VITAL For cleaner, more climate neutral, industrial value chains

Compostable isn’t enough: Unlocking the full potential of biobased materials through recycling

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Introduction

When you think about biobased materials, “recycling” is not the first word that comes to mind. “Biodegradable” and/or “compostable” might be up there, but in reality, not all biobased materials are biodegradable or compostable; for example, polyolefins such as polypropylene (PP) may now be made from biobased raw materials[1], but they degrade in the environment exactly as slowly as fossil petroleum-based polyolefins.

Biobased – at least partially derived from biomass carbon rather than fossil carbon.

Biodegradable – able to undergo degradation to carbon dioxide and water in relevant biological environments (90% conversion to CO2 in 6 months under composting conditions, or >50% conversion to biogas within 2 months – depending on the standard followed).

Compostable – able to be degraded by microbial activity in relevant biological environments.

In a circular economy mindset, the resources used in creating biobased materials are extremely valuable and we want to keep them in circulation for as long as possible and at as high a value as possible[2]. Some ways we can do that are shown in *Figure 1*. Additionally, certain bioplastics (including project VITAL’s bioplastic of main interest, polylactic acid/PLA) are manufactured from 1st generation biomass, which is often edible, and are therefore in competition with food production. Reducing the reliance of the manufacturing industry on that 1st generation biomass is therefore a desirable goal[3].

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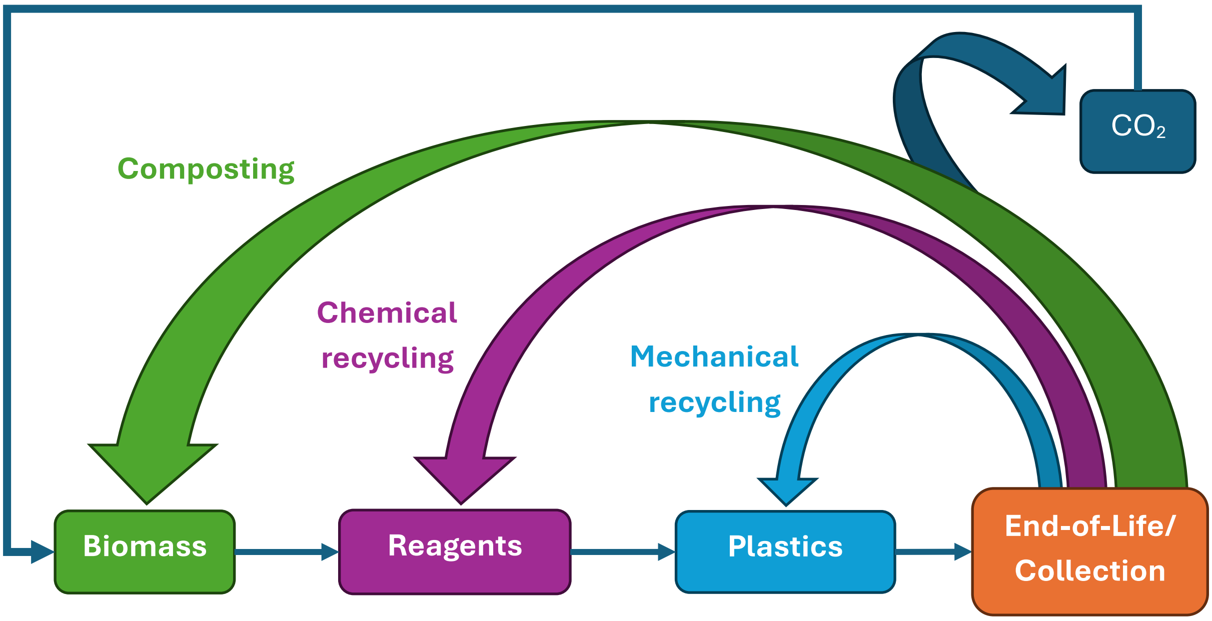

Figure 1. A portion of the circular economy model showing mechanical recycling, chemical recycling, and composting of bioplastics. The smaller the recapture loop, the more desirable that loop is for the circular economy. This diagram represents the "ideal" system with no loss of material at any stage, although in real life there is almost certainly some loss.

Cosate de Andrade et al carried out a life cycle assessment (LCA) of some of the end-of-life options for PLA – in particular mechanical recycling, chemical recycling and composting[4]. Other end of life options such as incineration for energy recovery or landfilling of waste are less compatible or incompatible with circular economy principles, so were not considered. Some of the pros and cons of these routes are discussed below and *Figure 2* shows a summary of which route is best for different circular economy aspects.

Mechanical recycling involves washing, grinding and remelting the plastic to be used for the creation of new products. Mechanical recycling of fossil-based thermoplastics is well understood and carried out commercially for several materials. Unfortunately, the thermal energy required can cause breakdown of the polymer over several recycling cycles, so there is often a loss of value over time – this is well known even for paper and conventional plastics. A further disadvantage is difficulty recycling mixed plastic articles, such as multilayer barrier films used to increase food shelf-life.

Chemical recycling involves chemically breaking down the plastic into its component starting materials, which can then be used to make new plastics of the same type, or other chemicals. Several types of processes are available, depending on the type of plastic to be recycled – some of these processes can handle mixed plastic articles. This process needs more energy than mechanical recycling, but the output is a brand new, high value biobased material. For biopolyesters that can be separated from other polymers, the most attractive processes selectively break the polymer down into its original starting materials, or a close derivative. Coltelli et al prepared an excellent review of these processes in 2024, highlighting various ways in which researchers are working to reduce the energy demand of these promising processes[5]. McKeown and Jones have also reviewed this subject in recent years[6].

Composting or biodegradation of biobased, biodegradable materials has the longest return cycles. Depending on the conditions of the degradation method[1], some of the carbon may be returned to the soil, which can help to grow more biomass for future biobased materials, and some or all is released to atmosphere in the form of the greenhouse gas, carbon dioxide (CO_2). Because the carbon in these materials comes originally from biomass rather than fossil sources, the CO_2 released is of the “short cycle” type and is overall neutral in its effect on the greenhouse gas concentration in the atmosphere. However, the value that was created by manufacturing the biobased polymer is lost in this route. Studies show that PLA is relatively slow to degrade compared to some other bioplastics, and higher temperatures and humidities may be required for effective breakdown[7].

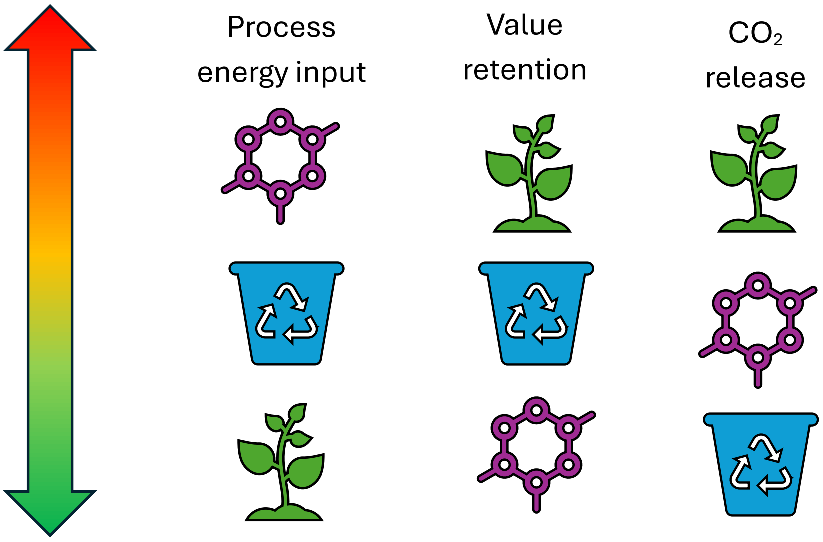

Figure 2. A comparison of which biobased polymer “recycling” routes are best for different circular economy considerations (energy input, value retention, CO2 release).

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[1] “compostable” and “biodegradable” have separate definitions which depend on the environment, physical conditions and microbial conditions under which the material degradation takes place, as well as the products released under the degradation process.

Mechanical Recycling of PLA – The Current Challenges

Next, we will consider the mechanical recycling of PLA specifically, as this is a bioplastic we are using extensively in the VITAL project, and we are focusing on improving this process within our project. Within mechanical recycling, there are several challenges that need to be resolved for industry to be able to achieve a more effective, circular economy for PLA specifically and biobased polymers in general. These fall broadly under 3 areas:

1. Poor cost effectiveness of recycling due to low manufacturing volumes – therefore there is limited infrastructure available

It has been estimated that a critical production mass of any single bioplastic of approximately 200 kilotons per year is needed to enable cost effective recycling of it to take place[8]. At the time that estimate was made (2007), the global production capacity of PLA was 148 kilotons per year so production capacity in any one area was significantly lower than needed to entice recycling companies to take much notice of the new bioplastic. By 2022, the global production capacity had reached 459 kilotons per year and recent new investment in production facilities is expected to push that to >2 million tons per year before 2030[9]. This capacity is distributed globally, therefore it seems that in several locations there is likely to be sufficient PLA-based packaging in circulation to allow cost-effective recycling.

Mechanical recycling infrastructure centers focus predominantly on handling poly(ethylene terephthalate) (PET) and polyethylene (PE) (and chemical recycling infrastructure is far behind mechanical recycling in terms of coverage and capacity). Investment will therefore be needed to develop the recycling infrastructure to enable effective recycling of PLA and other bioplastics.

2. Effective collection and sorting of bioplastics – challenges of compatibility with existing recycling, and consumer knowledge

There are several challenges around collection and sorting of bioplastics that will need to be resolved in the move to a more circular economy.

Firstly, collection. Bioplastics are currently labelled as “category 7/other” – there is no differentiation between the different types of bioplastics such as PLA, polyhydroxyalkanoate (PHA), thermoplastic starch (TPS, and polybutylene succinate (PBS). This category also includes non-biobased plastics such as polycarbonate and other plastics for which there is not a recycling route such as multilayered films. Even if the bioplastics were clearly labelled, it is often unclear to consumers how bioplastics should be disposed of. Additionally, the level of recycling segregation required of consumers varies hugely by region.

Secondly, sorting. Bioplastic contamination in rPET can cause significant quality issues, so contamination levels need to be tightly controlled[8]. Segregation at the collection stage could reduce the risk of contamination, but the more complex the segregation task consumers are required to do, the less likely they are to do it. Therefore, technological solutions to the sorting challenge are required.

Researchers have shown that the current NIR technology, with some re-programming to recognize the new bioplastics, is able to distinguish all the key bioplastic types from PET (the closest conventional plastic match)[10,11]. It has also recently been found that the order in which plastics are sorted for can have a strong influence on residual contamination[12]. For example, if PLA sorting is carried out after PET/PE/PP, the contamination rate of PLA in the PET could be around 1%. In contrast, if PLA sorting is carried out first, the contamination rate of PLA in PET could be as low as 0.05%, which should be below the threshold for optical effects on clear recycled PET (rPET) bottles[8].

3. Improving quality of outputs – demonstrating the successful use of recycled PLA in real products

As already mentioned, even in conventional thermoplastics, the heat and mechanical forces used to reprocess plastics during mechanical recycling can cause degradation of the polymer by mechanisms such as polymer chain breaking, hydrolysis in the presence of moisture, and oxidation. Biopolyesters, such as PLA, are particularly prone to hydrolysis reactions in the presence of water, as this is the main mechanism through which biodegradation occurs, therefore pre-process drying is important. The melting point of PLA (~150°C) means that processing is typically conducted around 180-190°C to achieve a suitable melt flow viscosity: this is unfortunately not that far from the thermal degradation onset temperature of 220-250°C (depending on the PLA grade). At the same time, forces within the processing equipment generate localized "hot spots" within the material. Consequently, precise control of process conditions - including temperature profile, residence time, and stress on the material - is critical. The combination of degradation reactions leads to impacts on the PLA properties such as crystallinity, hardness, stiffness and melt viscosity [7,13–16].

Practices used in upgrading conventional thermoplastics polyesters include solid state polymerization[14], addition of chain extender additives[15], antioxidants[5], reinforcement agents[13,16], and blending recyclate with virgin polymer. Where these approaches have been trialed and reported for PLA, the relevant studies are referenced.

A final point to consider is that the lactic acid monomer used to prepare PLA has a right- and left-handed version – it is "stereoisomeric". Properties (especially crystallinity) of commercial PLA are therefore frequently tuned by adjusted the content of the different versions of lactic acid. Blending these different PLAs into a single recycled PLA will therefore always lose some of the value that was inherent in the original polymer. How to address this challenge in mechanical recycling processes is not clear currently.

Mechanical Recycling of PLA – The Next Steps for Project VITAL

In the VITAL project we are developing machine learning methods to improve the mechanical recycling of PLA and retain the ability to make high value, lightweight foamed products using this recycled bioplastic. The key goal for us is limiting the degradation occurring during the recycling process by intelligent control of process parameters and use of selected additives.

In our technical development programme, we have first conducted simulations to analyse PLA behavior across several reprocessing cycles within the extruder environment. The primary goal was to understand the thermal and mechanical experience of PLA within the extruder and how it changes with additional reprocessing cycles as the PLA structure changes. This analysis enables the identification of optimal operating conditions and equipment designs to reduce PLA degradation.

Subsequent trials involving PLA reprocessing across five cycles revealed a significant decline in mechanical properties beginning at the third cycle. To mitigate this decline, we are using a dual approach of modelling and experimentation, testing modified equipment designs and incorporating additives such as antioxidants and chain extenders. These strategies aim to enhance the recyclability of PLA while maintaining its performance for high-value applications.

Thanks to our links with partner projects under the Biomatters cluster, and related project groups, we may also be able to learn from their experience and developments in related areas. The following projects include a focus on bioplastics recycling:

Ambiance project are investigating how their biomaterial final properties are affected by recycling, and measuring the number of recycling cycles it can tolerate.[17]

Waste2BioComp project are developing biobased packaging films (preferably recyclable, at least biodegradable), and textile fibers based on PHA. They are also developing microwave-assisted chemical recycling for end-of-life valorisation.[18]

Bio-Uptake are working on products made with combinations of PLA, polyamide composites and polycaprolactone (PCL). Their focus is on “design for recycling” – ensuring that the polyesters will be easily separable from polyamide to allow recycling of all parts to take place individually. [19]

Green-Loop project are integrating "recycling" of process waste back into injection moulding processes and focusing on the widest circularity loop of "organic" recycling. Their biobased polymer focus is predominantly PHA. [21]

ReBioCycle are developing a portfolio of bioplastic sorting and recycling technologies – focusing on PLA. PHA and biocomposites, keeping the polymer value as high as possible and assessing integration with current waste management practices. Technologies under investigation include mechanical, chemical, microbial and enzymatic systems.[20]

Conclusions

In summary, the recycling of bioplastics is not just a desirable goal, it is an essential part of delivering the transition to a circular economy. Composting and biodegradation have a role to play in managing the end-of-life of these materials, but keeping the raw materials in circulation for as long as possible will have several benefits including reducing costs, reducing requirements for biomass in competition with food, and reducing CO_2 emissions. The best route for recycling bioplastics is not yet clear, with several competing technologies in the running, but the ultimate solutions need to balance minimising energy input with maximizing output value.

There are several complex, interlinked challenges that must be resolved for recycling of bioplastics to become a viable end-of-life option in the circular economy. Promising work is ongoing led by a variety of academic and industrial researchers to resolve as many of those individual challenges as possible, but ultimately policy action at a national and international level will be required to make the large-scale changes needed in standardization and infrastructure development. As bioplastic manufacturing and use starts to mature, these decisions and actions become more urgent.

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