PET<PLA<PS	\	Ecoinvent 3.2
						Ozone depletion	2.18×10^{-7} g CFC^{-11} eq	PP<LDPE<HDPE<PS<LLDPE<PET<PLA		
						Terrestrial	0.0218 kg SO_2 eq	LLDPE<HDPE<PP<L		

						acidification		DPE<PS<PET<PLA		
						Freshwater eutrophication	0.0004 kg P eq	LLDPE<HDPE<LDPE<PS<PP<PET<PLA		
						Marine eutrophication	0.0065 kg N eq	LLDPE,HDPE<PET,LDPE,PP<PS<PLA		
						Human toxicity	9.4123 kg 1,4-DB eq	LLDPE<PP<HDPEPS<LDPE<PET<PLA		
						Photochemical oxidant formation	0.0115 kg NMVOC	LLDPE<PP<HDPE<PET<LDPE<PS<PLA		
						Particulate matter formation	0.0063 kg PM10 eq	PP<HDPE<LLDPE<LDPE<PS<PET<PLA		
						Terrestrial ecotoxicity	0.0089 kg 1,4-DB eq	LLDPE<HDPE<LDPE<PP<PS<PET<PLA		
						Freshwater ecotoxicity	0.0090 kg 1,4-DB eq	LLDPE<PP<HDPE<LDPE<PS<PET<PLA		
						Marine ecotoxicity	3.5355 kg 1,4-DB eq	LLDPE<PP<HDPE<LDPE<PS<PET<PLA		
						Ionizing radiation	0.1398 kBq U235 eq	HDPE,LLDPE,PP<LDPE<PS<PET<PLA		
						Agricultural land occupation	1.1321 m^2a	LLDPE,LDPE,PP<HDPE<PS<PET<PLA		

						Urban land occupation	0.0674 m^2a	LLDPE<LDPE,PP,HDPE<PS<PET<PLA		
						Natural land transformation	0.0004 m^2	PS<HDPE<PP<LDPE<LLDPE<PET,PLA		
						Water depletion	0.2726 m^3	HDPE<PP<LDPE<LLDPE<PS<PET<PLA		
						Metal depletion	0.1538 kg Fe eq	PP,HDPE<LLDPE<LDPE<PS<PLA<PET		
						Fossil depletion	0.8246 kg oil eq	PLA<PET<LLDPE<LDPE<PP<HDPE<PS		
						Non-renewable energy	41.739 MJ primary	PLA<PET<LLDPE<PP<HDPE<LDPE<PS		
Carus, 2017	LCA, from cradle to gate	1 kg PLA resin	Corn	Vink, 2015	ReCiPe 2016	Global warming potential	2.44 kg CO_2 eq	PE < PLA	\	PlasticsEurope
	LCA, from cradle to grave						2.09 kg CO_2 eq (incineration)	PLA<PE		
Ingrao et	LCA,	1 kg of	Corn in the	Firsthand	IMPACT 2002+	Non-renewable	103.36 MJ primary	\	Monte Carlo analysis	Ecoinvent

al., 2017	from cradle to grave	equally dimensioned PS-trays	United States	data from company Ecoinvent 2.2		Energy				
						Global Warming	5.85 $kgCO_2eq$			
						Respiratory Inorganics	0.004 $kgPM_{2.5}eq$			
						Land Occupation	1.2 m^2org.arable			
						Terrestrial Eco-Toxicity	96 kg TEG soil			
Hottle et al., 2017	LCA, from cradle to grave	1 kg of polymer	Corn in the United States	Ecoinvent v2 (PLA landfill and Eol) Vink et al. (2010a) (PLA production)	TRACIv2.1	global warming eutrophication ecotoxicity acidification ozone depletion smog formation carcinogens non-carcinogens respiratory effects fossil fuel depletion	\	Before EOL: bio-PE produced by sugar cane grown in Brazil greater ENV impact. PLA and TPS produced by corn have greater AP & EP than any other fossil-based plastic EOL: PLA&TPS landfill < composing; recycle good	\	Franklin Associates Revised Final Report (2011)
Changwichan et al.,	LCA, from	1000 boxes	Cassava and	Literature (from cradle	Undefined		70 %L, 100 %C, 100 %R, 100 %I		\	Ecoinvent

2018	cradle to grave	(35.2kg)	sugarcane in Thailand	to industry gate) Ecoinvent 3.0 (PLA product manufacturing, EOL) Thai national life cycle inventory database (Transportation)			+30 %C						
						Global warming potential	110\115	95\100	5\10	100\110	Sugarcane < cassava		
						Acidification potential	0.85\0.7	0.9\0.7	0.45	0.7	Cassava < sugarcane		
						Eutrophication potential	0.05	0.04	0.04	0.04	Cassava < sugarcane		
						Fossil depletion potential	5	5	-2	5	Sugarcane < cassava		
						Land occupation potential	130	130	10	130	Cassava < sugarcane		
						Toxicity potential	3.4	3.4	3.2	3.5	Sugarcane < cassava		
Choi et al., 2018	LCA, from cradle to grave	a film of 300 × 250 mm with a thickness of 0.06 mm for a	Corn in the United States	Vink et al. (2015)	CML-IA	Global warming potential	1.2×10^4 kg CO_2 eq (100% incineration)				Landfill < Recycling < Incineration Before EOL: PLA < LDPE < PLA/PBAT Incineration: PLA/PBAT 7 times to PLA, 2 times to LDPE	\	Ecoinvent
							5.0×10^3 kg CO_2 eq (100% landfill)						

		normal packaging bag						Landfill: PLA<LDPE< PLA/PBAT		
Morão & de Bie, 2019	LCA, from cradle to gate	1 ton PLA	Sugarcane in Thailand	Agri-footprint V2.0 Ecoinvent Operation data from Corbion Thailand in 2016	ILCD 2011 +	Global warming potential	501 kg CO_2 eq	\	\	\
						Water Consumption and Water Depletion	36.01 m^3			
						Marine eutrophication potential	13.9 kg N eq			
						Terrestrial eutrophication potential	34.8 mol N eq			
						Acidification potential	18.2 molc H + eq			
						Particulate matter	1.7 kg PM2.5 eq			
						Non-renewable energy use	28.8 GJ			
						Renewable energy use	60.4 GJ			
Maga et al.,	LCA,	tray with	Corn	Gabi	ILCD	Carbon footprint	0.054 kg CO_2 eq	PP < PLA < RPET <	\	Not clear

2019	from cradle to grave	a volume of about 1 L for preserving 500 g of fresh meat (13.9 g)		database NatureWorks (for PLA production)				XPS < APET		
						Acidification potential	\	XPS < PP &PET< PLA		
						Marine eutrophication	\	XPS OC<PP<PET<PLA		
						Terrestrial eutrophication	\	XPS<PP<PET<PLA		
						EOL energy recovery efficiency	\	PLA < PET < PP < PS		
						Land Use	\	XPS < others < PLA		
						Ozone depletion	\	XPS<PS<PP<PET<PLA		
						Photochemical ozone formation	\	XPS<others<PLA		
						Water depletion	\	PS best		
						Resource depletion	\	XPS worst		
Benavides et al., 2020	LCA, from cradle to grave	1 kg PLA waste	Corn in the United States	Natureworks (Vink et al., 2007; Vink and Davies, 2015).	GREET model(for GHG emission and FEC calculation)	Greenhouse gas emission	1.7 kg CO_2 eq (Landfill+ 0%BD)	Bio-PE<PLA landfill with 0% biodegradable (BD)<HDPE<LDPE< PLA composting with	\	Literature
							3.7 kg CO_2 eq (Landfill+ 60%BD)			
							3.3 kg CO_2 eq			

							(Composting+ 60%BD)	60% BD<PLA Landfill with 60% BD		
Pia Desole et al., 2021	LCA, from cradle to grave	1000 1-L bottles (26kg PLA)	Sugarcane in Thailand	Ecoinvent 3 Total Corbion	IMPACT 2002+	Carcinogens	\	PLA ≈ 98% PET	\	Ecoinvent 3
						Non-carcinogens		PLA ≈ 70% PET		
						Respiratory inorganics		PLA ≈ 77% PET		
						Ionizing radiation		Bottle production (77%)		
						Ozone layer depletion		Bottle production (75%) + the decontamination phase in the bottled milk packaging process (19%)		
						Respiratory organics		PLA ≈ 73% PET		
						Aquatic ecotoxicity		Bottle production (67%) + the decontamination phase in the bottled milk packaging process (13%)		
						Terrestrial ecotoxicity		Bottle production (61%) + the decontamination phase in the bottled milk packaging process (14%)		
						Terrestrial acid/nutria		Bottle production (75%) + the decontamination phase		

								in the bottled milk packaging process (9%)		
						Land occupation		Bottle production (16%)		
						Aquatic acidification		Bottle production (80%) + the decontamination phase in the bottled milk packaging process (10%)		
						Aquatic eutrophication		Bottle production (70%) + the decontamination phase in the bottled milk packaging process (18%)		
						Global warming		PLA ≈ PET		
						Non- renewable energy		PLA production affect most		
						Mineral extraction		EOL (-21%)		
Tamburini et al., 2021	LCA, from cradle to grave	1095 PLA bottles	Corn	Ecoinvent	Recipe Midpoint(H)	Global warming potential	0.616 kgCO2 eq	PET < PLA	\	Ecoinvent
						Ozone depletion potential	9.17×10^{-8} kgCFC-11 eq.	PET < PLA		
						Acidification of soil and water potential	27.5×10^{-4} kgSO2 eq.	PET < PLA		
						Eutrophication	5.90×10^{-4} kgPO4 eq.	PET < PLA		

						potential				
						Photochemical ozone formation potential	25.20 × 10 $^{-4}$ kgNMVOC	PET < PLA		
						Fossil fuels depletion potential	0.247 kg oil eq	PET < PLA		
						Human toxicity potential	0.218 kg 1,4-DB eq.	PET < PLA		
						Eco-toxicity potential	9.86 × 10 $^{-3}$ kg 1,4-DB eq.	PET < PLA		
						Water depletion potential	8.92 liters	PET < PLA		
						Particulate matter formation	13.4 × 10^{-4} kg PM10 eq.	PET < PLA		
						Land occupation potential	32.28 × 10 $^{-3}$ m^3	PET < PLA		
Moretti et al., 2021	LCA, from cradle to grave	1000 200-mL bottles 4.6kg	Corn in the United States Sugarcane in Thailand	Vink et al. (2015) (PLA from corn) Morão et	undefined	Climate change	17.48 kg CO_2eq	PP<PLA<PET	\	PlasticsEurope
						Ozone depletion	-7.99×10^{-7} kg CFC-11 eq	\		
						Particulate matter	6.28×10^{-3} kg PM2.5 eq	PP <PET<PLA		
						Ionizing radiation Human Health (HH)	1.29 kBq U235 eq	\		

				al.(PLA from sugarcane)		Photochemical ozone formation	6.87×10^{-2} kg NMVOC eq				PP <PET<PLA		
						Acidification	9.98×10^{-2} molc H+ eq						
						Terrestrial eutrophication	0.261 molc N eq				PP <PET<PLA		
						Freshwater eutrophication	1.07×10^{-3} kg P eq				\		
						Marine eutrophication	4.18×10^{-2} kg N eq				\		
						Land transformation	91.98 kg C deficit				\		
						Water use	5.66 m^3				\		
						Resource use, minerals and metals	1.5×10^{-5} kg Sb eq				\		
						Resource use, fossil fuels	177.48 MJ				PLA< PP <PET		
Bishop et al., 2021	LCA, from cradle to grave	51.2kg PLA food waste package	Corn	Ecoinvent 3.5 (Based on NatureWorks)	Environmental Footprint, LCIA		BAF	SAD	SComp	SIncin	\	Monte Carlo simulations	Ecoinvent 3.5
						Global warming potential (kg CO_2 eq)	250	230	350	280			

						Acidification terrestrial and freshwater (mol H+ eq)	1.2	1.5	2.25	1.4			
						Cancer human health effects (CTUh)							
						Ecotoxicity freshwater							
						Eutrophication freshwater							
						Eutrophication marine							
						Eutrophication terrestrial							
						Ionizing radiation Land use							
						Non-cancer human health effects							

						Ozone depletion						
						Photochemical ozone formation						
						Resource use, energy carriers						
						Resource use, mineral and metals						
						Respiratory inorganics, disease incidence						
						Water scarcity						
Riofrio et al., 2022	LCA, from cradle to factory gate And from cradle to consume	1 m^2 PLA film	sugarcane	Vink et al., 2003	ILCD 2011 midpoint		From cradle to factory gate	From cradle to consumer gate	From cradle to factory gate	From cradle to consumer gate	\	Not clear
						Climate change	0,00078446	0,00095953	HDPE<PP<PET<PLA	LDPE<PLA		
						Ozone depletion	2,5505 * 10^{-5}	3,4338 * 10^{-5}	PP<HDPE<PET<P	LDPE<PLA		

	r gate								LA			
						Human toxicity, non-cancer effects	-0,0091435	-0,00665945	PLA<PP<HDPE<PET	PLA<LDPE		
						Human toxicity, cancer effects	-0,00108467	0,00385696	PLA<PP<HDPE<PET	PLA<LDPE		
						Particulate matter	-2,8414 * 10^{-6}	0,0002939	PLA<PP<HDPE<PET	LDPE<PLA		
						Ionizing radiation HH	-0,0011061	-0,00075216	PLA<HDPE<PP<PET	PLA<LDPE		
						Photochemical ozone formation	0,00014974	0,00024991	PLA<PP<HDPE<PET	PLA<LDPE		
						Acidification	0,00019227	0,00035813	PP<HDPE<PLA<PET	LDPE<PLA		
						Terrestrial eutrophication	0,00022506	0,00031259	HDPE<PP<PET<P	LDPE<PLA		

									LA			
						Freshwater eutrophication	$-1,6131 * 10^{-5}$	$2,6253 * 10^{-5}$	PLA<HDPE<PP<PET	PLA<LDPE		
						Marine eutrophication	0,00074147	0,00073208	HDPE<PP<PET<PLA	LDPE<PLA		
						Freshwater ecotoxicity	-0,00602235	-0,00159358	PLA<PP<HDPE<PET	PLA<LDPE		
						Land use	$6,1549 * 10^{-6}$	$6,0458 * 10^{-6}$	PP<HDPE<PET<PLA	LDPE<PLA		
						Water resource depletion	-0,00113103	-0,00087635	PLA<PET<HDPE<PP	PLA<LDPE		
						Mineral, fossil & ren resource depletion	0,00027462	0,00026842	PP<HDPE<PLA<PET	LDPE<PLA		

A4 The carbon neutral policies framework constructed by the European Union

Table 4: Main policies and strategic plans for EU carbon neutrality

Category		File	Institutions	Release Date	Main content
Policy framework	Law	European Climate Law [106]	European Commission	04.03.2020	Proposing legally binding targets with 6 main steps
	Path	European Green Deal [103]	European Commission	11.12.2019	Proposing a course of action and seven transition pathways towards climate neutrality in the EU
		Fit for 55 [107]	European Commission	14.07.2021	Adopting nine proposals to meet the 2030 target of reducing greenhouse gas emissions by at least 55% compared to 1990
Key industry measures	Energy	Promoting a climate-neutral economy: Energy Systems Integration Strategy [108]	European Commission	08.07.2020	Proposing specific energy policy and legislative measures, identify six pillars and propose concrete measures to address barriers to the energy system
	Industry	Our Vision for A Clean Planet for All: Industrial Transition [109]	European Commission	29.11.2018	A vision of industrial transformation that empowers industries to maintain the EU's industrial leadership by introducing policies and supporting industrial transformation
	Transportation	Sustainable Transport - European Green Deal [103]	European Commission	11.12.2019	4 key actions proposed to reduce EU transport emissions by 90% by 2050
	Forestry	New EU Forest strategy for 2030 [110]	European Commission	16.07.2021	Presenting a vision for forest development and a concrete action plan
Technology layout	Research and development	Sustainable Europe Investment Plan [111]	European Commission	11.12.2019	Mobilizing at least €1 trillion over the next 10 years to support the financing plans of the European Green Deal

		Innovation Fund [112]	European Commission	15.06.2020	Approximately €20 billion in funding for innovative low carbon in the period 2020-2030
		Environment and climate action under the LIFE Program[113]	European Commission	25.10.2018	430.7 million euros mobilized to finance 142 new environment and climate projects in 6 categories
		European Green Deal R&D tender [103]	European Commission	22.09.2020	1 billion euros mobilized to tender for innovative R&D projects in 11 areas including energy, construction and transport
		Additional instructions for the operation of the Innovation Fund[114]	European Commission	26.02.2019	By 2030, applied innovation projects with broad technological representation and geographical coverage will be deployed
Fiscal and financial measures	Finance, taxes and subsidies	Multiannual Financial Frameworks (2021-2027)[115]	European Parliament	01.01.2020	10 fiscal and financial initiatives to invest at least €108 million in climate and environment over the next 7 years
		Action Plan for the Planet[116]	European Commission	12.12.2017	10 investment transformation initiatives to consolidate the EU's international leadership in the fight against climate change
		Energy Modernization Fund [117]	European Commission	09.07.2020	Approximately €14 billion allocated from the carbon trading system for the period 2021-2030 to invest in modernizing the energy system
		Promoting a climate-neutral economy: Energy Systems Integration Strategy [108]	European Commission	08.07.2020	Revision of the Energy Taxation Directive to align sectoral taxation with EU environmental and climate policy and to phase out direct fossil fuel subsidies.
	Carbon Emissions Trading System and	Promoting a climate-neutral economy: Energy Systems Integration Strategy [108]	European Commission	08.07.2020	Extending the carbon trading system to new sectors and providing more consistent carbon price signals between the energy sector and member states
		Fit for 55 [107]	European	14.07.2021	Improving the emissions trading system, taking into account

	Carbon Price Mechanism		Commission		fairness, and achieve a 61% reduction in emissions from the sectors covered by the carbon trading system by 2030 compared to 2005