LCA

Environmental footprint of polylactic acid production

TotalEnergies Corbion
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Abbreviations

DLUC: Direct Land Use Change
DQR: Data Quality Requirements
EOL: End-of-life
GHG: Greenhouse Gas
GLO: Global
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
LCIA: Life Cycle Impact Assessment
PCW: Post-Consumer Waste
PIW: Post-Industrial Waste
PLA: Polylactic acid
RoW: Rest of World
rPLA: Recycled Polylactic acid
vPLA: Virgin Polylactic acid

Summary

TotalEnergies Corbion produces polylactic acid (PLA) in Rayong, Thailand and sells it under the brand name Luminy®. The original feedstock is sugarcane, a renewable and biobased feedstock. TotalEnergies Corbion also developed its own recycling process to produce rPLA made from externally collected Post-Industrial Waste (PIW) and closed-loop Post-Consumer Waste (PCW).

The environmental impact of Luminy® polylactic acid (virgin and recycled) production has been assessed using cradle-to-gate Life Cycle Assessment (LCA). This study was conducted in accordance with ISO 14040/44/67, ensuring scientific rigor and third-party verification. The sixteen environmental impact categories (Annex A) as recommended in the Product Environmental Footprint (PEF), were considered for the hotspot analysis. The results of the identified relevant impact categories for 1 kg of Luminy® virgin polylactic acid and 1 kg of Luminy® polylactic acid with 100 % attributed recycled content are presented in Table 1 below.

Table 1. LCA results for 1 kg of virgin PLA production and 1 kg of 100% recycled PLA production at TotalEnergies Corbion factory gate for the relevant impact categories[1].

Impact category	Unit	Luminy® Virgin PLA	Luminy® 100% recycled PLA
Climate change	kg CO_2 eq	2.12 (0.29 including the biogenic CO_2 in the product)	1.18 (-0.65 including the biogenic CO_2 in the product)
Photochemical ozone formation	kg NMVOC eq	7.78E-03	5.29E-03
Particulate matter	disease inc.	3.76E-07	2.94E-08
Acidification	mol H+ eq	4.28E-02	6.89E-03
Eutrophication, marine	kg N eq	1.70E-02	2.36E-03
Eutrophication, terrestrial	mol N eq	0.128	0.018
Land use	Pt	212.24	15.13
Resource use, fossils	MJ	18.72	14.38
Resource use, minerals & metals	kg Sb eq	1.10E-05	4.28E-06

The results show that recycled PLA production has a significantly[2] lower environmental impact for the relevant impact categories compared to the production of virgin PLA. The reduction ranges from 23% (for resource use–fossils) to 93% (for land use) and is due to the elimination of the sugarcane production step, as well as the other raw materials and energy required to produce lactic acid via fermentation.

[1] The most relevant impact categories are those cumulatively contributing to at least 80% of the total environmental impact, starting from the largest to smallest contributions, at the level of the normalized and weighted results.

[2] Defined threshold for significant changes when results range more than 10%.

For virgin PLA, the largest contributions to climate change come from lactic acid (production of chemicals, steam used, and transport of material inputs to the site) and sugar production. For recycled PLA, the environmental impact is driven by the use of steam for the depolymerization and new rPLA production processes, the production of post-industrial waste (PIW) and post-consumer waste (PCW) pellets, the transport of raw materials, the solid waste treatment, and the electricity use.

The cradle-to-gate carbon footprint of the production of 1 kg of Luminy® virgin PLA is 2.12 kg CO_2 eq, excluding the biogenic carbon embedded in the product (-1.83 kg CO_2 eq/kg PLA). Therefore, when including the biogenic carbon in the product, the carbon footprint of 1 kg of Luminy® virgin PLA produced at the TotalEnergies Corbion site in Rayong is 0.29 kg CO_2 eq. For this product, the impact on climate change is primarily driven by the production of chemicals (43%)—mainly the production of lime— followed by the production of sugar (23%), steam (19%), and transport (9%).

For the production of recycled PLA, the cradle-to-gate carbon footprint is 1.18 kg CO_2 eq/kg Luminy® 100% recycled PLA, excluding the biogenic carbon embedded in the product (-1.83 kg CO_2 eq/kg PLA). Therefore, when including the biogenic carbon in the product, the carbon footprint becomes -0.65 kg CO_2 eq/kg Luminy® 100% rPLA. The impact on climate change is mostly determined by the use of steam for the chemical recycling process and the new rPLA production process, including lactide production (36%), the production of PIW (12%) and PCW (15%) pellets, transport (14%), waste incineration (10%) and electricity (7%).

TotalEnergies Corbion also offers a grade of Luminy® rPLA with 30% attributed recycled content. This means that 30% of the lactic acid is produced via the chemical recycling process, while the remaining 70% comes from the sugar fermentation process. Based on the results presented above, the LCA results for this grade fall between Luminy® virgin PLA and Luminy® 100% recycled content. The carbon footprint of Luminy® 30% rPLA is, therefore, 1.84 kg CO_2 eq/kg rPLA when excluding biogenic carbon and 0.00 kg CO_2eq/kg rPLA when the biogenic carbon embedded in the product is included. Figure 1. illustrates the carbon footprint results of three Luminy® grades: virgin PLA, 100% recycled PLA, and 30% recycled PLA.

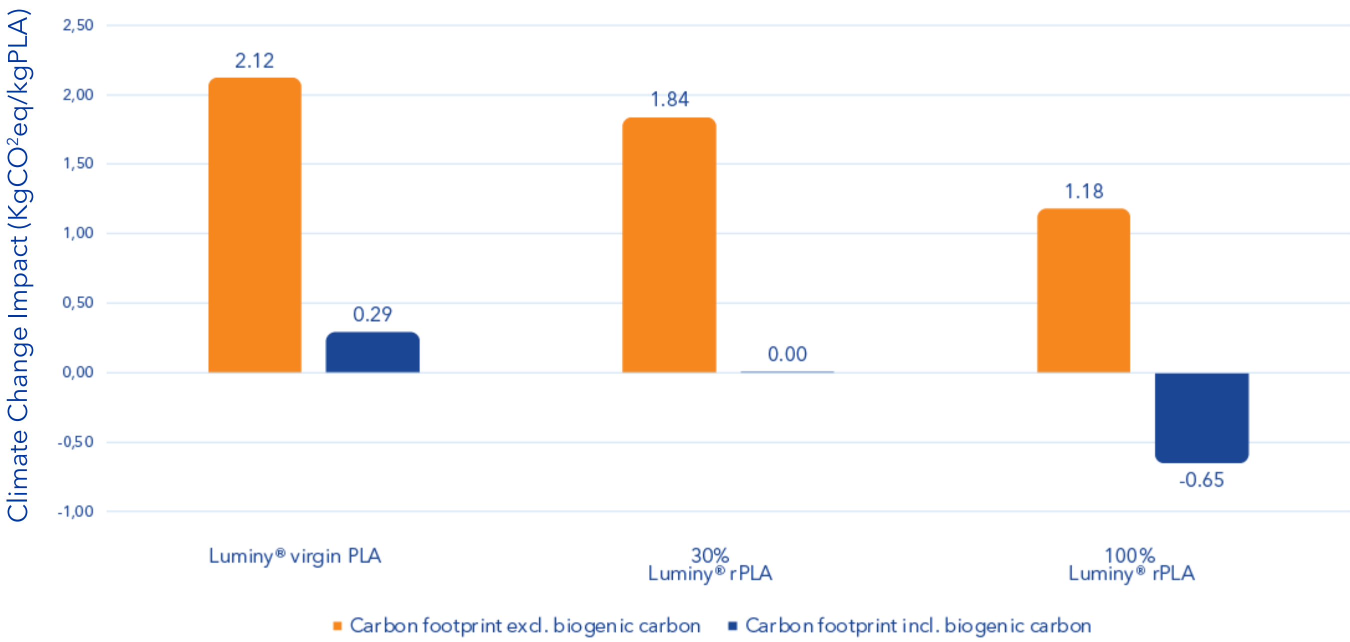


Figure 1. Overview of the cradle-to-gate carbon footprint of the Luminy® PLA grades - The biogenic carbon originates from biomass and is stored in the product until its potential emission at end-of-life

The multifunctional approach used in the study was economic allocation. Sensitivity analysis is performed to estimate the effects of the chosen allocation approach by using system expansion as an alternative scenario. In the case of virgin PLA, the choice of allocation is negligible for all impact categories (less than 3%). In the case of recycled PLA, the impact of multifunctionality choice is significant for most of the relevant environmental impact categories (i.e., acidification, particulate matter, terrestrial eutrophication, and land use). In this case, a significant reduction in the environmental impact is noticed due to the replacement of lactic acid, thus avoiding the burdens of its production that are mostly associated to the production of sugar. Another sensitivity analysis is performed where the PLA from PIW and PCW is transported as flakes instead of pellets. This results in a significant reduction in particulate matter, resource-use fossils, climate change, and acidification.

Major improvements in the environmental impact of virgin PLA can be achieved by replacing the conventional lactic acid input in the lactide production step with lactic acid produced by Corbion's circular lactic acid production process, which is lime-free. The improvements are due to the elimination of lime and sulfuric acid, as well as the gypsum by-products. Switching to circular lactic acid feedstock in the production process of virgin PLA would significantly reduce climate change (22%), particulate matter (19%), acidification (17%), and water use (26%) in the PLA environmental footprint. This initiative currently in development reflects the ongoing sustainability efforts of both the JV and Corbion.

Introduction

TotalEnergies Corbion, a 50/50 joint venture between TotalEnergies and Corbion, is a global leader in producing Luminy® PLA, a biobased, compostable, and recyclable polymer derived from sugarcane. With a production capacity of 75,000 metric tons annually, Luminy® PLA resins are used in diverse applications, from food service ware to 3D printing and cosmetics packaging. TotalEnergies Corbion is strongly involved in the full value chain of its products from the beginning of life to the end of life, building commercial collaborations and research projects to drive the circularity of the plastics market.

Luminy® PLA is made from lactic acid from sugar fermentation. The sugar comes from ethically farmed Thai sugarcane grown in Thailand. The fermentation and PLA production occur at Corbion's and TotalEnergies Corbion's Rayong facility. Lactic acid is used as raw material for the PLA polymerization process. The first step is the dehydration of lactic acid, which produces lactide as an intermediate. Lactide is then polymerized into polylactic acid. The final product sold by TotalEnergies Corbion is the PLA pellets.

In the materials market, especially for plastic, end-of-life (EOL) options are a key aspect for producers to consider. After being used, PLA offers multiple end-of-life options. It can be incinerated with energy recovery, industrially composted (certified EN13432 and ASTMD6400), mechanically or chemically recycled. The adequate end-of-life depends on the type of application, the local infrastructure, and the regulations in place. Today, PLA is not sorted out from municipal waste due to its low share in the global plastics market, but it has been proven that it can be efficiently sorted out with existing technologies (Thoden van Velzen et al., 2022). The current streams used for mechanical or chemical recycling come from industrial waste or closed-loop systems like events, hotels, airports, etc. Mechanically recycled PLA is usually reused in 3D printing applications or for garden furniture where food contact is not required. Chemically recycled PLA offers a high quality similar to virgin, enabling it to be used in applications, including food contact.

To support the sustainable EOL management of PLA, TotalEnergies Corbion has developed its own chemical recycling process to showcase and accelerate the recyclability of PLA. TotalEnergies Corbion collects a mix of post-industrial and post-consumer PLA waste from the market. This waste is then depolymerized after some pre-processing steps, converting PLA waste streams back to lactic acid. The process to produce PLA from lactic acid is the same, both for virgin lactic acid (e.g., lactic acid produced from sugarcane) and recycled

[3] Use of mechanically recycled plastics such as PLA in food contact application has regulatory constraints.

lactic acid from PLA waste. To commercialize PLA with recycled content, a mass balance tracking system is used to allocate credits based on the recycled lactic acid consumed in the polymerization plant. This mass balance allocation system is verified by SCS Global Services whose certification scheme is based on ISO 22095. Luminy® recycled PLA from chemically recycled lactic acid has the same quality and regulatory compliance (e.g., Food Contact) as Luminy® virgin PLA.

Methodology

This study provides an assessment of the Luminy® PLA environmental impact as well as the Luminy® recycled content PLA based on actual production values from TotalEnergies Corbion's plant in Rayong, Thailand.

The environmental impact of PLA production presented in this report is assessed using the requirements of ISO 14040 (2006), ISO 14044 (2006), and ISO 14067 (2018). To validate conformity with these standards, a critical review was performed by an external and independent reviewer, PRé Sustainability.

Goal

This study quantifies the environmental footprint of Luminy® PLA produced at TotalEnergies Corbion's Rayong, Thailand facility, highlighting opportunities for sustainable innovation.

The first PLA type assessed is Luminy® virgin PLA, produced from lactic acid coming from a sugar fermentation process.

The second PLA type assessed is Luminy® 100% recycled PLA produced by chemical recycling of post-industrial and post-consumer PLA waste.

The intent of this report is to provide information on the environmental impact of polylactic acid to internal and external stakeholders and to identify possible improvements throughout its life cycle.

It is key for TotalEnergies Corbion to continuously improve the sustainability of its product by evolving its production process and creating a recycled PLA grade. Offering a biobased material with recycled content is a unique value proposition that significantly reduces the environmental impact by avoiding the agricultural phase of the production process for lactic acid production and answering the circularity objectives of TotalEnergies Corbion's customers.

Scope

This study concerns TotalEnergies Corbion PLA production in Rayong, Thailand.
The capacity of the plant is 75,000 metric tons of Luminy® PLA per year.

The environmental impact of polylactic acid production is assessed using the LCA methodology, including impacts from the extraction of the raw materials up to the completion of the finished products at the factory gate (cradle-to-gate). The use phase of the PLA resins and the end of life of the final products are excluded due to the large variety of options. For the PLA waste used as feed, the EOL allocation approach selected is cut-off, i.e., it is assumed that these waste streams have no environmental burden. For a better understanding, the simplified system boundaries are presented in Figure 2.

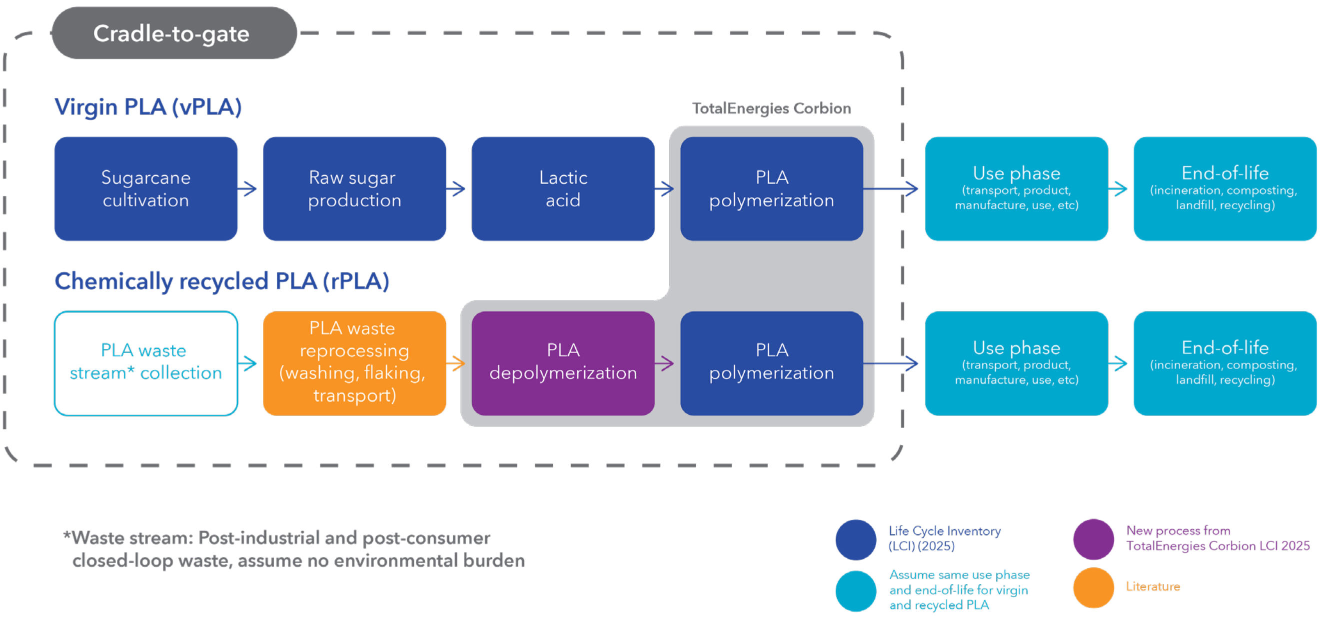


Figure 2. Virgin and recycled PLA life cycle stages included in the scope of the study.

Functional units

The functional unit is defined for 100% virgin PLA and for PLA with 100% recycled content.

Production of Virgin PLA:

Declared unit: 1 kg of PLA pellets produced from sugarcane at TotalEnergies Corbion's production plant in Rayong, Thailand, in 2024, at factory gate, without packaging (vPLA).

Production of PLA with attributed recycled content:

Declared unit: 1 kg of 100% recycled PLA (rPLA) pellets produced from chemically recycled PLA at TotalEnergies Corbion's production plant in Rayong, Thailand, in 2024, at the factory gate, without packaging.

Process description

This study examines the production of PLA through two different production systems: virgin and recycled PLA. For the recycled PLA, the production routes considered are the production from post-industrial and post-consumer waste (presented in Figure sections below).

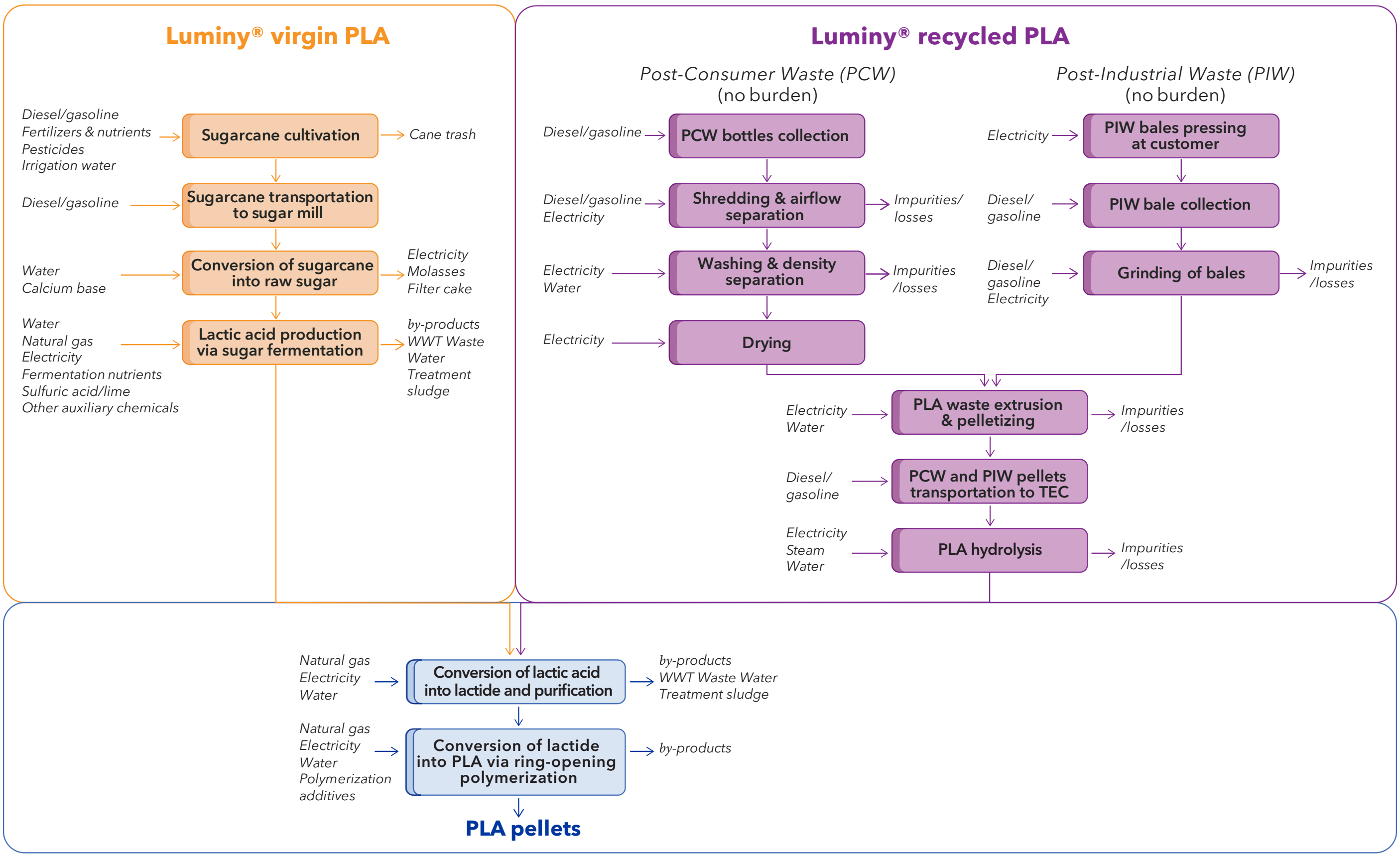


Figure 3. Manufacturing process of virgin PLA (vPLA) and recycled PLA (rPLA) from post-consumer (PCW) and post-industrial waste (PIW).

Virgin PLA

The production of a virgin PLA can be divided into four main stages:

- Sugarcane production and transport to sugar mill
- Sugarcane conversion into raw sugar
- Raw sugar fermentation to produce lactic acid (by Corbion)
- Conversion of lactic acid into lactide and PLA (by TotalEnergies Corbion)

Sugarcane production and processing into raw sugar

Several sugar mills supply raw sugar for the production of lactic acid to the manufacturing plant of Corbion in Rayong. These sugar mills source sugarcane from their surrounding area and have been in operation for many years.

Sugarcane cultivation

Sugarcane cultivation requires the use of agrochemicals, energy, and water, as well as CO_2 from the atmosphere. Sugarcane grows for about 6-7 months and is harvested in the harvest season of about 5 months. Sugarcane is immediately transported to the mill by trucks and processed to avoid losses.

Harvesting sugarcane can be done mechanically or manually. Manual harvesting can include burning residue crops on the field. Open burning of residues is not desirable because it reduces sugar yields, releases a number of air pollutants, and impacts the soil quality. The Thai government aims to reduce sugarcane burning to 20% by stipulating sugar mills purchase at least 80% of fresh sugarcane from Thai farmers (Tridge 2021). In the case of mechanical harvesting, a machine cuts the cane at the base of the stalk, strips the leaves, chops the cane into consistent lengths, and deposits it into a transporter, which follows alongside. The machine then blows the dead leaves and the top of the sugarcane back onto the field. This mechanical harvesting does not require the dead leaves and tops of the sugarcane (i.e., the residue) to be set on fire in an open field. Instead, the residue remains in the field to be used as nutrients for the next round of planting. The impact of the crop residues left on the field is included in the modelling of the production of sugarcane.

The sustainability of this feedstock is key for TotalEnergies Corbion and Corbion. Measures have been developed to ensure limited environmental impact from sugarcane production. The upstream supply chain has to comply with the Cane Sugar Code developed by Corbion. Moreover, part of the supply chain is Bonsucro certified. Based on satellite images, it has been proven that the entire cultivation of sugarcane occurs free of deforestation and in areas that are not protected or with a high biodiversity risk. (TotalEnergies Corbion 2023)

Sugarcane processing into raw sugar

In a typical Thai sugar mill, sugarcane is crushed to extract cane juice, while bagasse, the fibrous material that remains from sugarcane, is burned in a co-generation unit to produce electricity and steam. The energy produced is used within the mill. Typically, the mill is self-sufficient, and in many cases, there is excess electricity that can be exported to the grid. Sugar mills have a few energy-intensive steps, such as evaporation, heating, and crystallization.

The cane juice is clarified using heat and lime, which is used to adjust the pH and prevent the inversion of sucrose. A heavy precipitate is formed and separated from the juice by filtration. The filter cake is mainly used as a soil conditioner or fertilizer on the nearby sugarcane plantations. The purified juice is evaporated, crystallized, and centrifuged to produce raw sugar and molasses. The feedstock used in Corbion's plant in Thailand is raw sugar. Molasses can be used as a food supplement/ingredient, raw material for the production of ethanol, citric acid, or as a purer molasses syrup used in baking.

Lactic acid production

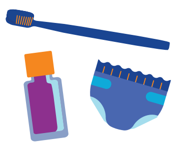
Sugar is transported from the sugar mills to Corbion's site in Rayong in bulk by trucks. The first step in the production of conventional lactic acid is the fermentation of sugar. The pH of the fermentation is controlled using lime, resulting in the formation of calcium lactate. Nutrients are added to aid the fermentation. The fermentation broth is concentrated, and calcium lactate is acidulated with sulfuric acid (H_2SO_4) to recover crude lactic acid. This step results in the precipitation of gypsum ($CaSO_4$), a by-product of the lactic acid production process, which is removed by filtration.

The final step is lactic acid purification, which removes various impurities. This separation results in a by-product stillage. Stillage has multiple applications, such as animal feed, biogas production, and biofuel. Due to the activity of bacteria, some biogenic CO_2 is released during fermentation as air emissions.

The main product, lactic acid, is transported via a pipeline to the TotalEnergies Corbion premises, where it is used as a source for lactide production.

Lactide and PLA production

First, purified lactic acid is converted into crude lactide through a dehydration and depolymerization process. The crude lactide is then purified to remove any residual lactic acid, oligomers, and other impurities.



PLA is produced through a ring opening polymerization of the purified lactide. After the polymerization is complete, any remaining lactide monomer is removed and recycled within the PLA process. The PLA melt is pushed through a pelletizing system to become solid pellets. The PLA pellets are further crystallized, cooled, and packed in the downstream process.

During startups and shutdowns, off-spec PLA is produced, which will be chemically recycled on the same site.

Recycled PLA

For the production of 100% recycled PLA, the source of lactic acid is the PLA waste. The lactide and PLA synthesis steps remain the same as for the virgin process.

Production of recycled PLA

Today, PLA is typically not sorted out of mixed plastic waste, nor does it have large-scale commercial separate sorting. This situation is based on waste availability rather than technical feasibility, given that it is compatible with high-efficiency sorting facilities. Conventional plastic streams still represent the vast majority of mixed plastic waste. From a technical perspective, it has been demonstrated that PLA can be easily sorted from mixed waste and does not contaminate other existing recycled streams
(Mhaddolkar et al., 2021, Theoden van Velzen et al., 2022). This study reflects the current typical practice, and therefore, recycling mixed plastic waste is out of scope. TotalEnergies Corbion's chemically recycled PLA (Luminy® rPLA) is produced from post-industrial waste (PIW, also called pre-consumer waste) and closed-loop post-consumer waste (PCW). TotalEnergies Corbion collects reprocessed PLA waste from different PLA converters and post-consumer closed-loop systems. To estimate the environmental impact of rPLA, two representative cases were defined:

Post-industrial waste (PIW) from a PLA fibre application in Europe

In this application, PLA resin is melted and extruded into PLA fibres by converters. The PLA waste from this process may be diverse in appearance, ranging from amorphous spin-ware to highly oriented PLA filaments, but it is chemically identical. It is typically compressed into bales, which are ready for recycling. Due to the low density of the bales, transport can be costly and ineffective, therefore, the bales are converted by melt-processing into PLA pellets, during which melt filtration may occur to filter off any solid contaminants. These filtered solids can be polymers with a higher melting temperature like Polyethylene terephthalate (PET, wood, or any accidental contaminant. The treatment of this waste stream is considered in the model based on literature data, since other information is not available. The pellets are subsequently shipped to a PLA production facility, in this case at TotalEnergies Corbion manufacturing plant in Rayong, Thailand, where they are converted to lactic acid.

Post-consumer waste (PCW) of bottle streams from Asia

In a closed-loop system–including restaurants, hotels, events, or corporate spaces–the bottled drinks supplier collects empty used PLA bottles when bringing a new delivery of fresh bottles. The waste bottles are then sorted, washed, and flaked in a facility in the same country. The cleaned PLA flakes are extruded, pelletized, and subsequently transported to the PLA production facility for chemical recycling in Thailand.

Chemical recycling of both streams is achieved via hydrolysis, which converts PLA back to lactic acid. The retrieved lactic acid is then further purified to reach the required quality for the polymerization process. The losses occurring during this process are linked to the purification, meaning that they vary depending on the composition of the incoming PLA waste.

The resulting recycled lactic acid is mixed with virgin lactic acid and re-converted into high molecular weight PLA. The polymerization process is the same as for virgin PLA, as described above. The high degree of purification occurring during the polymerization steps is a double assurance of the quality of the recycled PLA.

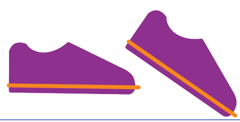
Recycled lactic acid cannot be differentiated from virgin lactic acid as there is no identity preservation after mixing both streams. To offer Luminy® PLA with recycled content, TotalEnergies Corbion uses the mass balance approach, allocating the credits of the recycled PLA to the final product.

System boundaries

The life cycle inventory includes all the flows (inputs and outputs) passing the system boundary, including raw materials from nature: carbon dioxide, water, land, and the emissions to air, water, and soil. All processes are included–with a cut-off lower than 1% –based on material and energy flows.

The system under study includes upstream processes (e.g., raw materials extraction) and core processes (e.g., production and processing), while downstream processes (e.g., packaging, transport and use of the product) are excluded from the scope of the study.

The cut-off method was used to model the PLA waste input (Figure 2.). This means the PLA from PIW or PCW bears no environmental burden from the first life. Therefore, the system boundaries from recycled PLA include the collection, transportation, and reprocessing steps of the waste streams to the PLA monomer (recycled lactic acid). The steps from recycled lactic acid to rPLA are the same as for vPLA.



Multifunctionality and allocation of by-products

PLA production has multiple by-products, as identified in Figure 3., which are interlinked and cannot be subdivided. In attributional modelling, when sub-division is not possible, the allocation between co-products should be applied. Economic allocation is applied as the default scenario for the by-products from all PLA manufacturing steps except the sugar mill. Energy allocation is used for the sugar mill by-products because of the large fluctuations in the market prices of the by-products of sugar, electricity, and molasses. The impact of the allocation approach on the results of the environmental assessment is addressed in the sensitivity analysis.

Environmental impact categories & characterization models

For the environmental assessment of PLA, the impact is calculated for all sixteen impact categories of the EF 3.1 method, adapted in SimaPro. The definitions of the sixteen impact categories are listed in Annex A. The relevant impact categories are identified based on weighting
of the results and defined by those cumulatively contributing to at least 80% of the total environmental impact. Classification and characterization are conducted by the LCA software (SimaPro 9.6) according to the characterization models used within the software.

Data usage and quality requirements

To ensure reliable results, primary industrial data are combined with LCA information from the latest versions of ecoinvent and Agrifootprint databases, using SimaPro 9.6 software. Data quality is judged by its precision, completeness, and representativeness.

Data quality requirements

The data used to create the inventory model shall be as precise, complete, consistent, and representative as possible with regard to the goal and scope of the study. Measured primary data are considered to be of the highest precision, followed by calculated and estimated data.

This evaluation of data is based on the data quality requirements (DQR) scoring (European Commission 2020). The data are scored from very good (score 1) to very poor (score 5) based on four criteria: time representativeness, geographical representativeness, technology representativeness, and precision. An evaluation of the data quality was conducted for this study, showing a result considered as good quality, fulfilling the purpose of the study.

Data sources

The data collection sources rely on the preferential use of primary data retrieved from industrial production in combination with LCI information from the databases Agri-footprint V6.0, Energy allocation (only for the production of sugar), and ecoinvent 3.10, cut-off (for all other inputs), as implemented in SimaPro 9.6 software. The primary data used in this study represents the current technology to produce lactic acid, lactide, and PLA in Rayong, Thailand, including consumption of raw materials and energy as well as the production of waste and by-products. The input data are collected in consistency with the reference year (2024) and the geographical area (Thailand).

Data gaps and secondary inputs are modelled using generic LCI datasets for similar materials and processes. For generic data, LCI datasets from ecoinvent 3.10 cut-off are used. The secondary datasets were modified, when relevant, with specific data concerning the geographical region, technology, or temporal reference. For agricultural products, energy allocation is selected for its simplicity and objectivity as it does not depend on external factors such as market fluctuations or policy interventions. Both databases used, ecoinvent 3.10 cut-off and Agri-footprint V6.0, are based on an attributional approach with the same scope and boundaries considered. Thus, their mixing does not introduce significant inconsistencies. Furthermore, Agrifootprint
uses ecoinvent cut-off in the background datasets. The combinations of databases are unavoidable in order to have the best data quality in terms of representativeness (geographical, temporal, and technological).

Data collection

The sections below describe the data collection process, including the methodological assumptions on the modelled process and the related datasets.

The data collection and modeling assumptions for virgin PLA production are listed in Table 2, and for recycled PLA, they are listed in Table 3. As mentioned before, in system boundaries for recycled PLA, the waste streams from PIW and PCW bear no environmental burden from the first life (cut-off approach for end of life). As PLA waste is collected in a closed-loop environment, no contamination from a mix of plastic collected is assumed.

Table 2. Data sources and assumptions for the LCI of virgin PLA

Process step	Data sources and assumptions
Sugarcane farming	The agriculture process of cultivating sugarcane is based on a background dataset from Agri-footprint v6 Sugarcane at farm/TH Energy, adapted with supplier-specific data. Supplier-specific data at farm level is based on an average of multiple years (2018-2022). Emissions from land transformation and direct land use change are based on high-resolution satellite images and enhanced vegetation index time series analysis over the period between 2001 and 2020, performed by GRAS. These studies cover land conversion from forest, grassland, tree plantations, shrubland, and peat land to sugarcane.
Sugar mill	The production of raw sugar is based on the background dataset from Agri-footprint Sugar, from sugarcane, at processing/TH Energy, and adapted from the information from suppliers. The number of outputs, material, and energy inputs from this dataset are replaced by the type of inputs and values shared by Corbion suppliers based on the most recent year of data available for each supplier.
Lactic acid	• Lactic acid production data primarily from Corbion's bill of materials 2024. • **Electricity:** Corbion sources 100% renewable electricity generated from photovoltaic power plants since 2023 • **Steam:** Corbion purchases steam generated by a natural gas-fired combined heat and power plant (CHP). Natural gas input and calculation of allocation between produced steam and power has been provided by the supplier. • **Water:** The site uses raw water taken from a river to produce 'industrial water', which is further treated to obtain deionized water, here referred to as 'reverse osmosis water'. Both industrial and reverse osmosis water are used in the process. Chemicals and energy used in the water treatment are included in the model based on primary data. • The wastewater from the production of lactide and PLA is treated within the facilities of Corbion, combining anaerobic and aerobic biological treatment steps with biogas generation. The WWT is modelled by adjusting the ecoinvent 3.10 dataset 'Wastewater from maize starch production {CH }| treatment of, capacity 1.1E10l/year'. Effluent parameters based on primary data: nitrogen, biological, and chemical oxygen demand. • **Solid waste:** A small amount of production waste is sent to incineration. This is modelled with the ecoinvent 3.10 dataset 'Municipal solid waste {RoW}| treatment of municipal solid waste, municipal incineration | Cut-off, U'. • **Lime:** the background datasets Lime, hydrated, lose weight {RoW}|production, and Quicklime, in pieces, loose {RoW}| production were used and adapted to Thailand by changing the datasets of electricity, heat, and water used in the lime production process. The information on fuel type and consumption is obtained from lime suppliers, and this is reflected in the modified background datasets. • **Other chemicals and fermentation nutrients:** Datasets from the Ecoinvent v3.10 for the geographies Global (GLO) or Rest of the World (RoW), adapted to Thailand (TH) by changing the heat, electricity and water datasets to the Thai geography.

Process step	Data sources and assumptions
Lactide and PLA	• Actual 2024 production data from the TotalEnergies Corbion lactide and PLA plants. • **Electricity, Steam, Water, Wastewater, and Solid Waste:** These are the same as lactic acid, as the utilities are shared with Corbion. • Natural gas is also used in the PLA production plant for heat production. Modelling is based on ecoinvent heat dataset 'Heat, district or industrial, natural gas {RoW}| heat production, natural gas, at boiler condensing modulating >100kW. • **Chemicals:** Only a few chemicals, like polymerization catalysts and additives, are used in lactide and PLA synthesis steps. In line with the mass cut-off criteria, raw materials representing less than 1% of the input mass are excluded from the analysis.

Table 3. Data sources and assumptions for the LCI of recycled PLA.

Steps considered for PLA recycling

Post-Consumer Waste	Post-Industrial Waste	Data sources and assumptions
PLA waste collection and reprocessing in Asia. • Bottle collection & transport • Shredding & air flow separation • Washing • Drying • PLA waste extrusion & pelletizing	PLA waste collection and reprocessing in Europe: • PIW bale pressing at customer • PIW bale collection & transport • Grinding of the bales • PLA waste extrusion & pelletizing	Inventory data from literature. Waste treatment of process losses: 35% landfill and 65% recycling (Maga, Hiebel et Thonemann 2019) (Moretti 2021) Geography: RoW or GLO
Transportation of PLA pellets from Asia to Rayong, Thailand (TotalEnergies Corbion data).	Transportation of PLA pellets from Europe to Rayong, Thailand (TotalEnergies Corbion data).	Average distances, based on TotalEnergies Corbion supply chain.
PLA hydrolysis and purification.	PLA hydrolysis and purification.	Actual production data from TotalEnergies Corbion from 2024. Modelling of energy, water and waste streams – same as virgin PLA (see Table 2)
Conversion and polymerization of PLA hydrolysate to recycled PLA pellets.	Conversion and polymerization of PLA hydrolysate to recycled PLA pellets.	Actual production data from TotalEnergies Corbion from 2024. Modelling of energy, water and waste streams – same as virgin PLA (see Table 2)

Biogenic carbon accounting

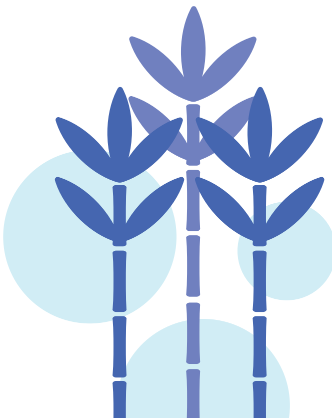
In the case of products containing carbon derived from biomass[4], the biogenic carbon content in the product is equal to the carbon removal from the atmosphere during plant growth. This biogenic carbon content calculated using the biomaterial storage approach is 1.833 kg CO_2 for 1 kg of PLA. It can then be released in the end-of-life stages.

The lifetime of PLA and the final products containing PLA can vary, but they are often used for more durable applications with different end-of-life options. Therefore, the biogenic carbon content is provided as additional technical information and has no intent to claim a carbon credit. After the use of PLA, the biogenic carbon can be released in the use or end of life stages (e.g., incineration or composting). When PLA is recycled further, the sequestered carbon is effectively kept out of the atmosphere longer.

Biogenic carbon is an intrinsic property of the material, according to the definition in EN16785 and in line with EN 15804+. By using this approach, the biogenic carbon considered for the recycled PLA does not correspond to a CO_2 uptake, but to the biogenic carbon present in the waste used as raw material. When biogenic CO_2 content is included in the carbon footprint, for both virgin and recycled PLA, the emission of this biogenic CO_2 shall be considered for climate change impact at the ultimate end of life of PLA (e.g., incineration or composting). We acknowledge that there is no consensus on the accounting approach for biogenic CO_2, and for waste streams, this topic is even more complex. This approach is in line with recent recommendations from the EU Directorate-General for the Environment (DG ENV) for the Product Environmental Footprint methodology which have not yet been implemented, and therefore, it is a limitation of the study. Given the lack of consensual guidance, we ensure full transparency on the approach taken and limitations.

Furthermore, for the rPLA, we consider that the carbon in the waste is fully biobased because the waste collection is segregated, and we assume that all contaminates are removed before entering the polymerization step.

The carbon footprint is composed of Greenhouse gas emissions (biogenic GHG emissions, net fossil GHG emissions) and removals and emissions from land use change (DLUC), which are negligible for the systems under study (Annex B). Biogenic GHG removal is equal to the sum of biogenic CO_2 released at the end of life. According to ISO 14067 removals of CO_2 into biomass are characterized as -1 kg CO_2eq/kg CO_2 and emissions of biogenic CO_2 are characterized as $+1$ kg CO_2eq/kg CO_2.



[4] Lactic acid is produced directly through the fermentation by specific microorganisms (consumption of sugar) and lime (hydrated lime (Ca (OH)2)) is used afterwards only for neutralization, there can be no other carbon in lactic acid besides the one that comes from the sugar. Results from testing (C14) on lactic acid are also available.

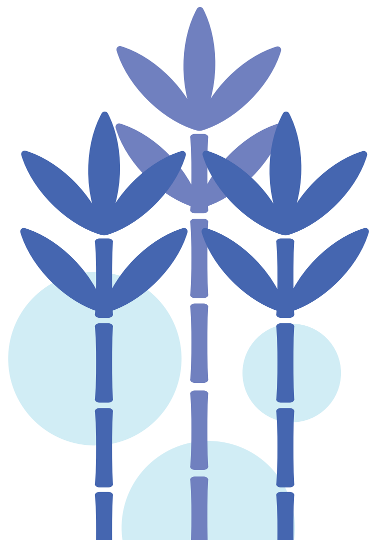
Life Cycle Impact Assessment results

Table 4. presents the Life Cycle Impact Assessment (LCIA) results for producing 1 kg of Luminy® virgin PLA and 1 kg of Luminy® recycled PLA, based on the EF 3.1 method.

Table 4. Environmental impact of the production of 1 kg of polylactic acid, based on the EF 3.1 (adapted) method.

Impact category	Unit	Luminy® virgin PLA	Luminy® 100% recycled PLA
Climate change	kg CO_2 eq	2.12 (0.29 incl. biogenic carbon)	1.18 (-0.65 incl. biogenic carbon)
Ozone depletion	kg CFC11 eq	2.18E-07	1.25E-08
Ionizing radiation	kBq U-235 eq	1.54E-02	2.11E-02
Photochemical ozone formation	kg NMVOC eq	7.78E-03	5.29E-03
Particulate matter	disease inc.	3.76E-07	2.94E-08
Human toxicity, non-cancer	CTUh	1.58E-08	8.03E-09
Human toxicity, cancer	CTUh	3.57E-09	2.78E-09
Acidification	mol H+ eq	4.28E-02	6.89E-03
Eutrophication, freshwater	kg P eq	6.72E-04	9.63E-05
Eutrophication, marine	kg N eq	1.70E-02	2.36E-03
Eutrophication, terrestrial	mol N eq	0.128	0.018
Ecotoxicity, freshwater	CTUe	30.41	8.02
Land use	Pt	212.24	15.13
Water use	m^3 depriv.	0.624	0.297
Resource use, fossils	MJ	18.72	14.38
Resource use, minerals and metals	kg Sb eq	1.10E-05	4.28E-06

These LCIA results indicate potential environmental impacts, not absolute effects, serving as reliable indicators for assessing sustainability performance.



Interpretation

Using the EF 3.1 method, the study identifies key impact categories based on their significant contribution to the overall environmental footprint.

For virgin PLA, the key impact categories—climate change, particulate matter, acidification, terrestrial and marine eutrophication, resource use (fossils), and land use—account for over 80% of the environmental footprint.

For recycled PLA, the primary impact categories include climate change, resource use (fossils and minerals/metals), acidification, photochemical ozone formation, particulate matter, and terrestrial eutrophication, contributing to 82.6% of the total impact, which is 70% lower than virgin PLA.

The total weighted impact of the recycled PLA process is 70% lower than that of virgin PLA. The difference in environmental hotspots is linked to the production of sugar and also the use of chemicals that are used for the production of lactic acid, for example, lime and sulfuric acid that have a significant impact in environmental impact categories like land use change, acidification, and particulate matter. The overall impact and contributions for all relevant impact categories for both processes will be analyzed in detail in the following sections.

Water use and land use (in the case of recycled PLA) are not environmental hotspots for the analyzed processes. Nevertheless, it is included in the analysis reference because of their relevance for the biobased industry.

Environmental hotspots and impact categories – virgin PLA

The LCIA results for the most relevant impact categories of the production of virgin PLA are summarized in Table 5. As shown in Table 5, most of the contributions in all relevant impact categories are due to the stages of sugar production and lactic acid production.

Table 5: Relevant environmental impact categories to produce 1 kg of virgin PLA at cradle-to-gate divided across different stages of the production system based on the EF 3.1 (adapted) method.

Impact category	Unit	Total	Sugar production	Lactic acid production	Lactide production	PLA production
Climate change	kg CO_2 eq	2.12 (0.29 incl. biogenic carbon) **100%**	0.487 **23.0%**	1.266 **59.7%**	0.306 **14.5%**	5.905E-02 **2.8%**
Particulate matter	disease inc.	3.76E-07 **100%**	2.477E-07 **65.9%**	1.218E-07 **32.4%**	4.719E-09 **1.3%**	1.746E-09 **0.4%**
Acidification	mol H+ eq	4.28E-02 **100%**	2.719E-02 **63.5%**	1.479E-02 **34.5%**	6.715E-04 **1.6%**	1.701E-04 **0.4%**
Eutrophication, terrestrial	mol N eq	0.128 **100%**	0.1175 **91.9%**	8.610E-03 **6.7%**	1.386E-03 **1.1%**	3.883E-04 **0.3%**
Eutrophication, marine	kg N eq	1.70E-02 **100%**	1.171E-02 **68.9%**	4.385E-03 **25.8%**	8.641E-04 **5.1%**	4.688E-05 **0.2%**
Resource use, fossils	MJ	18.72 **100%**	2.534 **13.5%**	10.840 **57.9%**	4.493 **24.0%**	0.857 **4.6%**
Land use	Pt	212.24 **100%**	196.58 **92.7%**	7.450 **3.5%**	5.591 **2.6%**	2.620 **1.2%**
Water use	m^3 depriv.	0.624 **100%**	0.241 **38.7%**	0.271 **43.3%**	0.088 **14.1%**	0.024 **3.9%**

Climate change

The climate change impact for 1 kg of virgin PLA equals to 0.285 kg CO_2eq, when including the biogenic carbon embedded in the product. Figure 4 shows the split of the climate change impact per production stage starting from the atmospheric carbon capture.

The production stages with the largest contributions are the lactic acid production (60%) and the sugar production (23%).

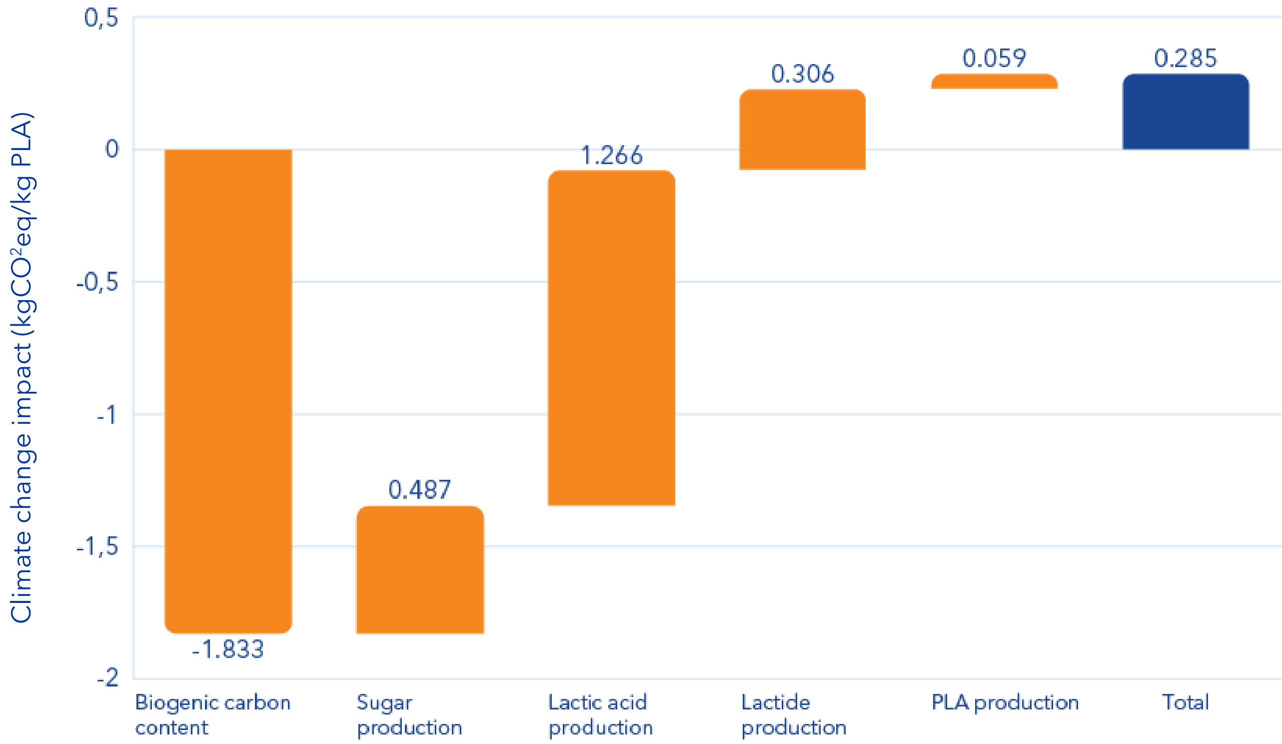


Figure 4. Overview of contributions to climate change impact for 1kg of Luminy® PLA.

Lactic acid production, representing 60% of the climate change impact, is the production step with the highest contribution. This contribution is mainly due to the production of chemicals (43%) used during the production process, with the biggest contributor being lime. The other significant contributors after lime are the use of steam for the production process and the transport of raw materials to the Corbion facility.

For the sugar production (23% of the total climate change impact), 14% of the total impact comes from the processing in the sugar mill, while the rest comes from the agricultural stage (86%). The main contributions to the farming of sugarcane are the direct N2O and CO_2 emissions from fertilizers use, production of these fertilizers, emissions from field residues burning, and energy use for farming machines. Other significant impacts are the transport of sugarcane from farm to mill, the transport of chemicals to the sugar mill, and the emissions from bagasse burning. CO_2 emissions from land transformation (direct land use change) are only 0.06% of the total sugar-related emissions. This value is relatively low because the extent of land transformation in the sourcing areas is low. Particularly, deforestation in these regions, which are used historically for sugarcane plantations, is negligible and has been verified by satellite images over the last 20 years.

In terms of the energy used for lactide and PLA production, steam contributes 19% of the total impact, electricity contributes 4%, and natural gas makes a negligible contribution of 1%.

The transport of raw materials to the production sites (TotalEnergies Corbion and Corbion) has a contribution of 9% to the total climate change impact.

Other relevant impact categories

Water use

According to the hotspot analysis, water use is not a relevant impact category; however, it is added to the interpretation with the goal of providing insights into water-related impacts, as this is considered relevant for the biobased industry.

In the EF method, the impacts on water are assessed in terms of the quantity of water deprived. As shown in Table 4 and Figure 5, 43% of water impacts come from the lactic acid production stage–production of sulfuric acid (52%) and fermentation nutrients (20%), industrial water use (29%), and steam and electricity used (8 and 9% accordingly), 39% comes from the production of sugar (water used at farm level) and 14% from the production of lactide (steam (37%), electricity (34%), and industrial water use (23%). In the wastewater treatment step, water is returned to the same water basin, which results in negative contribution on water use impact category.

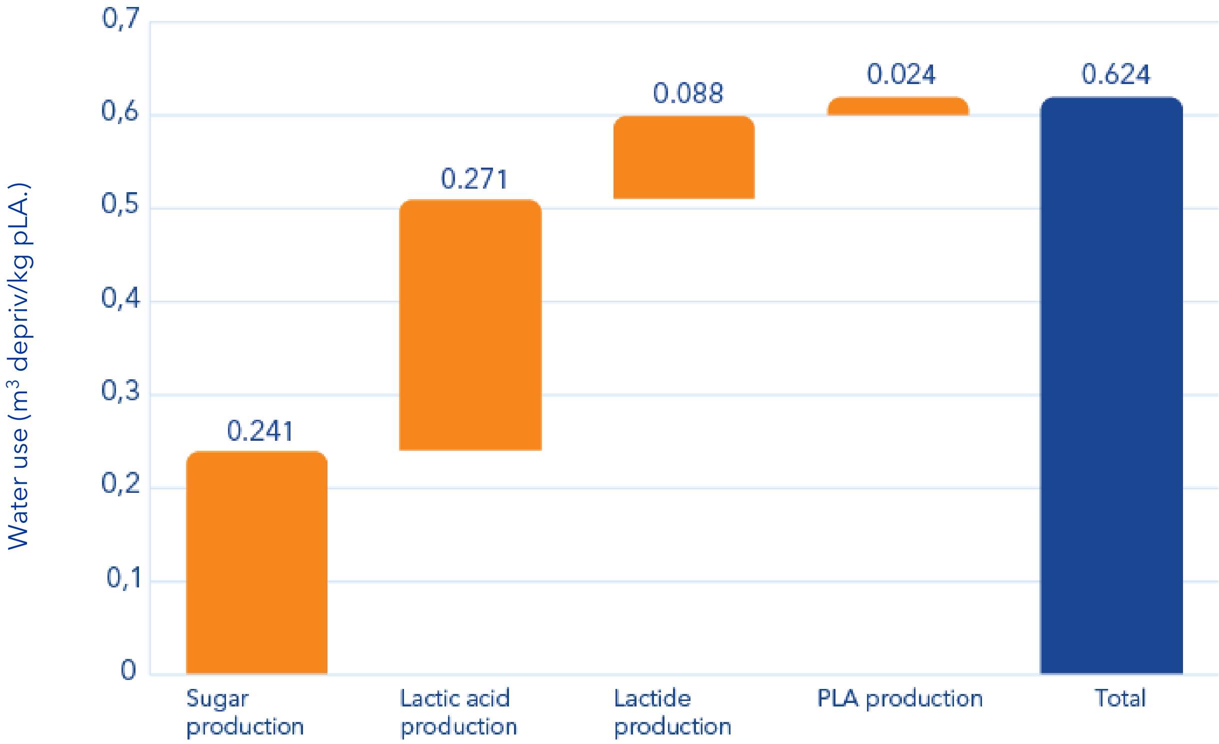


Figure 5. Contribution analysis of the production stages for 1kg of PLA to the water use impact category

Particulate matter

The main contributions to particulate matter are from the production of sugar (66%) and the production of chemicals (28%). More specifically, for the production of sugar, from the 66% of the total impact, 28% comes from the bagasse combustion in the sugar mill and 71% come from the direct emissions in the farm level, mostly from the direct emissions of ammonia in the air due to the fertilizer application and cane burning in the field. Regarding the production of chemicals, the main impact comes from the production of lime (9% of the total impact) and the production of sulfuric acid (18% of the total impact) that are used during the production of lactic acid. The additional emissions are from small particles (< 2.5 μm and >2.5 μm) from the combustion processes including transport (4%) and electricity production (1%).

Acidification

Acidification is mainly caused by air emissions of sulfur dioxide, nitrous oxide, and ammonia which cause a change in its acidity when deposited in soil. As shown in Table 5, the impacts on acidification come from the production of sugar (64%) and the lactic acid production stage (35%). For the production of sugar, most of the emissions are caused during the cultivation of sugarcane mostly due to ammonia emissions to air deriving from the fertilizers' application and cane burning in the field. For the lactic acid production stage, the main contributions come from chemicals (primarily sulfuric acid and lime production).

Eutrophication, terrestrial and marine

Eutrophication is associated with the environmental impacts of excessively high levels of nutrients that lead to shifts in species composition and increased biological productivity. Terrestrial and marine eutrophication are primarily driven by sugar production (92% and 69%, respectively), due to ammonia and nitrate emissions from fertilizer use and cane burning. Lactic acid production contributes up to 26% of marine eutrophication via wastewater emissions.

Resource use, fossils

The impact category 'resource use, fossils' is directly linked to the consumption of fossil energy during the agricultural phase and the manufacturing steps of lactic acid, lactide, and PLA.

Fossil resource use is mostly impacted by the production of lactic acid (58%), lactide (24%), and sugar (14%). Regarding the production step of lactic acid, the impact (58%) comes mainly from the production of chemicals—and more specifically the production of lime (28%) and sulfuric acid (11%, due to the consumption of fuels during the production processes for these chemicals), transport of raw materials and waste (21%, also due to the burning of fuels and mostly petroleum), and also the production of steam (22%, mostly due to the combustion of natural gas). For the step of production of lactide, the majority of the impact is due to the steam required for the process (83%). Finally, the impact of sugar production comes from the energy and transport required mostly during the cultivation stage of the sugarcane. The PLA (polymerization) production step contributes to 5% of the total impact.

Land use

Land use covers the impacts due to the use of soil from erosion resistance, mechanical filtration, physicochemical filtration, groundwater regeneration, and biotic production. It is expressed as a dimensionless soil quality index and is based on both global and spatially differentiated characterization factors at country level. Land use depends on many factors: crop type, average local and regional yields, the allocation procedure used to account for the multiple crop products, the percentage of fermentable sugars in the crop, and the efficiency of recovery of these sugars along with the efficiency of the conversion steps to lactic acid. Land use for the sugar production contributes to 93% of the total impacts from the PLA production. The rest of the impact on land use originates from lactic acid production (4%) and lactide production (3%), mostly due to the impact of renewable electricity production. The total contribution of renewable electricity is 5%, and it is due to the land transformation into industrial areas and the occupation of industrial areas that are required.

Environmental hotspots and impact categories – 100% recycled PLA

The LCIA results for the most relevant impact categories of the production of recycled PLA are summarized in Table 6. As it is shown in Table 6, the contributions to the most relevant impact categories are distributed among the different production stages.

Table 6. Relevant environmental impact categories to produce 1 kg of recycled PLA at cradle-to-gate divided across different stages of the production system based on the EF 3.1 (adapted) method.

Impact category	Unit	Total	PIW pellets production	PCW pellets production	PLA hydrolysis	Lactide production	PLA production
Climate change	kg CO2 eq	1.18 (-0.65 incl. biogenic carbon) **100%**	0.137 **11.6%**	0.182 **15.4%**	0.496 **42.0%**	0.307 **26.0%**	5.914E-02 **5.0%**
Resource use, fossils	MJ	14.38 **100%**	2.190 **15.2%**	1.475 **10.3%**	5.356 **37.2%**	4.502 **31.3%**	8.582E-01 **6.0%**
Acidification	mol H+ eq	6.89E-03 **100%**	5.043E-04 **7.3%**	6.918E-04 **10.0%**	4.856E-03 **70.5%**	6.719E-04 **9.7%**	1.704E-04 **2.5%**
Photochemical ozone formation	kg NMVOC eq	5.29E-03 **100%**	5.041E-04 **9.5%**	4.527E-04 **8.6%**	3.707E-03 **70.1%**	4.621E-04 **8.7%**	1.631E-04 **3.1%**
Resource use, minerals and metals	kg Sb eq	4.28E-06 **100%**	2.965E-07 **6.9%**	1.119E-07 **2.6%**	1.646E-06 **38.4%**	1.502E-06 **35.1%**	7.284E-07 **17%**
Particulate matter	disease inc.	2.94E-08 **100%**	7.355E-09 **25.0%**	6.298E-09 **21.4%**	9.250E-09 **31.5%**	4.719E-09 **16.1%**	1.751E-09 **6.0%**
Eutrophication, terrestrial	mol N eq	1.78E-02 **100%**	1.274E-03 **7.1%**	1.542E-03 **8.7%**	1.319E-02 **74.2%**	1.387E-03 **7.8%**	3.893E-04 **2.2%**
Land use	Pt	15.13 **100%**	1.180 **7.8%**	0.260 **1.7%**	5.478 **36.2%**	5.590 **37.0%**	2.620 **17.3%**
Water use	m^3 depriv.	0.297 **100%**	0.020 **6.6%**	0.062 **21.0%**	0.102 **34.5%**	0.088 **29.8%**	0.024 **8.1%**

Climate change

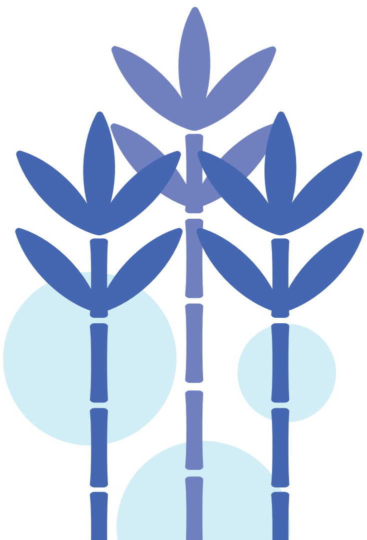
The climate change impact for 1 kg of recycled PLA is -0.652 kg CO_2 eq, when including the biogenic carbon embedded in the product. Figure 6 provides an overview of the process contributions for 1 kg of Luminy® recycled PLA to the impact category of climate change, starting from the biogenic carbon present in the PLA waste.

The production stages with the highest contribution to climate change are the waste preparation before chemical recycling and the hydrolysis process.

The main contributing parameters are:

- The use of steam for the depolymerization and polymerization process at TotalEnergies Corbion (36%).
- The production of pellets from PIW and PCW (12% and 15% respectively), including transport and reprocessing. For the PIW, Its impact comes from the transport of the PLA waste between a PIW partner (49%) and a PLA recycling plant. 43% of the impact is due to the electricity used during the PLA reprocessing steps, and 13% is due to the landfill of residual waste. There is also a negative contribution (-5%) from the waste incineration due to the energy recovery. For the PCW, 80% of the impact comes from the electricity used during the reprocessing of the PLA waste, 29% due to the landfill of residual waste, and 1% due to the use of diesel. Similar to the PIW, there is also a negative contribution (-10%) from waste incineration due to the recovery of energy. The impact of transport of PCW is negligible because it is combined with the delivery of new goods.
- Transport of raw materials (chemicals and PLA pellets) (14%) to TotalEnergies Corbion. It is due to the transport of PIW and PCW to the TotalEnergies Corbion manufacturing site (99.9% of the impact of transport). As expected, the majority of the burden on climate change is due to the transport of PIW, which are shipped from Europe to Thailand (74%).
- The incineration of solid waste residue from the PLA hydrolysis step (10%).
- The production of electricity (7%) used during the lactide and PLA synthesis steps. The PLA hydrolysis step contributes to 42% and the lactide production step contribute to 38% to the total impact of electricity, and PLA production contributes to 20%.

The rest of the impact on climate change comes from the production of chemicals (3%) and natural gas use during the production of PLA (2%).



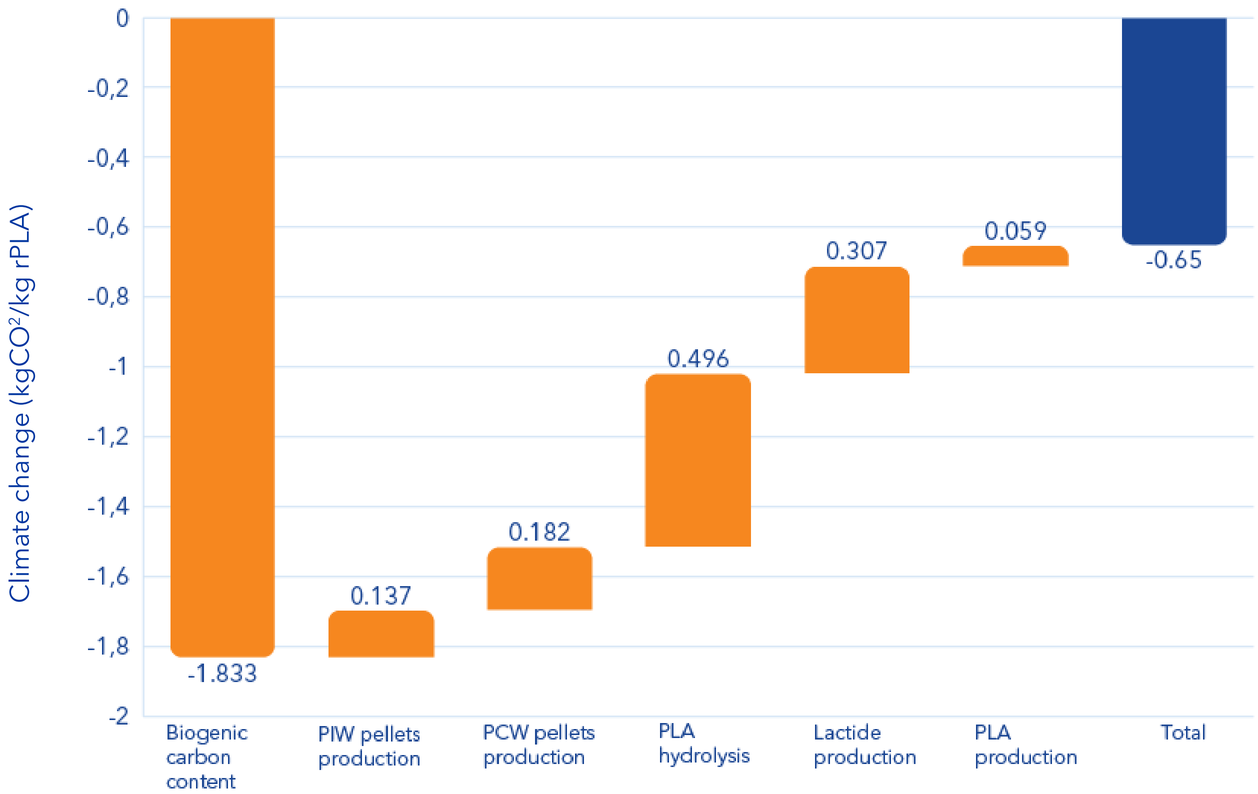


Figure 6. Overview of contributions to climate change impact for the production of 1kg of recycled PLA.

Other relevant impact categories

Water use

In the EF method, the impacts on water are assessed in terms of the quantity of water deprived. For this impact category, 35% of water impacts come from the PLA hydrolysis, 30% from the lactide production stage, 21% from the production of PCW pellets, 8% from the PLA production, and 7% from the production of PIW pellets. In the wastewater treatment step, water is returned to the groundwater, which results in negative impact on water use. In Figure 7, it is shown that the impact other than the production of the PIW and PCW (7% and 21% accordingly, as mentioned above) is due to the electricity used (26%), the production of steam (20%), the use of water (17%), and the production of chemicals (9%).

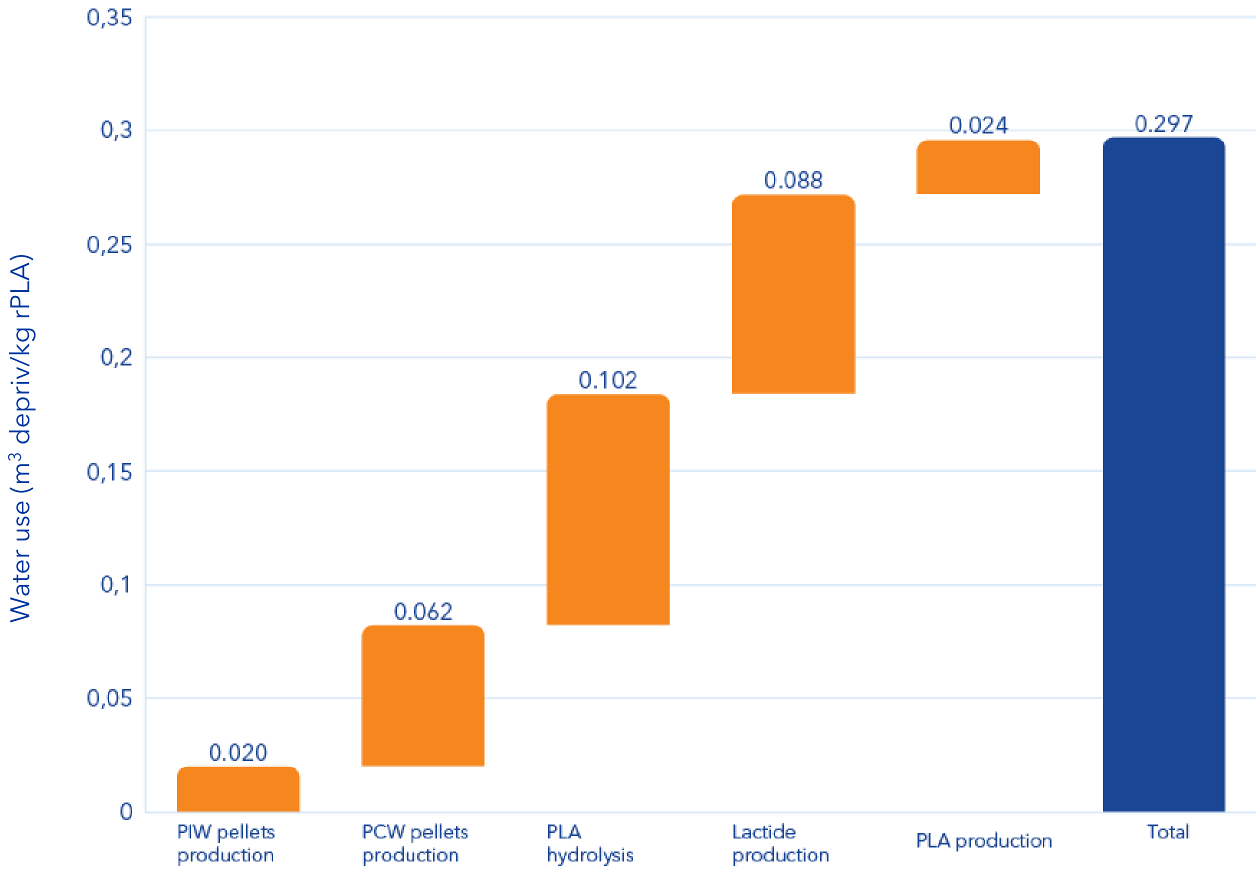


Figure 7. Contribution analysis of the production stages for 1kg of Luminy® rPLA to the water use impact category

Resource use, fossils

The resource use, fossils impact category is mostly influenced by the use of steam during the different processing steps (47%). This impact is shared between the lactide production step (55% of the impact of steam) and the PLA hydrolysis production step (43%), while the PLA production step contributes only up to 2%. The rest of the significant contributions come from the production of PIW and, more specifically, due to the use of electricity and transport to waste processing facilities as well as the transport to TotalEnergies Corbion site and the production of PCW pellets (electricity use during the processing). The rest of the impact in this category is due to the use of electricity (7%), natural gas during the PLA production processing step (3%), chemicals (3%), and waste incineration (1%). As mentioned above, the impact in this category is caused due to the combustion of fuels.

Acidification

For this impact category, the majority of the impact comes from the transport of raw materials–PCW and PIW PLA pellets–to the manufacturing site (63%) and, more specifically, due to the direct emissions of nitrogen oxides and sulfur dioxides in the air. A significant impact also comes from the production of The PCW and PIW pellets (10% and

7% accordingly) due to the electricity use and transport—in the case of PIW–to the waste processing facility and the use of electricity (8%) shared among the stages of the PLA hydrolysis (42% of the impact of electricity), the production of lactide (39% of the impact of electricity), and the production of PLA (20% of the total impact of electricity). The electricity used in these stages has an impact on acidification due to the emissions of sulfur dioxide, nitrogen oxides and ammonia in the air. The rest of the impact is due to steam use (7%), chemicals use (3%), and waste incineration (1%).

Photochemical ozone formation

Photochemical ozone formation is also majorly impacted by the transport of raw materials to the manufacturing site (62%) due to the direct emissions of nitrogen oxides and non-methane volatile organic compounds in the air. The production of PIW and PCW also contribute significantly to the total impact on this category (10% and 9%, respectively), mostly due to the transport required to get the waste to the waste processing sites. Other contributions to photochemical ozone formation are due to the use of steam (8%), the use of electricity (7%), the production and use of chemicals during the processing and waste incineration (2% each), and the use of natural gas (1%).

Resource use, minerals and metals

Resource use, minerals and metals, is impacted by the use of electricity during the different processing steps for the production of PLA (80%). Electricity production from solar panels uses different metals that have a high impact on this category. The next significant contribution comes from the production of PIW pellets (7%) and more specifically from the use of electricity during the production of the pellets. The rest of the contributions come from the use of chemicals and transport (4% each), the PCW pellets production (3%), and the use of steam (1%).

Particulate matter

The main contributions to particulate matter are from the production of PIW pellets (25%), the production of PCW pellets (21%), electricity (20%), and transport (19%). For the production of PIW pellets, the impact comes from the use of electricity and transport (12% and 88% accordingly), while all impact for PCW pellets is attributed to electricity use. Other contributions for this impact category come from the chemicals (7%) and, finally, steam (4%) and waste incineration (2%).

Eutrophication, terrestrial

Terrestrial eutrophication is impacted by the transport of materials during the PLA hydrolysis step (68%) due to the emissions of nitrogen oxides in the air from the transport of PIW and PCW to the TotalEnergies Corbion site. The production of PCW and PIW contribute to 9% and 7% to the total impact, respectively. The impact of these two processes is also affected mostly by the transport of waste to the site for the production of the pellets in both cases. Other contributions come from the use of steam (5%), electricity (6%), chemicals (3%), and waste incineration during the PLA hydrolysis (2%).

Land use

According to the hotspot analysis, land use is also not a relevant impact category, as it contributes to 1.5% of the total environmental impacts. It is added to the interpretation with the goal of providing insights into land-related impacts because this is considered relevant for the biobased industry. Land use covers the impacts of the use of soil from erosion resistance, mechanical filtration, physicochemical filtration, groundwater regeneration, and biotic production. It is expressed as a dimensionless soil quality index and is based on both global and spatially differentiated characterization factors at the country level. For this impact category, 37% of the impact comes from the lactide production stage, 36% comes from the PLA hydrolysis step, 17% comes from the PLA production stage, 8% from the PIW pellets production, and 2% from the production of PCW pellets. For all these stages, the most contributing process to land use is electricity due to the space required for the deployment of solar panels, which is 81% of the total contribution.

Sensitivity analysis

The sensitivity analysis is performed by calculating alternative scenarios. The scenario considered in this study is the allocation approach for by-products from the lactide and PLA production steps.

For the by-products of both virgin and recycled PLA production, the default allocation scenario (base case) is economic allocation. As an alternative scenario to examine the impact of this choice, system expansion is applied[5]. When economic allocation is used, the environmental burdens for the product and by-products are split based on the amounts produced and their market price. System expansion is an alternative method to handle systems with multiple products, which broadens the system boundaries to include the avoided impacts of alternative products that the co-products replace. For example, biogas is a by-product of PLA production, and, using the system expansion approach, it is modelled based on the amount of natural gas it replaces.

Based on this sensitivity analysis, the choice of economic allocation as the default scenario results in a conservative assumption, guaranteeing the robustness of the results of this study.

[5] The sensitivity analysis does not cover sugar and lactic acid steps

Future scenarios

Replacing conventional lactic acid with circular lactic acid.

The future scenario presented in this section covers the utilization of lactic acid from a different production process. Corbion has developed a new, innovative and circular technology for producing lactic acid with a lower environmental impact. For this study, design data were used to model the circular lactic acid manufacturing process.

In this scenario, the lactic acid used in the lactide production step is equally substituted with circular lactic acid produced from a lime-free process. The scenarios that were explored are the production of PLA with 100% circular lactic acid (the lime-free production process for lactic acid) and 50% from circular lacitc acid with 50% from conventional lactic acid.

Table 7. Future scenario: production of Luminy® Virgin PLA using circular lactic acid based on the EF 3.1 (adapted) method for the relevant impact categories.

Impact category	Unit	Luminy® Virgin PLA (Base case)	Circular lactic acid (100%)	Delta	50% Circular Lactic acid-50% conventional	Delta
Climate change	kg CO_2 eq	2.118	1.650	-22%	1.884	-11%
Particulate matter	disease inc.	3.76E-07	3.04E-07	-19%	3.40E-07	-10%
Acidification	mol H+ eq	4.28E-02	3.54E-02	-17%	3.91E-02	-9%
Eutrophication, terrestrial	mol N eq	0.128	0.123	-4%	0.125	-2%
Eutrophication, marine	kg N eq	1.70E-02	1.59E-02	-6%	1.65E-02	-3%
Resource use, fossils	MJ	18.72	19.43	4%	19.08	2%
Land use	Pt	212.24	200.39	-6%	206.31	-3%
Water use	m^3 depriv.	0.624	0.463	-26%	0.543	-13%

As shown in Table 7, large improvements in the environmental impact of virgin PLA production can be achieved when replacing lactic acid made in the conventional way with lime-free lactic acid. For both cases analysed, looking at the most relevant impact categories, significant reductions compared to the base case are achieved for climate change, particulate matter, acidification, and water use. A smaller decrease in the environmental impact is achieved for marine and terrestrial eutrophication and land use, while an increase is noted in the case of resource use, fossils. The reduction of the environmental impact is associated, to a large extent, with the elimination of lime and sulfuric acid from the process. The increase in the impact category of fossils for resource use is mostly due to the amount of natural gas used during the processing for the production of circular lactic acid. Corbion is investigating options to reduce these emissions as part of its Net-Zero program.

Use of flakes instead of pellets for chemical recycling

Regarding the production of recycled PLA, for incoming PLA waste streams that arrive at the TotalEnergies Corbion site, the default scenario is the conversion of PLA flakes into PLA pellets. There is also the possibility for this stream to be transported as flakes without needing the additional inputs of energy (i.e., electricity) required for the pelletization process. Since this option is technically feasible, this scenario is also examined. For this scenario, the electricity required for the pelletization is set to 0. There is no impact on the chemical recycling process if flakes are used instead of pellets.

The results for this scenario are presented in Table 8. The results show that the choice between flakes or pellets for the PLA from PCW can have an impact on the environmental footprint of recycled PLA. The categories that are affected the most are those where the PCW pellets production has a bigger impact, i.e., particulate matter (15%), climate change (11%), resource use fossils (14%), and acidification (9%). The lower impact that is noticed for all relevant impact categories is due to the lower energy use (electricity) for the production of the PLA flakes compared to that of the pellets.

Table 8. Sensitivity analysis for the form of PLA stream (from PIW & PCW) to TEC.

Impact category	Unit	Base case (pellets)	Alternative scenario (flakes)	Delta
Climate change	kg CO_2 eq	1.18	1.05	-11%
Resource use, fossils	MJ	14.38	12.34	-14%
Acidification	mol H+ eq	6.89E-03	6.27E-03	-9%
Photochemical ozone formation	kg NMVOC eq	5.29E-03	4.94E-03	-7%
Resource use, minerals and metals	kg Sb eq	4.28E-06	4.12E-06	-4%
Particulate matter	disease inc.	2.94E-08	2.50E-08	-15%
Eutrophication, terrestrial	mol N eq	1.78E-02	1.66E-02	-6%
Land use	Pt	15.13	14.80	-2%
Water use	m^3 depriv.	0.297	0.273	-8%

Discussion and Conclusions

The life cycle assessment of TotalEnergies Corbion's Luminy® virgin polylactic acid and Luminy® recycled polylactic acid provides a detailed and updated description of the production processes as well as their related environmental impacts, contributing to improving transparency on communication on the environmental impact of biobased materials. An evaluation of the data quality was conducted for this study, showing a result considered as good quality, fulfilling the purpose of the study.

The main conclusions are presented below.

Luminy® virgin polylactic acid production

- Virgin PLA's environmental footprint is primarily driven by sugar and lactic acid production. The key impact categories are climate change (0.29 kg CO2 eq/kg including biogenic carbon), particulate matter, acidification, eutrophication, resource use (fossils), and land use.
- Luminy® virgin PLA's carbon footprint is 0.29 kg CO_2 eq/kg (including biogenic carbon), a 0.21 kg CO_2 eq/kg reduction from the 2019 LCA, reflecting TotalEnergies Corbion's sustainability advancements (Morao and de Bie 2019). The comparison with other environmental impact categories is challenging because of the changes in the characterization method, databases and multifunctional approach.
- The impact of climate change is mostly determined by the production of chemicals, in particular lime, sugar, steam, and the transport of raw materials.
- In terms of future improvements, the replacement of conventional lactic acid with circular lactic acid can lower the climate change impacts by up to 22%, reaching a negative carbon footprint when including the biogenic carbon. Besides, it will have a significant reduction in other relevant impact categories, like particulate matter, acidification, and water use.

Luminy® recycled polylactic acid production

- Luminy® recycled PLA (rPLA) has a 44% lower climate change impact (-0.65 kg CO2 eq/kg including biogenic carbon) than Luminy® virgin PLA, driven by the use of steam, the production of pellets, the transport, and the use of electricity, with significant reductions in acidification, particulate matter, and eutrophication thanks to sugarcane production avoidance.
- Contrary to the Luminy® virgin PLA, there is not one step in the produciton process contibuting significantly more to the total impact than others, the impact in the relevant impact categories is distributed among all processing steps (i.e., production of PIW pellets, production of PCW pellets, PLA hydrolysis, lactide production, and PLA production).
- The choice to transport PLA from PCW as pellets (default scenario) or flakes has a significant impact for particulate matter (15% reduction) , resource use fossils (14% reduction), climate change (11% reduction), and acidification (9% reduction).

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Annex A
Definitions of Life Cycle Impact Categories

Impact category / Indicator	Unit	Description
Climate change	kg CO_2 eq	Indicator of potential global warming due to emissions of greenhouse gases to the air. Divided into 3 subcategories based on the emission source: (1) fossil resources, (2) biobased resources and (3) land use change.
Ozone depletion	kg CFC-11-eq	Indicator of emissions to air that causes the destruction of the stratospheric ozone layer.
Acidification	kg mol H+	Indicator of the potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulphur oxides.
Eutrophication – freshwater	kg P-eq	Indicator of the enrichment of the freshwater ecosystem with nutritional elements due to the emission of nitrogen or phosphor-containing compounds.
Eutrophication – marine	Kg N-eq	Indicator of the enrichment of the marine ecosystem with nutritional elements due to the emission of nitrogen-containing compounds.
Eutrophication – terrestrial	mol N-eq	Indicator of the enrichment of the terrestrial ecosystem with nutritional elements due to the emission of nitrogen-containing compounds.
Photochemical ozone formation	kg NMVOC-eq	Indicators of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalysed by sunlight.
Resources use – minerals and metals	kg Sb-eq	Indicator of the depletion of natural non-fossil resources.
Resources use – fossils	MJ, net calorific value	Indicator of the depletion of natural fossil fuel resources.
Human toxicity – cancer, non-cancer	CTUh	Impact on humans of toxic substances emitted to the environment. Divided into non-cancer and cancer-related toxic substances.
Eco-toxicity (freshwater)	CTUe	Impact on freshwater organisms of toxic substances emitted to the environment.
Water use	m^3 world eq. deprived	Indicator of the relative amount of water used, based on regionalized water scarcity factors.
Land use	Dimensionless	Measure of the changes in soil quality (Biotic production, Erosion resistance, Mechanical filtration).
Ionizing radiation, human health	kBq U-235	Damage to human health and ecosystems linked to the emissions of radionuclides.
Particulate matter emissions	Disease incidence	Indicator of the potential incidence of disease due to particulate matter emissions.

Annex B

Carbon footprint calculations for Luminy® virgin PLA and Luminy® recycled PLA.

Table 9. Breakdown of greenhouse gas emissions and removals for virgin PLA.

Emissions	Inventory of fossil and biogenic GHG flows (kg CO_2EQ/kg vPLA)
Biogenic CO_2 emissions (E1)	1.98
CO_2 emissions from DLUC (E2)	≈ 0.00
Fossil GHG emissions (E3)	2.11
Biogenic methane emissions (E4)	7.99E-3
Total fossil and biogenic GHG emissions = E1+E2+E3+E4	**4.10**
Biogenic CO_2 removals (R1=E1)	-1.98
Net fossil and biogenic GHG emissions and removals (E1+E2+E3+E4+R1)	**2.12**
Biogenic CO_2 removal and temporarily stored in the product* (R2)	-1.83
Carbon footprint of 1kg of virgin polylactic acid including biogenic CO_2 in the produc[6] (E2+E3+E4+R2)	**0.29**

Table 10. *Breakdown of greenhouse gas emissions and removals for recycled PLA.*

Emissions	Inventory of fossil and biogenic GHG flows (kg CO_2EQ/kg rPLA)
Biogenic CO_2 emissions (E1)	0.35
CO_2 emissions from DLUC (E2)	≈ 0.00
Fossil GHG emissions (E3)	1.18
Biogenic methane emissions (E4)	6.30E-4
Total fossil and biogenic GHG emissions = E1+E2+E3+E4	**1.53**
Biogenic CO_2 removals (R1=E1)	-0.35
Net fossil and biogenic GHG emissions and removals (E1+E2+E3+E4+R1)	**1.18**
Biogenic CO_2 removal and temporarily stored in the product* (R2)	-1.83
Carbon footprint of 1kg of recycled polylactic acid including biogenic CO_2 in the product[7] (E2+E3+E4+R2)	**-0.65**

***** *This carbon will be released at end of life (depending on the end of life)*

[6] This value is calculated as the sum of (2.12) + (-1.83) kg CO_2eq, where the second value relates to the biogenic CO_2 uptake in the product. This carbon is temporarily stored in the product and can be released at end of life. We express the biogenic CO_2 removals separately, aligning with the requirements of ISO 1406.

[7] This value is calculated as the sum of (1.18) + (-1.83) kg CO_2eq, where the second value relates to the biogenic CO_2 uptake in the product. This carbon is temporarily stored in the product and can be released at end of life. We express the biogenic CO_2 removals separately, aligning with the requirements of ISO 14067.

Annex C

Environmental footprint of PLA with 20% and 30% recycled content

In 2021, TotalEnergies Corbion announced the commercialization of Luminy® PLA resins with mass-balanced, chemically recycled content. As of 2023, Luminy® PLA is available with 20% or 30% allocated recycled content (Morao, et al., 2024). Since PLA with recycled content (20 or 30%) is a main commercial product for TotalEnergies Corbion, it is relevant to also calculate its environmental impact. The results are presented in Table A.1 below.

Table 11. Environmental impact of PLA with 20% and 30% recycled content.

Impact category	Unit/kg PLA	20% Luminy® rPLA	30% Luminy® rPLA
Climate change	kg CO_2eq/kg PLA	1.930 (0.098 incl. biogenic CO_2 in the produc[8])	1.836 (0.004 incl. biogenic CO_2 in the product[8])
Ozone depletion	kg CFC11 eq	1.77E-07	1.56E-07
Ionizing radiation	kBq U-235 eq	1.66E-02	1.71E-02
Photochemical ozone formation	kg NMVOC eq	7.28E-03	7.03E-03
Particulate matter	disease inc.	3.07E-07	2.72E-07
Human toxicity, non-cancer	CTUh	1.43E-08	1.35E-08
Human toxicity, cancer	CTUh	3.42E-09	3.34E-09
Acidification	mol H+ eq	3.56E-02	3.20E-02
Eutrophication, freshwater	kg P eq	5.57E-04	4.99E-04
Eutrophication, marine	kg N eq	1.41E-02	1.26E-02
Eutrophication, terrestrial	mol N eq	0.106	9.48E-02
Ecotoxicity, freshwater	CTUe	25.93	23.69
Land use	Pt	172.81	153.10
Water use	m^3 depriv.	0.558	0.526
Resource use, fossils	MJ	17.85	17.42
Resource use, minerals and metals	kg Sb eq	9.67E-06	9.00E-06

The environmental impact of both products is in between the results for virgin and recycled PLA with reductions noted as the recycled PLA content increases.

[8] These values are calculated as the sum of (1.930) + (-1.832) and (1.836)+(-1.832) kg CO_2eq for virgin and recycled PLA accordingly, where the second value relates to the biogenic CO_2 uptake in the product. This carbon is temporarily stored in the product and can be released at end-of-life.

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