Life cycle assessment of PLA through advanced recycling

Utilizing waste streams as feedstock for a biobased polyester

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INTRODUCTION

To achieve global climate goals and develop a circular economy, the evolution of product manufacturing is crucial. One of the solutions to limit our environmental impact is to switch to biobased materials. Creating a recycling stream for these biobased materials enhances their circularity.

Recycling a biobased plastic like polylactic acid (PLA) boosts circularity by keeping materials in the production loop and extending the atmospheric carbon storage in products. The need for virgin feedstock from biomass, can be significantly reduced, avoiding the environmental impacts of generating new materials. End-of-life, recycling, becomes the beginning of life for a new product.

Biobased materials, including biobased plastics like PLA, reduce the dependency on fossil resources because they are made from renewable carbon, replacing oil-based carbon; TotalEnergies Corbion produces Luminy® PLA made from sugarcane and from PLA waste in Thailand.

Using biomass as feedstock for plastics reduces greenhouse gas (GHG) emissions and contributes to achieving climate targets. Plants absorb atmospheric carbon dioxide as they grow, and this carbon is stored in the biobased polymer made from these plants. The carbon fixation in the biomass source material contributes to removing GHG from the atmosphere temporarily. Conventional plastics use carbon from fossil resources, which ultimately releases additional CO_2 into the atmosphere, therefore contributing to the increase of the atmospheric GHG concentration, responsible for climate change*. The carbon storage period offered by biobased plastics depends on the product's life span and its end-of-life. When incinerated, biobased materials release CO_2, known as biogenic CO_2, which was previously captured from the atmosphere, therefore having negligible impact on the atmospheric CO_2 concentration, we call it neutral emissions. When the biobased material is recycled, the stored carbon is kept 'in the loop' for longer and therefore out of the atmosphere. Temporarily stored CO_2 will be re-emitted sometime in the future when the product will reach an ultimate end-of-life like incineration or composting, Temporary carbon storage has important benefits as it delays the accumulation of emissions in the atmosphere in the next decades therefore reducing the rate of warming. This 'buys time' for the development and deployment of other climate change mitigation options, including options for permanent storage. It also gives more time for society and natural ecosystems to adapt to climate change.

Durable products like construction materials made from biobased materials also allow a temporary storage of the biogenic carbon in the product. This is referred to as negative emissions.

Figure 1 shows the carbon flows from biobased and fossil based materials as described above. The terms "positive", "negative" and "neutral" refer to the type of CO_2 emissions. An emission

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* Assuming that the plastics are ultimately fully oxidized to CO_2, for example by incineration, and that the combustion emissions are not stored. In case of landfill, CO_2 may also not be released.

is considered positive when additional CO_2 is released into the atmosphere. An emission is considered negative when CO_2 is captured from the atmosphere and then stored for a certain period of time. Neutral emission corresponds to CO_2 captured from the atmosphere and later on released, the final amount is the same.

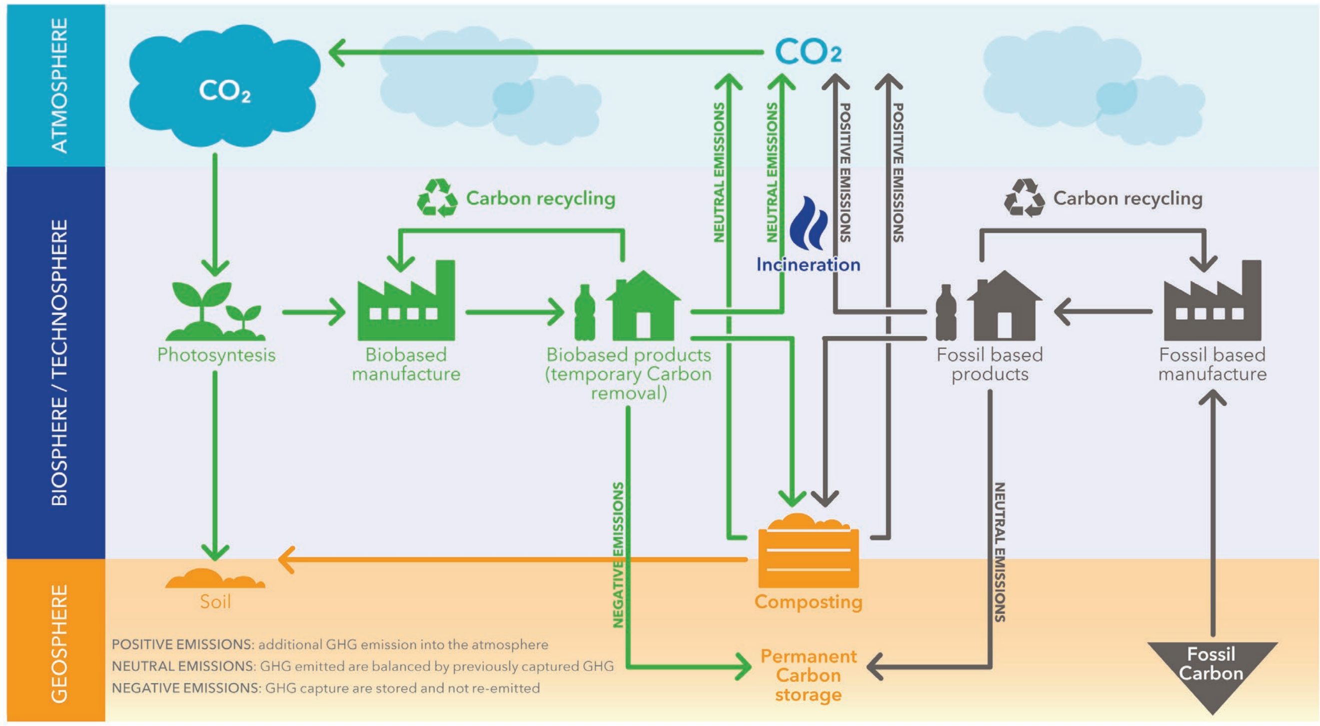

Figure 1: Carbon cycle throughout the life of a product

Polylactic acid is a biobased plastic offering different end-of-life options: incineration with energy recovery, industrial composting, mechanical recycling, and advanced recycling (also called chemical recycling).

PLA can be recycled using mechanical or advanced (or chemical) recycling methods. Mechanical recycling of thermoplastics is often accompanied by only minor purification, a decrease in (mechanical) properties and overall purities that do not guarantee food contact requirements are met. Chemical recycling of PLA, on the other hand, offers the possibility to obtain recycled PLA grades with the same quality as virgin PLA, meeting the regulations for food contact applications.

In 2021, TotalEnergies Corbion announced the commercialization of Luminy® PLA resins with mass-balanced, chemically recycled content (Luminy® rPLA). As of 2023, Luminy® PLA is available with 20% or 30% allocated recycled content. Since the start of its operation, TotalEnergies Corbion has been chemically recycling its internal waste, from virgin PLA production through a hydrolysis process. In this process, PLA is depolymerized back to its original monomers. This process was expanded to recycle external post-industrial PLA waste and post-consumer closed-loop PLA waste (Figure 2). This life cycle assessment (LCA) considers that feedstock used for rPLA is an average of these two waste streams.

This paper aims at providing information on the environmental impact of Luminy® recycled PLA, using life cycle assessment (LCA), covering seven environmental impact categories, including global warming potential, land use and water use. The reference point is virgin Luminy® PLA. The LCA of virgin PLA was published earlier, in 2019[1].

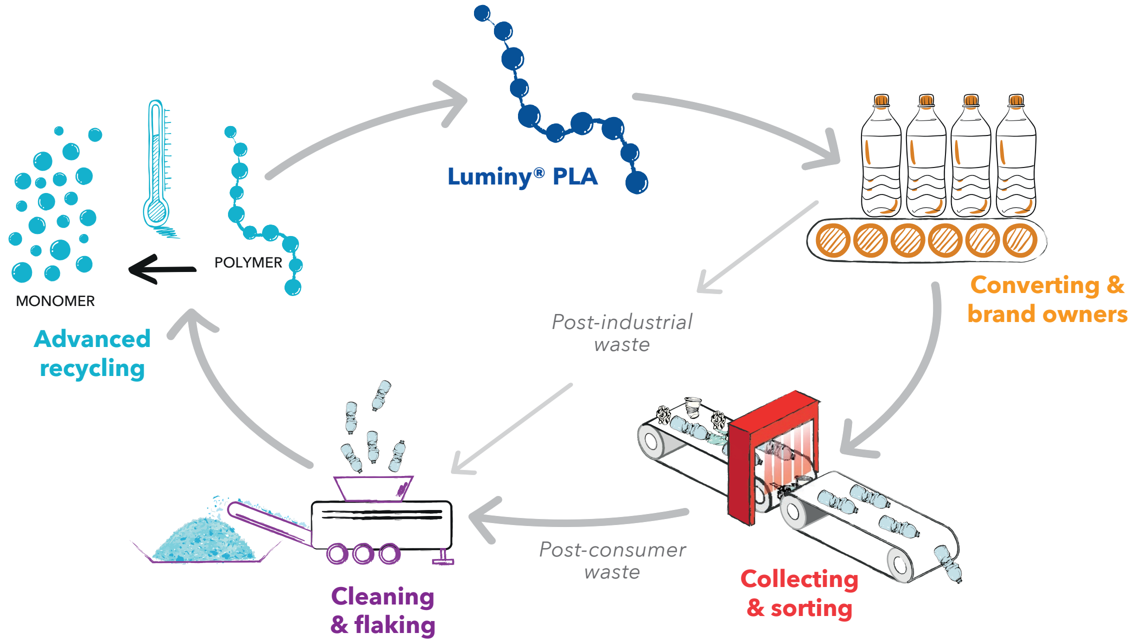

Figure 2: Luminy® PLA recycling loop

RECYCLED PLA LOOP: COLLECTING, CLEANING AND REPROCESSING OF PLA WASTE

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 feasability, given that it is compatible with high efficiency sorting facilities. Traditional 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[2]. This study reflects current, typical practice and therefore, recycling of mixed plastic waste is out of scope. Figure 3 shows a roadmap for the implementation of PLA recycling.

TotalEnergies Corbion's chemically recycled PLA (rPLA) is produced from post-industrial waste (PIW, also called pre-consumer waste) and closed-loop post-consumer waste (PCW). These two streams are already today used as feedstock for chemical recycling and, therefore, rPLA production.

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:

1. Post-industrial waste (PIW) from a PLA fiber application in Europe

In this application, PLA resin is melted and extruded into PLA fibers. The waste from this process may be diverse in appearance, ranging from amorphous spin-ware to highly oriented PLA filament, but it is chemically identical. It is typically compressed into bales 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. The pellets are subsequently shipped to a PLA production facility, in this case at TotalEnergies Corbion in Rayong, Thailand, where PLA is converted to lactic acid monomers

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

In a closed-loop system, such as restaurants, hotels, event or corporate spaces, the bottled drinks supplier collects used, empty PLA bottles when bringing a new delivery to the consumer. The waste bottles are sorted, washed, and flaked in a facility in the same country. The cleaned flakes are subsequently transported to the PLA production facility for chemical recycling in Thailand.

Chemical recycling of both streams is achieved using hydrolysis, which converts high molecular weight PLA macromolecules back to lactic acid. This conversion is the depolymerization step. The resulting recycled lactic acid is subsequently mixed with virgin lactic acid and re-converted into high molecular weight PLA via catalyzed ring-opening polymerization of lactide. The degree of purification associated with the lactide-to-PLA process, guarantees a high level of purity of the rPLA. Moreover, so-called surrogate-spiking and challenge tests have confirmed that the process is able to achieve very high purification factors for impurities of a range of volatilities and boiling points. During these tests, contaminants like heavy metals are intentionally added to the feed, and their concentration is assessed in the output. This can evaluate the capacity of the system to remove certain categories of contaminants.

Recycled lactic acid cannot be differentiated from virgin lactic acid; there is no identity preservation when mixing both streams. To offer Luminy® PLA with 20% and 30% recycled content, TotalEnergies Corbion uses the mass balance approach, allocating the credits of the recycled PLA to final products. Strict traceability is maintained. The chain of custody approach has been certified by SCS Global services (ISO 22095)[3].

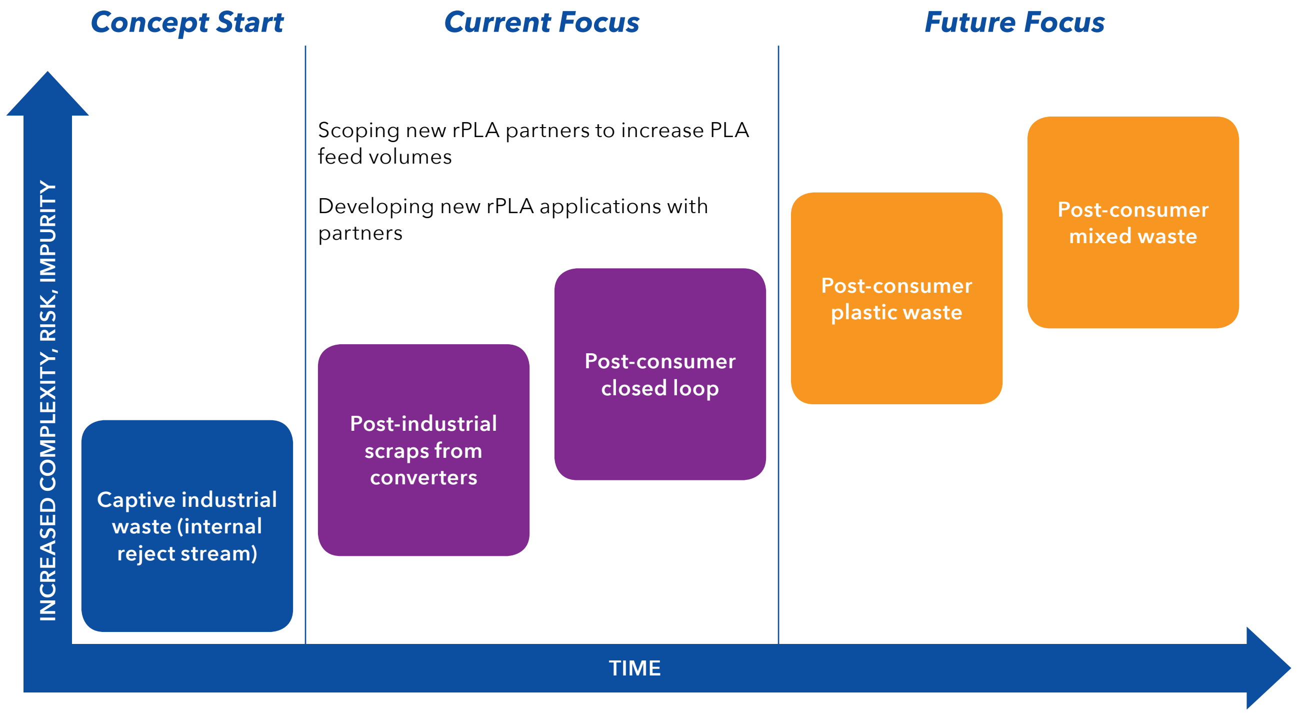

Figure 3: TotalEnergies Corbion's Luminy®rPLA development

METHODOLOGY

The LCA study is aligned with ISO 14040/4 and performed using the software SimaPro. This study is based on the LCA of PLA from sugarcane in Thailand (2019)[1] and quantifies the environmental impacts of PLA from recycled streams. To ensure consistency in the results the LCA methodology and data sourced are aligned with the 2019 study.

Goal and Scope

This study aims to quantify the environmental footprint of Luminy® recycled PLA (rPLA) produced at TotalEnergies Corbion in Rayong, Thailand. The intended use of the results is to provide information to PLA customers and other LCA practitioners to use as building blocks for LCA of PLA based products. Chemical recycling in the life cycle is here considered as a beginning of life not as the end-of-life. The results for Luminy® rPLA, with 20% and 30% recycled content, are compared with virgin PLA (vPLA)[1]. Recycled PLA and virgin PLA are considered as two separate products with no links.

The scope of the study is cradle-to-gate, including the process steps shown in figure 4. The functional unit is 1 kg of Luminy® PLA. Recycled PLA substitutes virgin PLA in the same amounts because the advanced chemical recycling process ensures identical quality and functional equivalence.

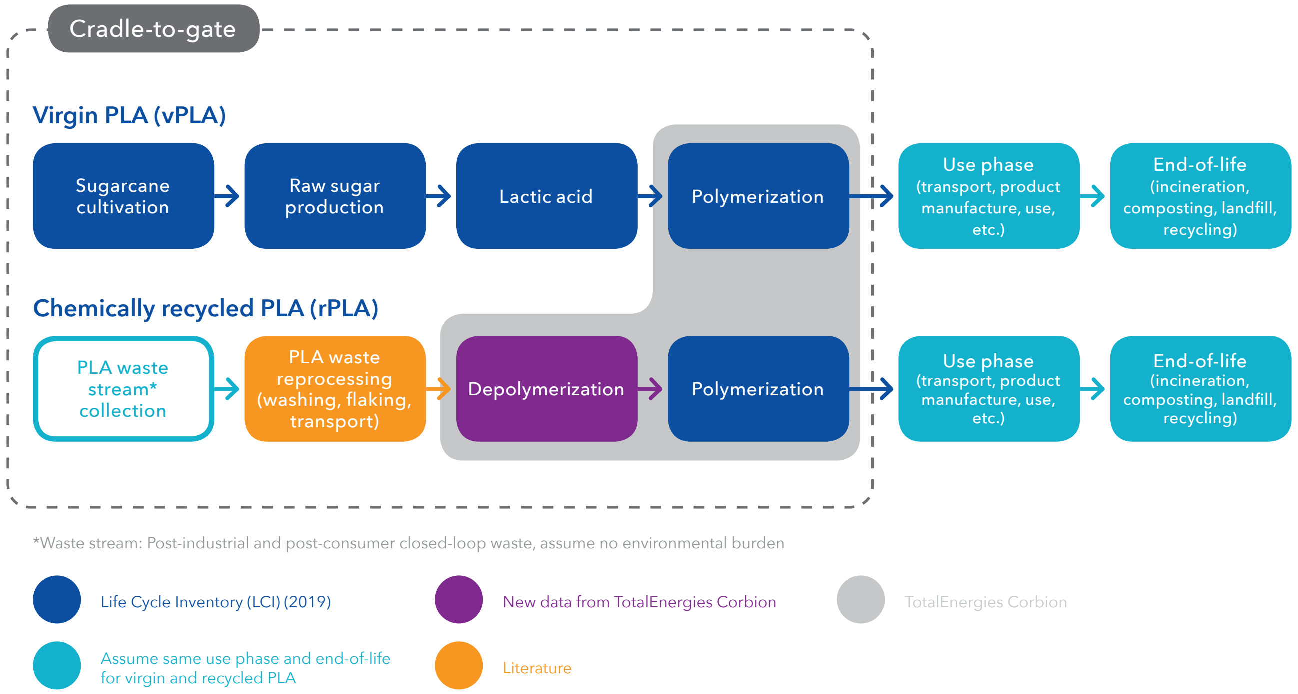

Figure 4: PLA and rPLA life cycles including study scope

System boundary and data assumptions

We use the cut-off approach for the advanced recycled PLA to define the system boundary. This means the PLA from PIW or PCW bears no environmental burden from the first life. The system boundaries from recycled PLA include the collection, transportation, and reprocessing steps to the PLA monomer and polymerization to PLA, as shown in detail in Table 1, including the main data sources and assumptions.

Table 1: Process steps included in the scope of the study for both waste streams (PCW and PIW). Data sources and assumptions for the Life cycle inventory (LCI)

		POST-CONSUMER WASTE (PCW)	POST-INDUSTRIAL WASTE (PIW)	DATA SOURCES AND ASSUMPTIONS
STEPS CONSIDERED FOR PLA RECYCLING	**1**	PLA waste collection and reprocessing: • Bottle collection & transport • Shredding & air flow separation • Washing • Drying • PLA waste extrusion and pelletizing	PLA waste collection and reprocessing: • PIW bales pressing at customer • PIW bale collection & transport • Grinding of the bales • PLA waste extrusion and pelletizing	Inventory data from literature[4] Waste treatment of process losses: 35% landfill and 65% recycling[5] Geography: RoW or GLO Background data: ecoinvent 3.8
	2	Transportation of PLA pellets to Rayong, Thailand	Transportation of PLA pellets to Rayong, Thailand	Average distances, based on TotalEnergies Corbion supply chain Background data: ecoinvent 3.8
	3	PLA depolymerization	PLA depolymerization	Process data from TotalEnergies Corbion; electricity from Thai grid mix Background data: ecoinvent 3.8 Same as processing of lactic acid from PLA . Electricity from Thai grid mix
	4	Conversion and polymerization of PLA hydrolysate to recycled PLA pellets	Conversion and polymerization of PLA hydrolysate to recycled PLA pellets	Same as processing of lactic acid from PLA[1]. Electricity from Thai grid mix

For the virgin PLA, the system boundaries include sugarcane cultivation, sugarcane conversion into raw sugar, fermentation to produce lactic acid, and conversion of lactic acid to PLA. The results for virgin PLA are based on the study by Morão and de Bie (2019)[1].

Environmental impact categories and biogenic CO_2

The environmental impact categories considered in this study are global warming potential (IPCC 2013 GWP 100a), land use as well as the most relevant impact categories considered in the LCA vPLA, based on the ILCD 2011 Midpoint +[1].

Biogenic carbon refers to carbon that is sequestered from the atmosphere during biomass growth. This carbon is found in a variety of natural materials, such as trees, plants, and other forms of biomass, and accumulates in pools such as soil organic carbon[6]. In this study, the GWP results include the biogenic CO_2 in the polymer, corresponding to the uptake of CO_2 during the growth of sugarcane and captured in the PLA waste used as feedstock for recycled PLA. The biogenic CO_2 is calculated based on the EN16785. This approach considers biogenic carbon as an intrinsic property of the material, aligned EN 15804+. By using this approach, the biogenic carbon considered for the rPLA does not correspond to a CO_2 uptake but to the biogenic carbon present in the waste used a raw material. Both for virgin and recycled PLA, the emissions of biogenic CO_2 shall be considered for the GWP at the ultimate end-of-life (e.g., incineration or composting).

RESULTS AND DISCUSSIONS

Global warming potential (GWP)

The cradle-to-gate GWP of virgin lactic acid is 501 kg CO_2 eq/ton of vPLA. This value includes the CO_2 uptake of 1833 kg CO_2/ton of vPLA, calculated based on the biogenic carbon content in the polymer. The results for vPLA are based on TotalEnergies Corbion's LCA published in 2019.

The cradle-to-gate GWP for Luminy® rPLA is significantly lower than for vPLA, as shown in Figures 5a and 5b. This significant lowering of in the GWP of rPLA is explained by the reduction of the high-impact inputs for vPLA manufacture, related to lactic acid production: sugarcane crop cultivation, lactic acid fermentation and purification. The depolymerization via hydrolysis is an energy-efficient process having a low contribution to the GWP of rPLA, as shown in Figure 5b. Likewise, the transport and processing of the waste has a relatively low impact compared with the production of the virgin monomer.

For one tonne of Luminy® rPLA with 20% recycled content, the GWP is reduced by 230 kg CO_2eq compared to one ton of vPLA. In one tonne of Luminy® rPLA with 30% recycled content, the GWP is reduced by 320 kg CO_2eq when compared to one tonne of vPLA.

For recycled PLA, the biogenic carbon content present in the first life cycle of the PLA is still stored and retrieved in the new recycled PLA. This allows a longer carbon storage in a biobased material, which with chemical recycling can be unlimited. For the above reason, in our GWP calculation of recycled PLA, we have included the biogenic content present in the material as shown in Figure 5b. For both materials, the biogenic CO_2 from virgin and recycled PLA is released at the ultimate end-of -life (incineration, composting) and shall be accounted in the cradle-to-grave GWP of the product.

Figure 5a: Cradle-to-gate carbon footprint of virgin PLA¹ and recyled PLA - 20% and 30% recyled content (For recycled PLA the biogenic content enters the system through the recycled waste while for virgin PLA it is absorbed during sugarcane growth)

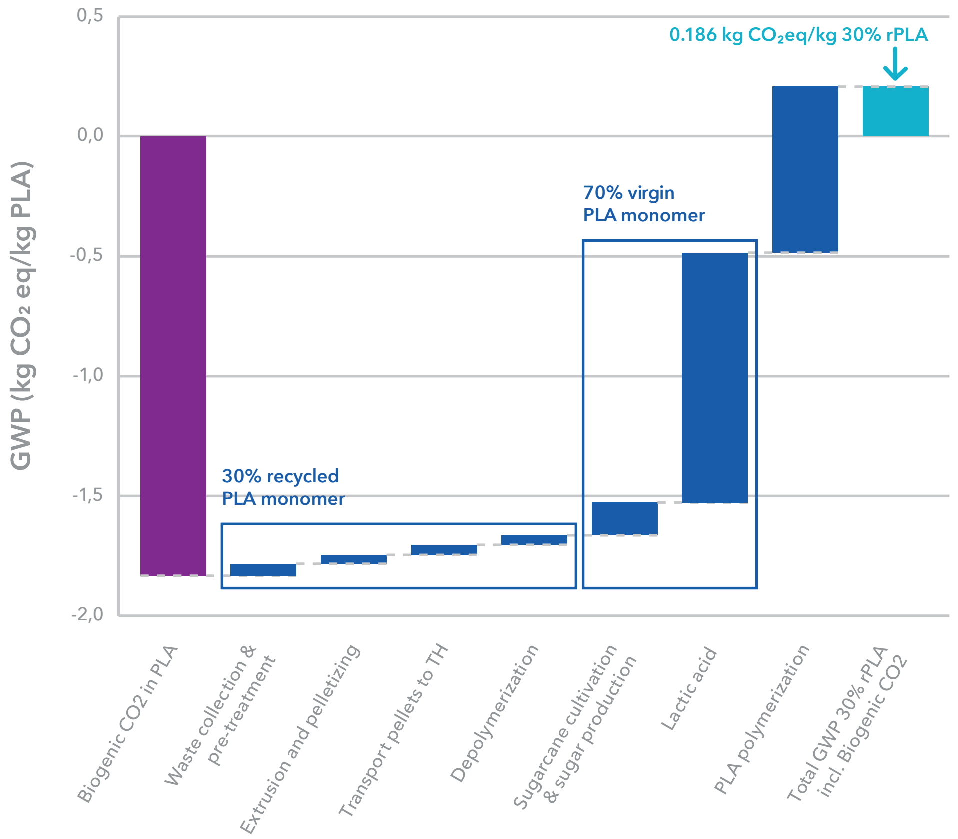

Figure 5b: Contribution of the different production stages to the total GWP of 30% PLA, starting with CO_2 uptake during sugarcane growth up PLA pellets production at TotalEnergies Corbion gate in Thailand. The biogenic CO_2 that is temporarily stored in the product can be released at the end of life (eg. incineration or composting) and shall accounted for the GWP of the product

Land use

Land use is an important impact category for biobased materials, as biomass production uses land. When recycling PLA, the plant-based feedstock is replaced by a collected PLA waste feedstock. Therefore, the amount of land use is proportionally decreased according to the amount of recycled content.

Figure 6 shows that for a 20% and 30% recycled content rPLA, the land use impact reduces by 20% and 30%, respectively.

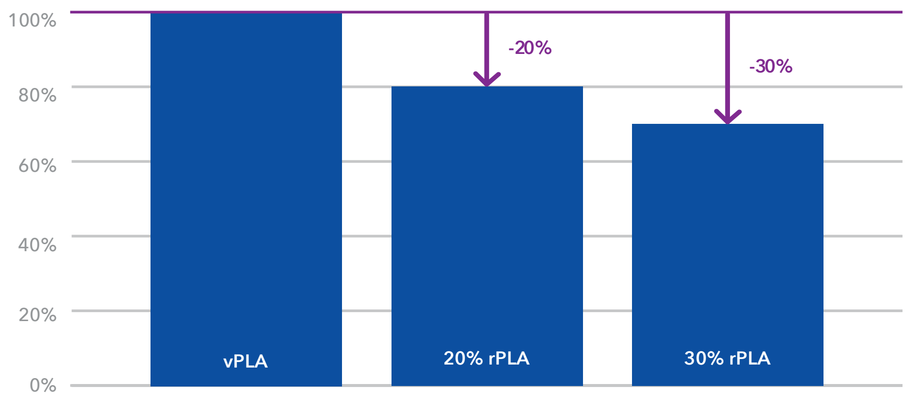

Figure 6: Percentual reduction in land use by including recycled content in PLA. vPLA – 100%

Overview impact categories

Table 2 shows that rPLA has lower environmental impacts in the seven categories covered by this study. Also, increasing PLA's recycled content decreases the PLA's ecological footprint. These results reflect that the main impacts of vPLA production are related to sugarcane farming and, through recycling, are partially avoided.

Table 2: LCA results for 1 kg of Luminy®PLA, Luminy® 20% rPLA and Luminy® 30% rPLA

LCA results for different Luminy® PLA grades		vPLA	20% rPLA	30% rPLA
Climate change	kg CO_2 eq	2.34 (0.51)*	2.13 (0.29)*	2.02 (0.19)*
Land use	kg C deficit	1.74E+01	1.4E+01	1.24E+01
Water use	m^3 water eq	3.61E-02	2.84E-02	2.45E-02
Terrestrial eutrophication	molc N eq	3.38E-02	3.05E-02	2.88E-02
Marine eutrophication	kg N eq	1.33E-02	1.11E-02	1.00E-02
Particule matter	kg PM2.5 eq	1.74E-03	4.43E-04	4.40E-04
Acidification	molc H+ eq	1.82E-02	8.44E-03	7.95E-03

**All the GWP values in brackets have a deduction of the biogenic carbon content (-1.83 kg CO_2/kg PLA)*

LIMITATIONS AND RECOMMENDATIONS

While bioeconomy and biobased materials are widely recognized as one part of the solutions to address climate change, accounting of the biogenic carbon lacks harmonized guidance, in particular for the accounting of temporary storage. Our approach in this paper is an attempt to deal with the complexity of the system in a transparent way and to enable industry to communicate the cradle-to-gate GWP of biobased recycled products. Yet, we recognize the need for the LCA community to further develop guidelines that bring harmonization, stability, verifiability and enhanced credibility of LCA results. While CO_2 removed from the atmosphere is only temporarily stored, being re-emitted in the future, and therefore not reducing the cumulative net CO_2 emissions, it allows to gain time in the near / mid term and to avoid the worse impacts of climate change while other solutions are developed. Accounting of temporary storage in LCA can be done with dynamic methods, which are emerging in LCA and that need further standardization. Applying such methods for recycled PLA could be a way to gain more insights.

This study is an extension of the TotalEnergies Corbion PLA study published in 2019. In the most recent years, we have gained insights in our value chains and there have been improvements both in terms of manufacturing efficiency and energy sources. A limitation of this study is that it does not include these new developments.

CONCLUSIONS

Luminy® rPLA is a step further in circularity and the sustainability of plastic, decoupling biobased plastics production from land use and agricultural-related impacts. Chemically recycling PLA offers significant advantages in terms of material security, sustainable waste management, and quality of recycled products. This study confirms that the collection of PLA waste from a closed-loop post-consumer system or an industrial plant and the reprocessing of this waste, including sorting, washing, pelletizing, and hydrolyzing, has a lower environmental impact than sugarcane production, sugar production, and lactic acid production via fermentation.

TotalEnergies Corbion has developed a new way of producing PLA using post-industrial waste and closed loop post-consumer waste as feedstock replacing sugarcane; The recycling process is based on hydrolysis.

This study provides cradle-to-gate LCA results for seven impact categories for Luminy® rPLA 20% and 30% recycled content which can be used as starting blocks for Luminy® PLA users (converters).

The LCA results of PLA products made of recycled PLA waste show a lower impact in the seven environmental impact categories assessed compared to the virgin PLA. Both products, virgin and recycled, were compared as separate and individual materials.

For instance, a Luminy® PLA grade with 30% recycled content has a global warming potential which is 320 $kgCO_2/kg$ PLA lower than a fully virgin Luminy® PLA grade.

This LCA study is a first step in the consideration of temporary carbon storage for biobased materials which is enhanced with recycling. Harmonization in biogenic carbon accounting is still required and will help for the consideration of product circularity.

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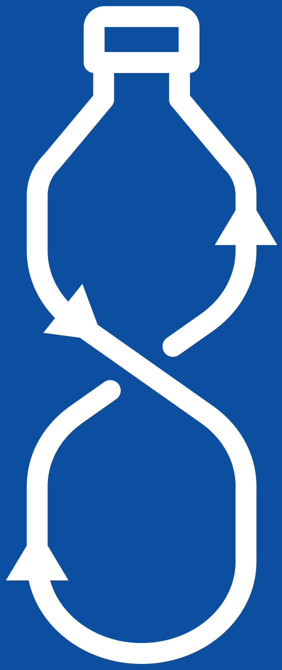

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