End-of-life options for bioplastics

Clarifying end-of-life options for bioplastics and the role of PLA in the circular economy

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1 Introduction

1.1 Introduction

Plastics bring many benefits to society, combining excellent functional properties with low costs. Plastics enable safe, hygienic and transparent packaging for food; they allow for part integration and electrical insulation in, for example, computers, smartphones and household appliances; and they help lightweighting in the transportation sector to drive down energy consumption. Plastics are durable, lightweight, transparent and - very often – a lower cost solution with reduced environmental impact when compared to alternative material solutions. However, mismanagement of plastic waste streams has led to unacceptable levels of plastic pollution in the environment. Plastic waste can be found on almost every street corner as well as in nature in our recreational areas, our rivers and oceans.

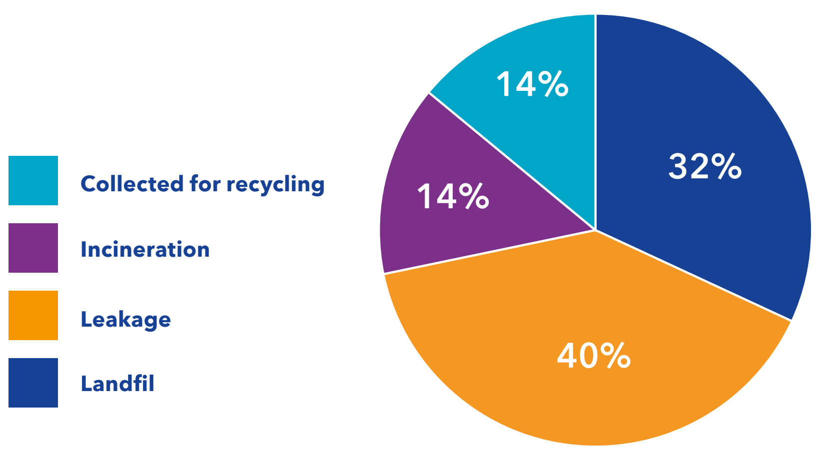
After a plastic product has served its useful purpose it can be reused and/or disposed of in various ways. In this whitepaper, we will share TotalEnergies Corbion's views and vision related to the various end-of-life options available for PLA bioplastic articles and products.

1.2 Linear plastics economy: produce, use, dispose

The current plastics economy can be described as one that is linear. From finite fossil fuels, plastics and plastic products are produced. Of the total estimated 8.3 billion tons of historic plastic production, more than 50% (or 4.9 billion tons) has ended up the environment or landfill, 0.8 billion tons was incinerated, 2.6 billion tons is still in use and only 9% of the plastic waste (or 0.6 billion tons) have been recycled, or about 7% of of all plastics produced[1].

On an annual basis, around 348 million tons of plastic is produced[2], of which 78 million tons is used in (mostly) single-use packaging or food serviceware applications. Of the 78 million tons of plastics, 72% ends up in landfills or in the environment, 14% is incinerated and only 14% is collected for recycling and just 10% actually recycled (Figure 1)[3]. In packaging, only 2% of raw materials used are plastics that have been used before. In recent years many consumers, NGOs, brand owners, retailers, converters and polymer producers have launched initiatives and made pledges to abandon the "produce-use-dispose" plastics economy[4]. Many companies have committed to implementing reusable, recyclable or compostable plastic packaging by 2025.

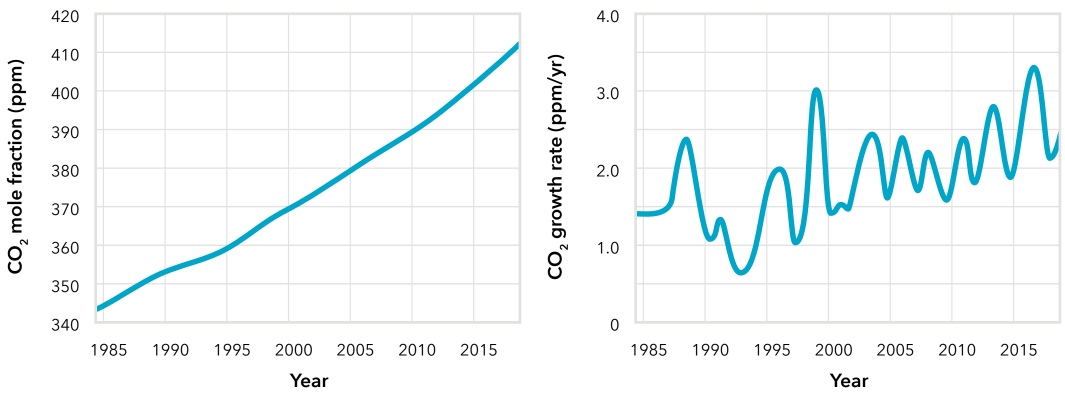
Figure 1: Current end-of-life streams of plastics used in single-use packaging or foodservice applications



1.3 Impact of CO_2 emissions on climate change

Research has shown that CO_2 emissions are growing at a rate of more than 2% per year and have reached a record high of 37 billion tons of CO_2 in 2018, with no sign of a peak in global emissions[5]. This has resulted in global average CO_2 levels rising from 345 ppm in 1984 to 408 ppm in 2018 (Figure 2). This long-term continuing trend means that future generations will be confronted with increasingly severe impacts of climate change, including rising temperatures, more extreme weather, water stress, sea level rise and disruption to marine and land ecosystems.

Figure 2: Globally averaged CO_2 mole fractions (a) and its growth rate (b) from 1984 to 2018[5]



Examples of climate change are already visible: oxygen levels in the world's oceans declined by roughly 2% between 1960 and 2010, which has led to a three-fold increase of the so-called 'dead zones' or oxygen-deprived zones.[6] The 5 year period between 2015 and 2019 has been the warmest five year period ever measured.[7]

Around 45% of global CO_2 emissions are associated with the making of products. Applying circular economy principles (reduce, reuse, recycle) in four key industrial materials (cement, steel, plastics and aluminum) could help reduce emissions by 40% in 2050. When these principles are extended to include the food production industry, the reduction could amount to 49%, which includes reducing food waste and applying composting.[8] Decoupling fossil fuel feedstocks from virgin plastic production by switching to biobased feedstocks will help to reduce the carbon footprint even further.

2 The role of PLA in the circular economy

Our core belief is that PLA bioplastics can have a real and meaningful impact towards creating a better planet for current and future generations. The biobased nature of PLA means that it helps to reduce our carbon footprint. PLA bioplastics can be used in a wide range of durable, multipurpose applications. At the end of their useful life, PLA products can be mechanically or chemically recycled. The compostability of PLA enables the reduction of greenhouse gas emissions via diversion of organic waste from landfill through industrial composting. For those applications which have a high risk of leaking into the environment (like agricultural mulch films), the fact that PLA is biodegradable will help to reduce negative impacts on the environment.

We believe that in the circular economy, so-called 'waste streams' and products at their 'end-of-life' can form the basis for new products, instead of being disposed of. This more comprehensive, sustainable approach replaces the linear economy with a circular, biobased economy where products are produced from sustainable, natural resources and are reused and recycled as much as possible. At their end-of-life, these products then have a range of options to transform them back into feedstock for new, value-added product life cycles. The following end-of-life options are available for PLA:

- Mechanical recycling
- Chemical recycling / feedstock recovery
- Composting / biodegradation
- Anaerobic digestion
- Incineration with renewable energy recovery

Figure 3: PLA and the circular economy

In the following chapters, we will share our views on these various end-of-life options. It is important to realize that different applications, regional differences in waste collection infrastructure and future ambitions of that waste collection infrastructure could lead to different end-of-life recommendations. Each end-of-life option has its pros and cons which should be evaluated in combination with the application, its intended use and the existing waste collection infrastructure.

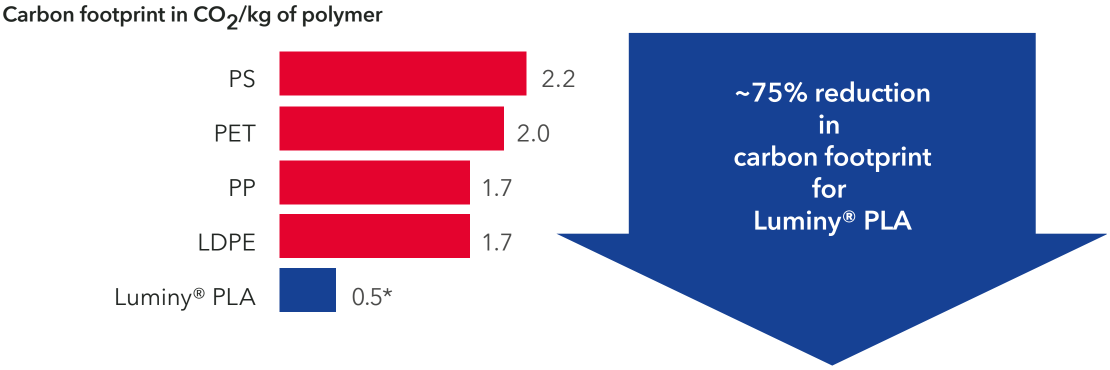
3 Beginning-of-life: using renewable resources for the production of bioplastics

At the beginning-of-life, biobased plastics have the inherent benefit of reducing our dependency on fossil fuels and fossil-based carbon building blocks. In order to advance towards a circular economy, we will need to reduce our dependency on fossil carbon and make a shift to renewable carbon.[9] Biobased plastics and chemicals often offer sustainability benefits over their fossil-based counterparts, such as a reduced CO_2 footprint, reduced dependency on fossil resources and an increased use of renewable energy during the production process. In situations where the end-of-life environmental impacts for different product-material combinations are equal, it is the beginning-of-life benefits of biobased materials that often make these the more sustainable solution.

3.1 Reduced carbon footprint of Luminy® PLA bioplastics

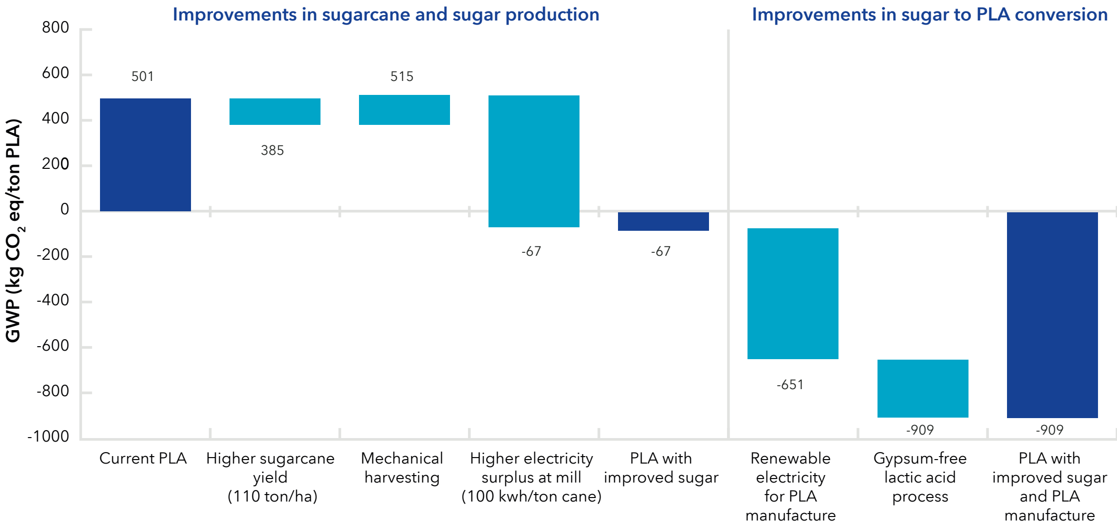
A peer reviewed Life Cycle Assessment (LCA) has confirmed the low carbon footprint of Luminy® PLA bioplastics.[10] From cradle-to-gate, the Global Warming Potential (GWP) of PLA is 0.5 kg CO_2 eq/kg PLA. This is a ~75% reduction in carbon footprint compared to most traditional fossil-based polymers such as PS, PET, PP and PE (Figure 4).

Figure 4: Carbon footprint of PLA compared to traditional fossil-based plastics



Land is required to produce biobased materials as well as to produce food, feed and biofuels. Land use is an important topic for biobased materials, as land use and changes in land use can lead to unintended environmental impacts; by definition, producing biobased materials requires more land area than that required for fossil-based counterparts. Land use change (LUC) has been analyzed using GRAS satellite imaging. The analysis showed less than 0.12% land use change in the area assessed in the period between 2008 and 2017. Moreover, improvements of various production steps in the supply chain from sugarcane to PLA have been identified to further reduce PLA's carbon footprint to a negative 909 kg CO_2 equivalent/ton PLA (Figure 5). In effect, Luminy® PLA will in that case become a carbon sink.

Figure 5: PLA carbon footprint improvement potential



3.2 Sustainable sourcing of feedstocks for bioplastics

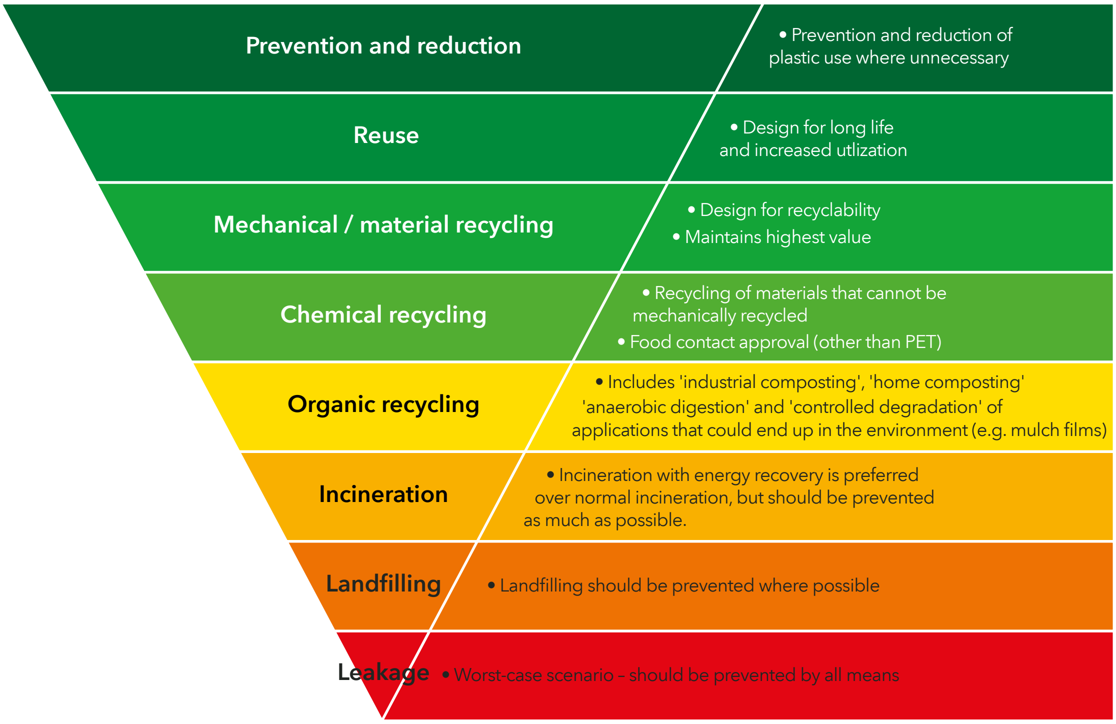
Sugar is today's most sustainable feedstock when looking at the annual carbohydrate yield per hectare[11]. We do believe that sugar production should be based on a sustainable supply chain and sourced responsibly, founded on principles of ethical business practices, human and labor rights and human protection. For this reason Corbion, our main lactic acid supplier, has developed a Cane Sugar Code that is applicable to all of its cane sugar suppliers. Furthermore, Corbion and TotalEnergies Corbion are Bonsucro chain-of-custody certified, enabling TotalEnergies Corbion to offer Bonsucro certified PLA to interested customers. At TotalEnergies Corbion, we believe that the concerns of using biobased feedstocks for plastics can be successfully identified and managed, and that the many benefits of these biobased, renewable feedstocks far outweigh their challenges. Corbion and TotalEnergies Corbion's joint view on the sustainable sourcing of feedstocks is published in the whitepaper for sustainable sourcing.[12]

4 Waste hierarchy

4.1 The pyramid of plastic waste management for bioplastics

Efficient waste collection and management are key to the European Commission's goal of a resource-efficient Europe and its circular economy vision to move from the current linear to the envisioned circular economy. The EU Waste Framework Directive (2008/98/EC) defines a five-step waste hierarchy ranking the treatments of waste based on their ability to conserve resources. Figure 6 shows an adapted version of this waste hierarchy pyramid for bioplastics. At TotalEnergies Corbion, we believe that in the long run, it is beneficial for our planet to actively pursue end-of-life options higher up in the pyramid. The ultimate goal is to avoid plastics entering the environment.

Figure 6: The pyramid of plastic waste management, adapted for bioplastics[13]



4.2 Prevention and reduction

Plastics should be used functionally and unnecessary use of plastics and bioplastics should be prevented. In applications where the functionality of the plastics is questionable, efforts should be made to reduce the usage. This reduction could be achieved by reducing the number of products (if the product is not useful, why offer it to consumers?), or by selecting alternative materials (like glass, wood, paper) if these are more suitable. Smart design also plays a role, along with selecting the optimal type of plastic for the application. That way, products can be made lighter which helps towards the reduction target.

PLA bioplastics offer many features which help to reduce plastic use; PLA has excellent barrier properties making it very suitable for fresh fruit and vegetable packaging but it also has high stiffness and strength, which allows for thin wall part design. PLA is suitable for various conversion technologies, including thin film extrusion, blown film extrusion or biaxially oriented film production.

These are all conversion technologies that limit the amount of plastic material needed per m^2 of packaging material.

4.3 Reuse

Reuse maintains the integrity of the product and has minimal environmental impact, because typically the only required processing step is cleaning. There are already a large number of plastic and bioplastic products which can be reused multiple times, also for durable applications. Examples include reusable, dishwasher-proof cups, plates and cutlery. TotalEnergies Corbion has developed high heat PLA and stereocomplex PLA technology, which is often required for these kinds of durable applications.

4.4 Recycling

4.4.1 Mechanical recycling

In the process of mechanical recycling, the first step is the collection, sorting and cleaning of plastic waste. The sorted plastic waste is compacted into bales by MRFs (Material Recovery Facilities) who then typically sell the plastic bales to recycling companies that remelt and repelletize them into recycled plastic granulate. Recycled plastic granulate can often be recognized by the 'r' preceding the polymer name, like rPLA, rPET or rHDPE.

As indicated in section 1.2, the estimated current global recycling rate for plastic packaging is 10%, with 8% in cascading or downgrading applications and 2% in closed-loop or equivalent applications. A more detailed figure is given in the publication on the lifecycle of plastics in the Netherlands, where we learn that of the 1994 ktons of plastic product demand in the Netherlands, only 316 ktons is actually recycled, representing 16% of the plastics demand.[14]

The signatories of the Global Commitment are using more recycled materials today (5.1% recycled content in 2018 and 6.2% in 2019) with the target to increase to 25% recycled content in 2025. To be able to meet this target, recyclers have committed to increasing their collective processing capacity by four times between now and 2025.[4]

In current mechanical recycling facilities, only a limited number of plastics are sorted and recycled. In general, the plastics with the highest market shares are sorted. In many cases these are PET, PP, PE and, in specific cases, PS. The volumes of other plastics are currently insufficient to be sorted economically. This means that these plastics are incinerated or landfilled. For consumers, it is difficult to distinguish between different types of plastic. In general, plastic waste is either collected via separate plastic waste collection or collected via the residual waste stream, and sorted from this waste stream at a later stage.

4.4.2 Challenges in mechanical recycling

There are items that are very difficult to recycle, even if they are made from recyclable materials. A good example are films as these are generally multi-layer structures. These type of films cannot be recycled in the current recycling infrastructure. Another example is nutrient-contaminated plastic. The nutrient-contamination results in lower recycling yields and reduced recycle quality, which in turn renders them economically nonviable to recycle. Multi-material packaging and nutrient-contaminated plastics are among the key plastic packaging segments that need fundamental redesign and innovation.[15]

Additional hurdles for the recycling of plastics are the strict regulations in place for obtaining food contact approval. At the moment, PET is the only plastic for which food contact approval can be obtained for mechanically recycled post-consumer plastic waste. There are some approvals in place for recycled PE and PP, but these are all based on closed-loop environments.

4.4.3 Mechanical recycling of bioplastics

Bioplastics can be divided into the categories 'drop-in' and 'new' materials. Examples of drop-in materials include biobased PE and biobased PET. The only difference to their fossil-based equivalents is that the polymers are wholly or partly produced from renewable resources. These drop-in materials can be recycled in existing, well-established mechanical recycling streams.

Other innovative bioplastics that have different molecular structures than existing fossil-based polymers can in some cases be biodegradable, and in many cases also be recovered with mechanical recycling technologies. This is especially applicable when sufficient volumes of homogeneous waste material streams are available, either via separate collection (like in closed-loop environments) or through sorting routines.

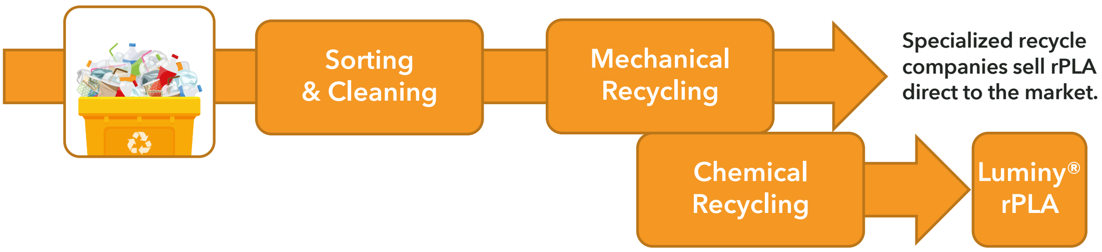
PLA bioplastics can be mechanically and chemically recycled and there are no technical barriers to doing so. It is a general misconception that biodegradable plastics are not recyclable. PLA bioplastics can be sorted from plastic waste very efficiently using industry-standard NIR (near infra-red) sorting technologies. Purities of 97% have been obtained using NIR sorting of PLA, higher than most traditional plastics.[16]

Another misconception is that PLA bioplastics contaminate the plastic recycling streams of traditional plastics. Various studies show that PLA does not contaminate the traditional plastic recycle stream any more than other traditional plastics. For example, research conducted in 2017 has shown that adding 10% PLA into polyolefin recycling streams does not have any different influence on the properties than adding 10% PET or PS to these streams[17]. Furthermore, no specific threats were found from PLA contamination in the PET recycling stream. Other substances like PVC and EVOH have a much greater negative impact on the quality of PET recycle.[18]

There are already several companies who are performing mechanical recycling of PLA waste, mainly from post-industrial or closed-loop environments. Since PLA is a relatively new polymer in the market, the associated volumes have not yet reached the critical mass required to sort PLA into a separate stream from post-consumer waste. In reality, many traditional polymers have also not yet reached a critical mass; PS, ABS, PC, PVC are also often not sorted and recycled.

At TotalEnergies Corbion, we believe that mechanical and chemical recycling should become viable, economically feasible and commonly used end-of-life solutions for PLA-based products. We are committed to developing the recycling value chain together with specialized PLA recycling companies to stimulate demand for PLA thereby increasing recycling rates for PLA-based products.

Figure 7: TotalEnergies Corbion's vision on recycling



"At TotalEnergies Corbion, we believe that mechanical and chemical recycling should become viable, economically feasible and commonly used end-of-life solutions for PLA-based products"

4.4.4 Solvent-based purification

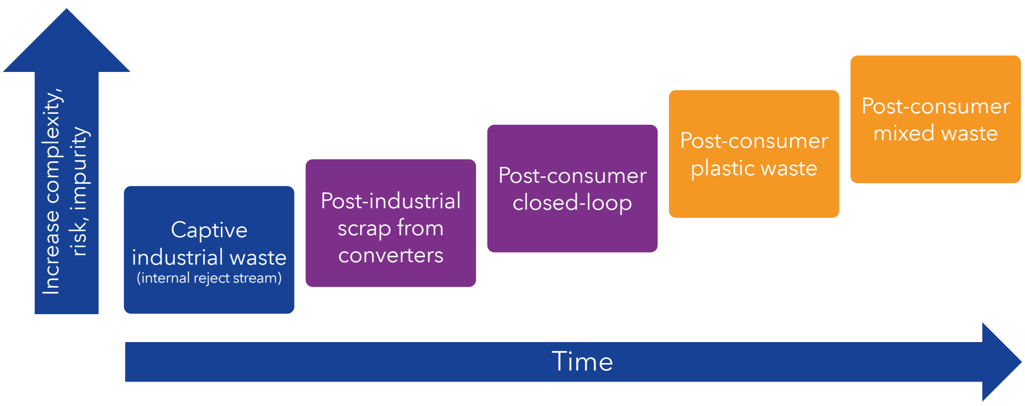
Another form of material recycling using physical separation techniques is solvent-based purification or solvolysis. In this process, solvents are used to dissolve plastic waste to selectively purify the target polymer type from the contaminants. Solvent-based purification has been applied successfully for a heterogenous post-consumer PLA waste stream containing ~30% impurities by implementing the CreaSolv® process.[19] In mechanical recycling and solvent-based purification, the polymer composition is not modified.

4.4.5 Chemical recycling

Chemical recycling, also known as feedstock recovery or tertiary recycling, is a process where plastics are converted into monomers, oligomers or hydrocarbons that can be used again to produce virgin polymers. There are two different forms of chemical recycling being investigated (i) thermal depolymerization and (ii) chemical depolymerization. Thermal depolymerization, also known as cracking or pyrolysis, can be used for polyolefins like PE or PP. It is an energy intensive process that requires large, high-investment facilities to operate cost efficiently. Chemical depolymerization can be used for polyesters like PET and PLA. In the case of PLA, the chemical depolymerization process is a simple hydrolyzation which can be relatively easily performed in small scale facilities.

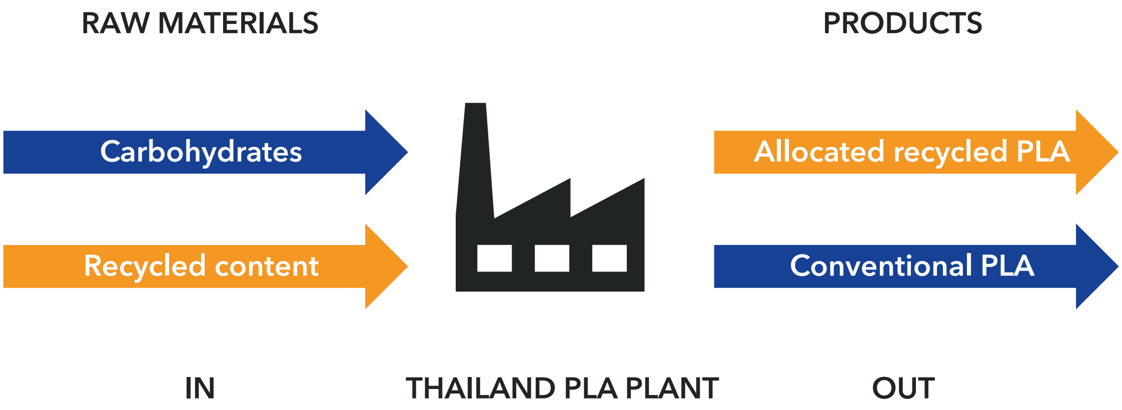
TotalEnergies Corbion has the infrastructure in place to perform chemical depolymerization of PLA in its commercial plant in Thailand. This technology is already being used to internally recycle off-spec PLA products. TotalEnergies Corbion is currently investigating how to use this technology to chemically recycle post-industrial scrap from converters and post-consumer plastic waste (Figure 8).

Figure 8: Risk vs timing of increasingly complex PLA recycle streams



Chemical recycling technologies can generate feedstock that can be used for production of virgin-grade polymers, compliant with regulations similar to virgin polymers. It is TotalEnergies Corbion's preference that these chemical recycling processes 'plug in' to our existing infrastructure in order to reduce cost and time-to-market. This is the reason that recycled feedstock will most likely not exist in physically separate flows, also called 'identity preserved' flows, and that they will instead be added together with the virgin raw materials in the manufacturing plant. To be able to account for the recycled input, TotalEnergies Corbion proposes to use the principles of mass balancing. Mass balancing is a well-known chain of custody approach that is already successfully implemented in, for instance, the FSC, BCI and BonSucro initiatives, where tracking identity preserved streams is costly and adds to the time-to-market. A mass balancing certification for chemical recycling is critical to enable the sale of certified recycled products down the value chain. Figure 9 gives a schematic overview of the provisional mass balancing concept for Luminy® PLA.[20]

Figure 9: Mass balancing concept for chemical recycling of PLA in the TotalEnergies Corbion plant in Thailand



4.4.6 Design for reuse and/or recycling

The preferred end-of-life option for bioplastics should be reuse or recycle, following the principles of the plastic waste pyramid as shown in Figure 6. As explained in section 4.3, reuse models are currently still in an early phase of development and PLA bioplastics are compatible with many of these types of models (e.g. reusable shopping bags, durable cups and plates, etc).

As explained in section 4.4.1, PLA bioplastics can be mechanically recycled and do not contaminate traditional recycling streams. To be able to recycle PLA bioplastics, the same general principles apply as for the recycling of traditional plastics.[21]

- Use labels and glues that can easily be washed off
- Do not use direct printing on the plastic article
- Use mono-materials where possible
- Do not use or add materials that will negatively impact the recycling (e.g. mineral fillers, silicones, PVC, hazardous inks or other polymers)

Currently, MRFs do not sort out PLA from post-consumer waste, as the volume is too small to justify installing a separate NIR sorting line. This does not mean that PLA is not being recycled today. There are several specialized companies that collect PLA waste from post-industrial sources (e.g. production scrap) and from closed-loop environments (e.g. festivals).

Typically, mechanically recycled PLA is not approved for food contact applications. To solve this issue, TotalEnergies Corbion has developed a chemical recycling process that is able to convert mechanically recycled PLA back into food contact approved PLA with the properties of virgin PLA. We are already using this technology for our internal industrial scrap and are now looking to expand this capability to post-industrial and post-consumer PLA. This will also create a market pull for mechanically recycled PLA.

Our chemically recycled PLA will need to be fit-for-use in applications where virgin PLA is used today, such as in food contact applications and/or transparent applications. We are looking for partners that can help us with collection, sorting and cleaning of post-consumer and/or post-industrial PLA waste. We are interested to source the sorted, cleaned and repelletized rPLA of consistent quality to add to our chemical recycling process.

4.5 Biodegradation / composting

Biodegradation is a process that is dependent on physio-chemical (chemical structure, temperature, humidity, pH, thickness) and microbiological parameters (quantity and nature of microbiological community present). In general, the higher the temperature, the humidity and the concentration of microorganisms, the faster the rate of biodegradation. The biodegradation process generally occurs in three phases. First, the material is hydrolyzed or disintegrated so fragments of lower molecular weight are obtained that can then be taken up by microorganisms and in the assimilation process thereafter it is then converted to CO_2 and biomass.

Biodegradation can furthermore be classified into two types. The first type are aerobic biodegradation processes that convert organic matter into CO_2 and H_2O in the presence of oxygen, typically found in composting conditions. During these processes the following conversion takes place:
$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$

The second type are anaerobic biodegradation processes that convert organic matter into CH_4 or methane in the absence of oxygen, typically found in anaerobic digestion conditions. In these processes the following conversion takes place:
$C_6H_{12}O_6 \rightarrow 3\ CO_2 + 3\ CH_4$

Most natural environments can be considered to be aerobic environments. Since biodegradability is dependent on many factors, multiple standards and certification schemes exist that mimic the variety of conditions that can be found in professional and natural environments. Biodegradation processes that take place in professional environments, like industrial composting and anaerobic digestion, are also called organic recycling. These standards are generally based on four tests using different testing conditions:

- Biodegradation: >90% of the material must be converted to CO_2 by means of biological activity
- Disintegration: >90% of the material must disintegrate into fragments smaller than 2x2mm
- Ecotoxicity: The material must not have a negative impact on the compost quality (plant growth test)
- Heavy metals content: The material must be safe for the environment

Although the EN13432 norm on industrial composting assumes 12 weeks disintegration time, in reality the composting process is shorter and typically only lasts 2-4 weeks. This has resulted in claims being made by composters that compostable plastics do not degrade fast enough to be compatible with their organic waste treatment practice.

A recent study by the Wageningen University (WUR) has demonstrated that compostable products which comply with the European standard EN13432 disintegrate fast enough in Dutch organic waste treatment systems. Compostable products made of PLA bioplastics disintegrated faster than, for instance, orange peels or paper, and could not be recovered even after one composting cycle of 11 days. This was not only the case for tea bags, but also for thicker products like plant pots. In addition, many composting facilities return their composting material back to composting for more than one cycle, which results in total retention times much longer than 11 days. The real problem in the organic waste treatment process was shown to be contamination from conventional, non-biodegradable plastics.[22] A similar result was obtained in a field study by the Witzenhausen Institute and the University of Bayreuth, which concluded that compostable bags, certified according to EN13432, do not pose any challenges to the quality of the compost. Also here, the vast majority of the plastic particles that were found (98%) were derived from conventional, non-biodegradable plastics.[23]

Table 1 lists the various biodegradation certification schemes and the key similarities and differences.

Table 1: Overview of biodegradation standards and conditions

	Environment				
	Industrial composting	Home composting	Aerobic soils	Aqueous medium	Marine environment
Standard	EN 13432:2000 ISO 14855 ASTM D6400 ASTM D6868	EN 17427 NF T51-800	ISO 17556	ISO 14851	ASTM D 6691
Certification example	OK compost Industrial	OK compost Home	OK biodegradable Soil	OK biodegradable Water	OK biodegradable Marine
Test temperature	58°C ± 2°C	28°C ± 2°C	25°C ± 2°C	20°C - 25°C	30°C ± 1°C
Biodegradation time	6 months	12 months	24 months	56 days	6 months
Disintegration time	12 weeks	6 months	Not required	Not required	84 days

Various certification bodies offer compostability certificates, including TUV Austria, DIN CERTCO and BPI. Most bioplastic resin producers certify their products against the highest thickness that still results in passing the 12 weeks disintegration requirements. The reason is that any thickness lower than the certified thickness will be able to get certified without extensive additional testing, resulting in lower costs and faster time-to-maket throughout the value chain. In reality, there are very little to no applications that actually require this thickness. Luminy® PLA LX175 is certified to a maximum thickness of 3.5 mm. The most commonly used applications are in the use of articles with a maximum thickness of 1 mm or thin films with a thickness of 50-100 micrometers. As a general rule of thumb, an article with a thickness of 45% of the originally certified material will disintegrate in 50% of the time. A PLA film of 100 micrometers is estimated to disintegrate within 1 week using this rule of thumb. This fast disintegration time was confirmed in the WUR study that showed that most PLA bioplastics could not be recovered after just one composting cycle of 11 days.

"Compostable products made of PLA bioplastics disintegrated faster than, for instance, orange peels or paper in Dutch organic waste treatment systems"

4.5.1 Anaerobic digestion

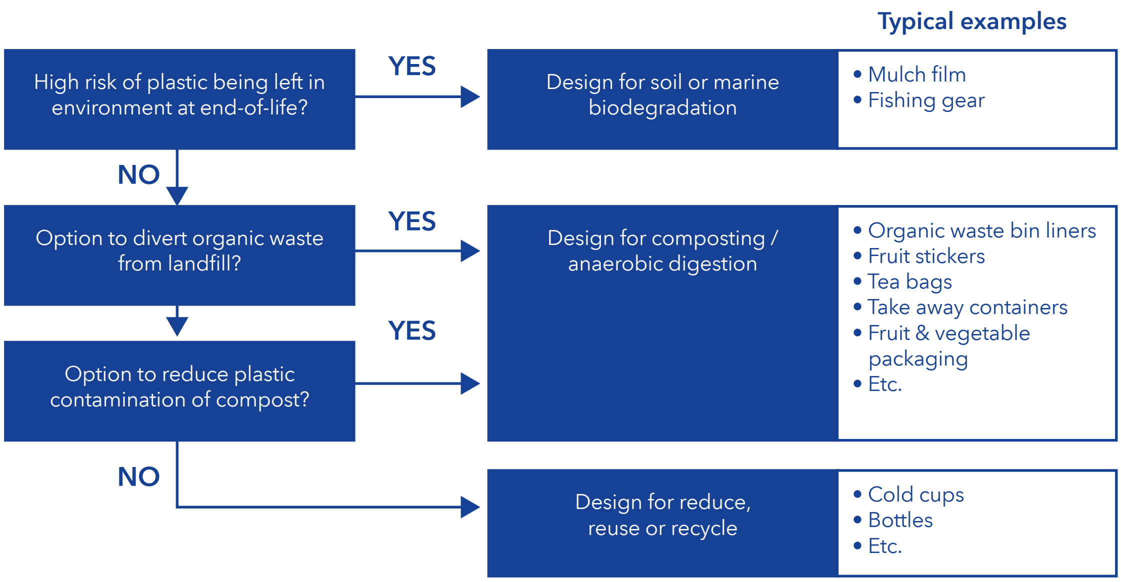
Anaerobic digestion is a process in which microorganisms biodegrade organic materials in the absence of oxygen into methane. This process is used for industrial or domestic purposes to manage waste or produce fuels. Anaerobic digestion also occurs naturally in some soils and in lake and oceanic basin sediments.[24] The anerobic digestion process is widely used as a source of renewable energy. The process produces biogas, consisting of methane, carbon dioxide and traces of other contaminant gases.

With anaerobic digestion, a lot of different technologies are used. Key differentiators are temperature (mesophilic or thermophilic), number of phases (one-phase or two-phases), moisture content (dry or wet) and process type (batch or continuous). Combinations of anaerobic digestion and composting are also possible. Unfortunately, no specific certificates or labels on anaerobic digestion currently exist or are expected in the near future.[25]

4.5.2 When to choose biodegradation as end-of-life option?

We believe that the key to increasing recycling rates starts with designing products with the right end-of-life option in mind. By thinking about this from the start, it will be easier to recycle the product after use so that the recycling rates can increase. Figure 10 shows a decision tree that helps to choose which design philosophy should be kept in mind when designing a product.

Figure 10: Decision tree for designing products with the right end-of-life option in mind



We believe that biodegradation should never be a reason to litter and that the appropriate end-of-life option should be used to dispose of the plastic in the right way after use.

There are, however, applications that have a high risk of plastic being left in the environment at the end-of-life. Typical examples are mulch film and fishing gear. For these applications, it is recommended to design for biodegradation in the environment in which it is likely to be left behind.

Mulch films are used in agriculture to modify soil temperature, limit weed growth, prevent moisture loss and improve crop yield. After use, the mulch film can be collected but much of the mulch film stays behind on the land or ends up in the environment. Making mulch films that are biodegradable under these conditions would result in less environmental pollution as well as reduced costs for the farmer as they do not have to collect the mulch films after harvest. These mulch films should meet the requirements of, for instance, the OK Biodegradable Soil certification scheme, thereby providing a guarantee that these products biodegrade in the soil within the appropriate time frames.

> *"We believe that biodegradation should never be a reason to litter and that the appropriate end-of-life option should be used to dispose of plastic in the right way after use."*

A recent study has found that 6% of all fishing nets, 9% of all traps and 29% of all lines are lost or discarded into our oceans each year.[26] Although it is obviously not recommended to discard fishing gear in the oceans, it is nonetheless happening a lot. For these types of applications, it is recommended to produce them from materials that biodegrade in fresh or sea water conditions. If this fishing gear is then left behind in the ocean (by accident or on purpose), it will not persist for decades like traditional fishing gear.

It is important to note that in general, PLA in sea water or other marine environments will not degrade as fast as when placed in an industrial composting facility.

Compostability is an end-of-life option that should only be used for specific applications. Composting can help to efficiently manage the biggest fraction of the municipal waste stream: bio-waste. Industrially compostable plastics can help to separately collect organic waste, divert larger volumes of bio-waste to organic recycling and reduce conventional plastic contamination in the bio-bin thereby ultimately reducing microplastics in compost.[27] In other words: compostable plastics should offer a co-benefit such as increasing the amount of food waste collected to be composted, or reducing the amount of fossil plastics ending up in the food and garden waste. In Europe, only 16% of the food waste that is generated is captured.[28] Compostable plastics can play a crucial role in helping to tap into this untapped potential.

Nutrient-contaminated plastics and multi-materials are in general not recyclable and currently have no end-of-life option besides incineration or landfilling, as was confirmed by the Ellen MacArthur Foundation. Replacing these with compostable plastics will provide an alternative end-of-life option for these applications. Especially for nutrient-contaminated plastics, the added benefit is that composting will lead to a reduction in greenhouse gas emissions compared to incineration, since incineration of organic waste costs more energy due to water content. The global substitution potential of compostable plastics in 2040 is estimated to be 38 million tons, of which 28 million tons substitution of monomaterial films.[2]

4.5.3 Benefits of composting

There are a number of benefits to compost that not everyone is aware of. Some examples are listed below[29]:

- Organic waste in landfills generates methane, a potent greenhouse gas. By composting wasted food and other organics, methane emissions are significantly reduced.
- Compost reduces and in some cases eliminates the need for chemical fertilizers.
- Compost promotes higher yields of agricultural crops.
- Compost can help aid reforestation, wetlands restoration, and habitat revitalization efforts by improving contaminated, compacted, and marginal soils.
- Compost can be used to remediate soils contaminated by hazardous waste in a cost effective manner.
- Compost can provide cost savings over conventional soil, water and air pollution remediation technologies, where applicable.
- Compost enhances water retention in soils.
- Compost provides carbon sequestration.

4.5.4 Design for biodegradation & composting

When designing a product and/or packaging for biodegradation, it is imperative to take the environment in which it will end up into account. For products that are likely to be left behind in the soil, like mulch films, one should design according to the OK Biodegradable Soil certification scheme, etc.

Most biodegradation standards are set up according to similar principles. For all of these standards, the following general principles can be applied:

- Please follow the biodegradation decision tree (Figure 10) to decide if biodegradation or compostability is the right end-of-life option to design for.
- Take the environment the product needs to biodegrade in into account and design the product to meet the relevant standards of that environment.
- Read and understand the relevant standards and determine if your product meets the requirements.
- Request information on compostability or biodegradability from your suppliers. Using only already certified substances will help the certification process.
- Make sure the use of non-biodegradable substances, or the use of substances with certain exemptions, meet the set threshold levels of the relevant standards.
- Understand and assess the factors that can negatively influence the disintegration process (e.g. thickness, multi-layers, additives, etc).
- Preferably, refrain from using any bright colors that can lead to visual issues in the compost.
- Preferably, refrain from adding any fluorochemicals to the packaging to make sure compliance with all standards is guaranteed.
- Work with an approved test laboratory to test the product according to the appropriate biodegradation / compostability standards.
- Request certification at certification bodies to get third party certification for your product.
- If the product is certified by a third party (e.g. BPI, TUV Austria, DIN CERTCO), use the logo on the product including your specific certificate number.
- Market the product in line with the product certification obtained. For example, market products that are EN 13432 certified as industrially compostable.
- Only market products for the selected end-of-life solution if the infrastructure to facilitate the recommended end-of-life option is actually available. For example, only market your product as compostable if compost collection infrastructure is available.

By following these guidelines, the chances of getting certification for your products is maximized while at the same time the products are optimally designed to biodegrade in the environments where they are likely to end up.

4.5.5 Communicating beginning- and end-of-life benefits on finished products

One of the advantages of PLA bioplastics is that they are produced from renewable resources, resulting in 100% biobased content. Claiming biobased content of a product should be based on internationally accepted test methods and certification schemes to avoid greenwashing. Examples of test methods are EN 16785-1 and ASTM D6866. These test methods are at the basis of the USDA Biopreferred, OK biobased and Biobased content certification schemes. In all cases, it is important to indicate clearly what part of the product the biobased claim is referring to (e.g. packaging, product, etc) and to use the valid certificate number in your marketing materials.

With regard to claiming benefits of compostability or biodegradation, the same applies as with biobased content: the claims should be based on internationally accepted test methods and certification schemes. An overview of these certification schemes is presented in section 4.5. With regard to composting, we believe that a valid claim can only be made if the compostable packaging is helping to divert organic waste from landfill to composters, or if the compostable packaging helps to reduce plastic contamination in compost. The existence of local composting facilities that will accept the compostable product or packaging is also important. It should be clear which part of the product the claim is referring to, and make sure to use the valid certificate number in your marketing materials.

4.6 Incineration and possible energy recovery

It is estimated that the most commonly used end-of-life option after landfill is incineration, with a total of 800 million tons of plastics incinerated since the introduction of plastics into the market.[1] The Ellen MacArthur foundation has confirmed this and has stated that 32% of plastic packaging is incinerated. Plastics Europe has published information that of the collected post-consumer plastic waste in Europe, 42.6% was incinerated in 2019.[30] In the Netherlands specifically, incineration is the most commonly used end-of-life option for plastics: 48% of the collected plastic packaging and 66% of the collected plastic in total was incinerated in 2018. Plastics that are collected but that cannot be recycled are incinerated in the Netherlands, as landfill is not permitted.[14]

In the case of the most commonly used end-of-life option in Europe (incineration), PLA bioplastics are always the lower carbon footprint solution due to the renewable carbon content. For PLA bioplastic products with a low moisture content after use, the carbon footprint can be negative. A high moisture content requires additional energy for incineration, which results in relatively high CO_2 emissions. For these applications, compostable bioplastics are the lower carbon footprint option and can result in organic waste diversion.[31]

4.7 Landfill

Globally, landfill is the most common end-of-life option for plastic packaging at 40%, closely followed by leakage into the environment at 32%. Landfill is considered to be the worst-case end-of-life option (after disposal in the environment), and for that reason some countries have implemented landfill restrictions for plastic waste such as Switzerland, Austria, the Netherlands and Germany.[28] Nevertheless, 7.2 million tons of plastic waste ends up in landfill in Europe, 24.9% of the total amount of plastic waste collected. In the United States, more than 75% of the plastic in municipal solid waste is landfilled, comprising 19% of the total MSW volume in landfill.[32] On a global level, 69% of plastic waste ends up in landfills.[2] PLA is no worse than traditional plastics in landfill and does not lead to methane formation.[33]

4.8 Leakage into the environment

The Ellen MacArthur Foundation has reported that 32% of plastic packaging leaks into the environment globally – a number that was reported to be even higher, at 41%, by the recent 'Breaking the plastic wave' study.[2] It is estimated that at least 8 million tons of plastics leak into the ocean each year, and this figure is expected to quadruple until 2050. Although only 45% of the plastics are produced in Asia, 82% of the leakage into the ocean occurs in Asia. The main reason for this is the lack of collection and waste handling infrastructure in many countries in this region. It is estimated that about 90% of the plastics that enter the ocean come from only 10 rivers, all located in Asia or Africa.[34]

We believe that biodegradability should never be a reason to litter. As a society, we need to put more efforts into putting in place infrastructure, regulations and a shift in mindset in order to stay higher on the waste hierarchy pyramid.

4.9 Comparative overview of end-of-life options

Table 2: Overview of end-of-life options for bioplastics compared to traditional plastics

	Bioplastics							(both)		Traditional plastics			
	PLA	PLA compounds*	PBAT	PBS	PHA	Starch	Multi-layer films	PET	PE	PP	PS	ABS	Multi-layer films
Biobased**	X	(X)		(X)	X	X	(X)						
Mechanical recycling	X	X	X	X				X	X	X	X		
Chemical recycling***	X			X				X	X	X	X		
Incineration	X	X	X	X	X	X	X	X	X	X	X	X	X
Industrial composting	X	X	X	X	X	X	X						
Home composting		X	X	X	X	X	X						
Biodegradable soil		X		X	X	X							
Biodegradable water					X	X							
Biodegradable marine					X	X							
Anaerobic digestion	X	X	X	X	X	X	X						

** PLA compounds typically contain up to 40% PLA in combination with starch, PBAT or PHA.*
*** X means 100% biobased, (X) means that it is partially biobased or can be either biobased or fossil-based.*
**** Chemical recycling is technically possible, but not in commercial stage yet for post-consumer plastics*

The optimal end-of-life option is dependent on many factors, including material type, level of contamination and most importantly, the presence of local infrastructure to actually apply the end-of-life option. Table 2 gives an overview of the various end-of-life options that are available for a variety of plastics, not taking into account local infrastructure availability. This table shows that PLA bioplastics, for instance, provide additional end-of-life options that are not available for traditional plastics.

5 The benefits of using bioplastics to increase recycling rates

We believe that PLA bioplastics provide additional end-of-life options when compared to traditional plastics. We believe that mechanical, chemical and organic recycling should become viable, economically feasible and commonly used end-of-life solutions for PLA bioplastics. At TotalEnergies Corbion, we are committed to a target of 30% total recycling rate for PLA bioplastics in 2030. What can we do to meet this ambitious target? Below are some examples of applications where bioplastics can provide benefits to increase recycling rates.

5.1 Articles that are inherently contaminated with food or that are likely to end up in the organic waste bin

According to European Bioplastics, plastic products should be produced from compostable plastics if the following criteria apply:

1. Contamination with food waste,
2. Likely to end up in the organic waste collection and unlikely to be effectively mechanically recycled in the plastic recycling stream,
3. Potential to reduce non-biodegradable plastics contamination of bio-waste collection,
4. No efficient redesign possible in order to move to reusable solutions.

Examples of applications that meet these requirements are bio-waste bags, thin fruit and vegetable bags, tea bags, coffee capsules/pads/filters, fruit stickers, cling-film, paper towels, catering items and multi-material flexible packaging for perishable food.[27] The recently published study by WUR has confirmed that compostable materials meeting the EN 13432 requirements are disintegrating fast enough in Dutch organic waste treatment systems, and even disintegrate faster than traditional organic waste like orange peels.[22]

It was shown that for a variety of compostable applications (including coffee cups, yoghurt cups, coffee capsules, tea bags and cucumber wrap film), composting does not contribute significantly to greenhouse gas emissions and fossil fuel consumption. In the case of composting compostable plastic packaging that includes high amounts of organic waste, a co-benefit can be seen that has a multiplier effect. For example, in the case of tea bags, 6.7 kilograms of organic waste is diverted from landfill to compost per kilogram of PLA bioplastics.[31]

Anaerobic digestion would allow for even more environmental benefits, as this would enable the recapture of energy embedded in the PLA while also returning the organic content back to the environment, resulting in the lowest greenhouse gas warming potential. For anaerobic digestion, the infrastructure still needs to be set up, which will be challenging. In the long run this is the most favorable solution. Setting up composting infrastructure could be seen as a first step towards this end goal, since in many cases, anaerobic digestion plants are often combined with industrial composting.

5.2 Closed-loop environments

Closed-loop environments can be any type of environment where the flow of materials coming in and coming out are managed by a professional organization. Examples include event locations, festivals, fast food restaurants, universities, stadiums, offices and clubs. Because the material flow is controlled, waste collection and separation can be managed more easily.

In closed-loop environments where food is served, a lot of disposable plastic items are used that are in many cases contaminated with organic waste after use. This has a negative impact on recycling and can lead to organic waste ending up in landfill. Diverting this organic waste from landfill to organic waste collection can be increased significantly by using compostable plastics.

The concept is to replace all disposable materials that are used in closed-loop environments by compostable plastics. By doing so, both the food waste and nutrient-contaminated plastic can be collected as organic waste, and then either organically recycled or composted. This way, the organic waste is handled in the correct way and there is less plastic waste to dispose of. In addition, there is less nutrient-contaminated plastic waste that is challenging to recycle. Depending on the waste disposal costs, this can lead to a significant cost saving.

Composting in closed-loop environments leads to the following advantages:
- By using compostable plastics, the amount of organic waste diverted from landfill will be significantly increased.
- Using biobased plastics leads to an improved sustainability profile that can create or reinforce a positive image and advance the sustainability agenda of organizations.
- Waste collection and separation will be less complex for the company and consumer as there will only be one waste stream that consists of organic waste and compostable plastics.

In the US, this concept is already in existence in many different locations. A very well-known example is the Green Sports Alliance. In various sport stadiums, waste diversion rate improvements of more than 30% have been obtained using compostable serviceware.[35]

The market volume of PLA is currently too small to be sorted out economically from household waste. Collection and sorting of PLA from household waste is therefore not possible at this moment. This does not mean that PLA cannot be recycled. Several companies are already active in the field of recycling of PLA waste from post-industrial or closed-loop environments. The process scraps resulting from the conversion of PLA or off-spec products can, for instance, be collected and recycled.

PLA can also be collected from closed-loop environments for mechanical recycling. Festivals provide an excellent opportunity, for example. During a festival, a lot of plastic is used. The main applications are plastic cups for cold drinks and plastic food serviceware for the food being served. In this case, the recommendation would be to separately collect the PLA cold cups after use. These cups are relatively clean and not contaminated with food waste and are therefore very well suited for mechanical or chemical recycling. Using PLA bioplastics for cold cups and collecting them for recycling, and using PLA bioplastics for the food serviceware and collecting them for composting together with the organic waste, are processes that are already being performed at commercial scale, for instance during the Lowlands festival in the Netherlands.[36] This can lead to significant increases in recycling rates.

Another relevant waste stream in closed-loop environments are PLA coated paper cups. In some cases, these paper cups are collected separately. Depending on the composition of the cups, they could either be composted after use (if certified compostable) or could be added to the traditional paper recycling stream. Tests performed by TotalEnergies Corbion together with Western Michigan University have shown that using a PLA coating is compliant with the paper repulping process and does not have a negative impact on traditional paper recycling streams.

A recent study by Eunomia confirmed that for some applications, biodegradable and compostable products can be beneficial: “The study concludes that some of the most potentially beneficial applications are biowaste bags, teabags and fruit labels whereas applications such as single-use bottles or clothing packaging bags constitute detrimental uses".[37] The study shows a 'compostable plastics beneficial use continuum' to show for which applications compostable plastics can be beneficial. In Figure 11, we show an adapted version of this continuum, where we have added some important categories that were not included in the original (e.g. coffee capsules – alternatives banned) and have added articles that have a high likelihood to be left in the environment (e.g. mulch films and fishing gear). We have added this as a scoring criteria for all categories, which explains some of the (minor) differences in scoring.

Figure 11: Biodegradable and compostable plastics beneficial use continuum (adopted from Eunomia report)

5.3 Chemical recycling as enabler for food contact compliant recycled PLA

Today, the only plastic that can be approved for food contact use from post-consumer plastic waste is PET. Unfortunately, this means that mechanically recycled PLA is not approved for food contact use. We believe chemical recycling can be the enabler for food contact approval of recycled PLA. Our target is to collaborate with third parties that collect, sort, and pelletize 'PLA waste' in a consistent quality so that we can add this to our chemical recycling unit in Thailand. After chemical recycling in our plant, the result will be food contact approved recycled PLA. We are actively looking for partners all over the world that can help us to close the loop for PLA recycling.

By increasing the mechanical and chemical recycling rates of PLA, the volumes of PLA will grow so that sorting PLA from household waste will become economically feasible in the future.

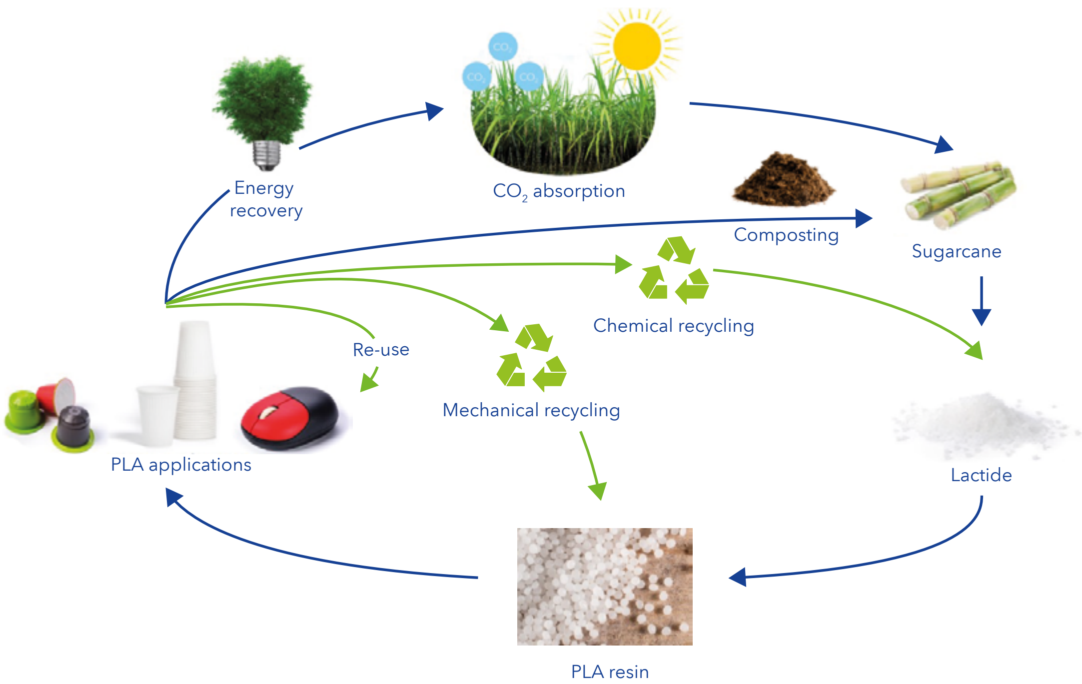
6 The role of PLA in the circular economy – continued

We believe that PLA bioplastics can play a vital role in the circular plastics economy in 6 main areas:

1. Biobased – helps to decouple from fossil feedstocks and reduce carbon footprint emissions.
2. Excellent functional properties – allows multiuse / durable applications and also allows for reduced use of material.
3. Mechanical/chemical recycling – helps to keep valuable resources in the circular economy
4. Organic recycling including composting and anaerobic digestion - helps to divert organic waste from landfill/incineration.
5. Biodegradable – for those applications that are prone to end up in the environment, biodegradable plastics help to reduce the burden on nature.
6. Incineration with energy recovery – incineration of biobased plastics is always the lower carbon footprint solution due to the renewable carbon content.

Figure 12 shows the role of PLA in the circular economy. It is an extended version of Figure 3 that takes into account all the available end-of-life options for PLA bioplastics. The preference is to design the product or packaging with the shortest end-of-life loop in mind to maintain the highest share of material value. Leakage and landfilling should be avoided, and incineration should only be used as a last resort.

Figure 12: The role of PLA in the circular economy – extended overview taking into account all available end-of-life options.



7 Glossary

Beginning-of-life
Origin of raw materials used for the production of a product. In the case of fossil-based plastics, the beginning-of-life is crude oil. For biobased plastics, the beginning-of-life is renewable resources.

Biobased product
A product made, in whole or partially, from renewable raw materials.

Bioplastics
Plastics that are either produced from renewable resources or are biodegradable.

Carbon footprint
The total CO_2 emissions caused by the production of a certain product.

Closed-loop environment
An environment where input and output streams are centrally managed providing options for a closed loop. Examples are offices, festivals, sport stadiums, etc.

End-of-life
Waste disposal option at the end of the useful life of a product. The various end-of-life options for bioplastics are explained in this whitepaper.

Global Warming Potential
The total CO_2 emissions caused by the production of a certain product.

Landfill
A landfill site is a site for the disposal of waste materials (Wikipedia).

Life Cycle Assessment (LCA)
A methodology to assess the environmental impacts associated with all the stages of the lifecycle of a commercial product, process or service (Wikipedia).

Materials Recycling Facility (MRF)
Specialized plant that collects, sorts, and prepares recyclable materials.

Municipal Solid Waste (MSW)
Also known as trash, garbage, or household waste, and consists of everyday items that are discarded by consumers.

Near Infra Red (NIR)
An identification technology that is able to separate various materials based on their spectrum.

Nutrient-contaminated
A plastic article or product that still contains (traces of) its original food-based or organic contents.

Post-industrial
Plastic waste that is generated during the production of plastic articles, like cut-offs, regrind or production scrap. Also known as pre-consumer waste.

Post-consumer
Plastic waste that is generated by consumers, which can be either in the plastic waste or in the mixed waste fraction.

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