Polylactic acid in food packaging materials

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Table of content

Executive summary

Plastic packaging plays a crucial role in modern consumer goods by protecting products and reducing food waste. However, its widespread use, particularly in single-use applications, presents significant environmental challenges due to low recycling rates and reliance on fossil-based materials. The need for sustainable alternatives has driven the development of biobased plastics (hereinafter referred to as bioplastics), particularly polylactic acid (PLA), which offers biodegradability, a strong safety profile, and suitability for food packaging applications.

This report explores the potential of PLA in the food packaging industry, focusing on material properties, production processes, and commercial viability. PLA is currently derived from first-generation (1G) feedstocks such as corn and sugarcane, but concerns about competition with food resources have led to increasing interest in second-generation (2G) feedstocks, such as agricultural residues and food waste, and third-generation (3G) options, like algae. While these alternative feedstocks offer sustainability benefits, challenges related to material performance, processing complexity, and economic feasibility remain.

PLA exhibits strong mechanical properties, transparency, and food safety certification, making it ideal for applications such as trays, bottles, and films. However, its brittleness, limited moisture barrier properties, and higher cost compared to traditional plastics pose challenges for widespread implementation. Innovations in material blending, coatings, and smart packaging solutions, offer promising pathways to improve PLA’s market competitiveness.

End-of-life considerations for PLA remain critical. While PLA degrades slowly in natural environments, industrial composting provides a viable disposal method. However, today’s small volumes and limited infrastructure hinders its full potential. Mechanical and chemical recycling of PLA are emerging solutions, with advancements in sorting technologies and chemical depolymerization showing promise for closed-loop recycling systems.

The techno-economic feasibility involves cost and scalability challenges associated with PLA production, particularly from second- and third-generation feedstocks. While production costs for PLA from first generation crops are competitive, alternative feedstocks require further technological advancements and infrastructure investment. However, studies suggest that integration with existing biorefinery and industrial systems could enhance economic feasibility.

As regulatory pressure on plastic waste, in particular single-use plastic, increases and consumer demand for sustainable packaging grows, PLA is well-positioned to play a significant role in the future of food packaging. Continued research, industry collaboration, and policy support will be essential to overcoming technical and economic barriers, ensuring the successful commercialization of PLA-based solutions.

Svensk sammanfattning

Plastförpackningar spelar en viktig roll i dagens konsumtionsvaror genom att skydda produkter och minska matsvinn. Samtidigt medför den omfattande användningen, särskilt för engångsprodukter, stora miljöproblem på grund av låga återvinningsnivåer och beroendet av fossila råmaterial. Behovet av hållbara alternativ har lett till utvecklingen av biobaseradplast (i.e., bioplast), där polylaktid (PLA) är ett lovande alternativ, tack vare dess nedbrytbarhet, goda säkerhetsprofil och lämplighet för livsmedelsförpackningar.

Den här rapporten utforskar potentialen för PLA i livsmedelsförpackningar, med fokus på materialegenskaper, produktionsprocesser och kommersiell genomförbarhet. PLA produceras för närvarande från första generationens (1G) råmaterial som majs och sockerrör, men risken för konkurrens med livsmedelsproduktion har lett till ökat intresse för andra generationens (2G) råmaterial, som biprodukter från jordbruk och livsmedel, samt tredje generationens (3G) råvaror som alger. Även om dessa alternativ erbjuder hållbarhetsfördelar finns det fortfarande utmaningar kopplade till materialens prestanda, komplexitet vid bearbetning och ekonomisk lönsamhet.

PLA har goda mekaniska egenskaper, är transparent och är säkert i kontakt med livsmedel, vilket gör det till ett bra alternativ för exempelvis tråg, flaskor och filmer. Däremot är materialet sprödare, har begränsade fuktskyddande egenskaper och är dyrare än traditionell plast, vilket gör att dess spridning på marknaden stött på hinder. Innovationer inom blandning av material, beläggningar och smarta förpacknings-lösningar erbjuder dock lovande vägar för att förbättra PLA:s konkurrenskraft.

Att hantera PLA vid slutet av livscykeln är en viktig fråga. Medan PLA bryts ned långsamt i naturliga miljöer, erbjuder industriell kompostering en fungerande bortskaffningsmetod. Dock begränsar dagens små volymer och brist på infrastruktur dess fulla potential. Mekanisk och kemisk återvinning av PLA är nya lösningar som växer fram, och framsteg inom sorteringstekniker och kemisk depolymerisering visar lovande resultat för att skapa slutna återvinningssystem.

Den teknisk-ekonomiska genomförbarheten innebär både kostnads- och skalbarhetsutmaningar för PLA-produktion, särskilt när det gäller 2G och 3G råmaterial. Medan PLA från 1G råvaror har konkurrensdugliga produktionskostnader kräver alternativa råmaterial ytterligare teknologiska framsteg och investeringar i infrastruktur. Studier visar dock att integration med befintliga bioraffinaderisystem och industriella processer kan förbättra den ekonomiska lönsamheten.

Med ett växande tryck på att minska plastavfall, särskilt engångsplast, och en ökad efterfrågan på hållbara förpackningar, är PLA väl positionerat för att spela en viktig roll i framtidens livsmedelsförpackningar. Fortsatt forskning, samarbete inom industrin och politiska stödåtgärder kommer att vara avgörande för att övervinna de tekniska och ekonomiska hindren, och säkerställa en framgångsrik kommersialisering av PLA-baserade lösningar.

Introduction

Plastic packaging is fundamental in modern consumer goods, providing protection, preserving freshness, and reducing food waste. Packaging applications represent the largest share, over 30%, of all plastic products and according to the *OECD's Global Plastics Outlook: Policy Scenarios to 2060* the use is predicted to more than double by 2060 (Figure 1) [1].

From a sustainability perspective, the use of plastic packaging presents significant challenges. Over 50% of plastic packaging is designed for single use, leading to vast amounts of waste that often end up in landfills, oceans, and natural ecosystems [2]. Despite advances in recycling, less than 10% of all plastic packaging is effectively recycled, due to material complexity and contamination.

The production of plastic packaging also contributes to resource depletion and greenhouse gas (GHG) emissions, as most plastics are derived from fossil fuels. Addressing these sustainability issues requires reduced plastic use, innovative design of biobased alternatives, improved recycling systems, and a shift toward a circular economy where packaging materials are reused, and waste is minimized.

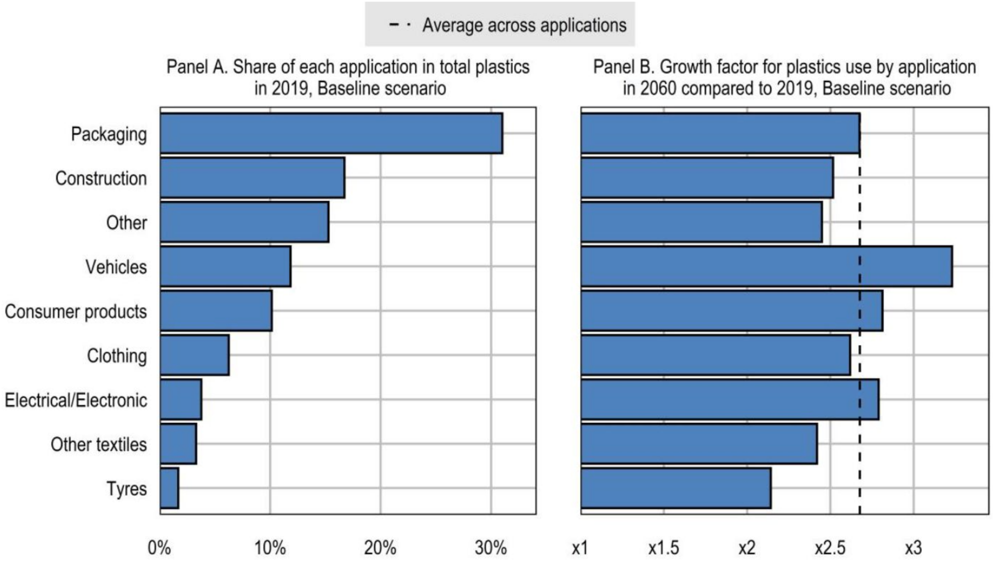

Figure 1. Plastics use and its predicted increase across different applications [1].

This report will focus on food packaging, which is currently the main application for biobased and biodegradable plastics. Fast-moving consumer goods, including food packaging, is the largest market for short-lived to medium-lived plastics and, where biobased plastics (i.e., bioplastics) have a great potential. Polylactic acid (PLA), with its suitable mechanical properties and safety profile, is particularly attractive as a replacement for conventional plastics in food packaging applications such as trays, bottles, and films [3].

1.1 Food packaging materials

Food packaging plays a critical role in maintaining food safety as well as ensuring quality and nutritional content throughout the supply chain. This is achieved through the protective function of the packaging material, that shield food from external factors such mechanical damage, light, moisture and microbes.

The material composition, design, and concept vary widely within the food packaging segment. Such variations influence both the food preservation efficiency as well as the sustainability and ecological footprint of the packaging used [4]. Other important properties are sealing and thermoforming capability, antifogging, printability, resistance to acid and grease, availability and not least cost.

The food packaging industry is rapidly evolving, driven by a growing global population and the need to balance food preservation with environmental sustainability. Traditional petroleum-based plastics, such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET/PETE), polystyrene (PS) and polyvinyl chloride (PVC), while effective, are unsustainable due to their long degradation times and reliance on fossil-based raw materials.

In response, bioplastics are gaining attention as a viable alternative, offering biodegradability and compostability. A range of bioplastics such as biodegradable polyesters, starch, cellulose-based bioplastics, and drop-in bioplastics have been proven safe for food contact use. However, most of the biodegradable bioplastics have lower tensile elongation (ductility), lower impact strength (toughness), and higher flexural modulus (stiffness) than conventional plastics [2]. In addition, most biodegradable bioplastics exhibit lower moisture barrier properties due to their hydrophilic nature, although their oxygen barrier performance is comparable to that of conventional plastics. Consequently, their initial applications are in packaging for products with rather short shelf lives.

1.2 Biobased plastics as an alternative source

Bioplastics currently represent less than 0.5% of the total plastic production [5]. Despite this, the global production capacity for bioplastics is expected to rise significantly, from 2.0 million tons in 2023 to around 5.7 million tons by 2029 [5], driven by an increasing demand for sustainable packaging solutions.

Biomass is classified as either first-generation (1G), second-generation (2G) or third-generation (3G) feedstocks. 1G biomass includes fermentable sugars from edible crops like corn and sugarcane and vegetable oils. A major concern with using 1G biomass in bioplastic production is the competition with food resources. Currently, only 0.01-0.02% of global agricultural land is used for bioplastics, but fully replacing fossil-based plastics with biomass would require over 50% of global corn production and exceed Europe’s annual freshwater withdrawal by 60% [6].

2G feedstocks are derived from non-edible biowastes and offers environmental benefits by reducing waste and reliance on non-renewable resources as well as circular value chains. 3G feedstocks include algae biomass. The use of 1G, 2G and 3G biomass to produce feedstock for bio-PLA is described in section 2.2.

Regardless of the progress in bioplastics research and development, challenges remain. The packaging materials derived from 2G or 3G feedstocks must also meet the food safety requirements, ensuring absence of harmful substances or contaminants. In addition, the quality and performance must be comparable to conventional materials which can be challenging with such varied and inconsistent waste streams [3].

Scaling up production while maintaining material quality and cost efficiency is currently difficult. Moreover, consumer acceptance of bio-based packaging depends on factors such as appearance, safety, and cost. Addressing these hurdles requires collaboration between researchers, industry, and policymakers to bridge the gap between advances in bioplastic technology and real-world applications [3].

2. Polylactic acid

Polylactic acid (PLA) is a versatile, biodegradable thermoplastic polymer (plastic) that could be used as a more eco-friendly alternative to conventional petroleum-based polymers. PLA's ability to degrade naturally over time, without leaving toxic residues, together with its safety profile makes it a good candidate for food packaging material as well as an increasingly popular alternative for reducing plastic pollution.

2.1 Introduction to PLA

PLA is a thermoplastic polyester, with a backbone configuration of $(C_3H_4O_2)_n$ (Figure 2). PLA exhibits good mechanical strength, transparency, biocompatibility, non-toxicity and biodegradability [7]. PLA can be biodegraded through industrial composting (~ 58 °C, 90% degradability within six months) or anaerobic digestion [8], see further section 4.4.

The starting material for PLA synthesis is lactic acid (LA; 2-hydroxy propionic acid). LA is an enantiomeric molecule, meaning that it has two isomers: *L*- and *D*-lactic acid (Figure 2). Whereupon the formed polymer has stereoisomers, such as poly(*L*-lactide) (PLLA), poly(*D*-lactide) (PDLA) and poly(*DL*-lactide) (PDLLA). The mechanical and thermal properties of PLA can be altered through the ratio and distribution of the two isomers (see further *Properties of PLA and Optimization*).

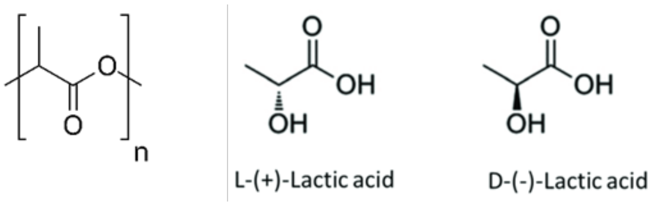

Figure 2. Chemical structure of PLA, *L*-lactic acid and *D*-lactic acid.

There are three main synthesis routes to obtain PLA: ring-opening polymerization (ROP), direct polycondensation polymerization and azeotropic condensation polymerization [9]. ROP is the most widely used method for obtaining high molecular weight PLA. Furthermore, short residence times, mild process conditions and absence of by-products are other advantages with ROP which makes it the preferred process for industrial-scale production [10].

2.2 Common feedstock sources for lactic acid

Lactic acid (LA) is an essential organic acid and a platform chemical used in food, pharmaceuticals, cosmetics, as well as being the monomer for PLA production. The widespread use of LA has led to a surge in its demand and is expected to reach 19.6 million tons in 2025 [11].

2.2.1 First-generation feedstock

LA can be generated through starch fermentation [12], [13], [14] or through chemical synthesis [15]. A majority of industrially produced LA is through anaerobic fermentation of starch-rich crops using 1G feedstocks such as, sugarcane, sugar-beets and corn [16]. Fermentation, in comparison to synthesis, has a lower environmental impact, potential to produce optically pure enantiomers and a lower production cost (especially for sugarcane fermentation) [15].

The land-use for bioplastics accounts for 0.01-0.02% of the global agricultural area (4.7 billion hectares) [17], [18], [6]. To avoid food resource competition, alleviate the pressure of cropland expansion as well as to lower the associated GHG emissions, 2G feedstocks such as lignocellulosic biomass (which should not drive deforestation) or municipal organic waste (biowaste/food wastes) and 3G feedstocks could be viable alternatives [19], [20].

2.2.2 Second-generation feedstock

In Europe, food waste is a growing concern, in 2022 around 132 kg of food waste per inhabitant were generated, resulting in a staggering 59 million tons discarded [21]. Additionally, agricultural residues have emerged as a significant environmental issue, primarily due to its potential to emit GHG when improperly managed. Utilizing these wastes (including food waste, agricultural residues, and municipal organic wastes) can reduce GHG emissions and align with the European Union’s goals for a circular economy, sustainable agriculture, and waste reduction.

Lignocellulosic biomass, derived from plant materials such as wood, straw, or agricultural residues, are abundant and are typically considered a byproduct by other industries. Lignocellulosic biomass is composed of three major components: cellulose, hemicellulose, and lignin. Cellulose and hemicellulose are polysaccharides that can be processed into fermentable sugars to produce LA. However, lignin will act as a barrier, making the breakdown of these polysaccharides more difficult. Therefore, fermenting lignocellulosic feedstock to LA is challenging without proper pretreatment, due to the recalcitrant nature of lignin [22].

Several pretreatment methods (physical, chemical, physicochemical, and biological) have been developed to enable isolation of the cellulose and hemicellulose from lignocellulosic biomass. These pretreatments technologies include processes such as acid hydrolysis, alkaline hydrolysis, organic solvent processes, ionic liquids, steam explosion, high-pressure processing, ultrasound and microwave assisted pretreatments, supercritical fluid and biological pretreatments [23]. All these methods have their advantages and limitations, ranging from high costs, negative environmental impact, and high energy requirements [23].

Moreover, the pretreatment process can lead to formation of unwanted byproducts, such as phenolic compounds, furan derivatives, and aldehydes, which can inhibit the growth of LA-bacteria during fermentation [24], [23], [11]. Therefore, the overall yield of LA from lignocellulosic biomass is often lower compared to using 1G feedstocks [25]. Achieving higher yields requires optimization of various factors, such as the type of pretreatment and fermentation conditions, which adds to the complexity of the process. Scalability also remains an issue as large-scale production of PLA from lignocellulosic biomass and food waste requires substantial investment in infrastructure and technology.

Furthermore, data on chemical composition, regional and seasonal availability of biowastes are currently lacking which also hinders large-scale production [26]. The diverse sources of food waste, ranging from crop processing to household leftovers, adds complexity to the collection and separation process, making bioplastic production from food wastes labor-intensive.

2.2.3 Third-generation feedstock

The limitations in the conversion technologies, difficulties in the collection of 2G feedstocks and high production cost of LA from 2G biomass has led to the exploration of a 3G feedstock, algal biomass.

Seaweed (macro algae) is considered a sustainable and renewable resource, as its growth rate is much faster than land-based crops and farming seaweed does not require fresh water, fertilizers, pesticides or arable land. Additionally, seaweed absorbs excess nutrients and CO_2 from the water, reducing eutrophication and GHG emissions. Furthermore, algae have a high carbohydrate composition (34-76% dry matter [27]) and a low lignin content, which reduces the issues caused by the recalcitrant nature of lignin (described in section 2.2.2). Brown algae fermentation has been used to produce ethanol, butyric acid, hydrogen and LA [28].

According to the Food and Agriculture Organization of the United Nations, the global aquaculture production of seaweed in 2020 was about 35 million tons, with Asia dominating the production (91.6% in 2020) [29]. From a north European context, brown algae such as, *Laminaria digitata*, *Alaria esculenta* and *Saccharina latissima* (Figure 3) could be suitable to aquaculture as these species thrive in cold and shallow waters [27].

Figure 3. *Saccharina latissima*, *Alaria esculenta* and *Laminaria digitata* [27]. Photo credits: Baralloco CC BY-SA 3.0; Ryan Hodnett CC BY-SA 4.0; Stemonitis, CC BY 2.5

However, in a European context, seaweed aquaculture production is not yet economically viable. In a recent review article by Bennett et al., [27] valorisation strategies for brown seaweed were covered. The study concluded that commercial production of seaweed biomass in Europe needs to target high/medium value products to enable competitiveness towards the Asian market. It was also pointed out that seaweed cultivation offers environmental, economic, and food security benefits, and that is has the potential to play a significant role in the future of Europe’s aquaculture industry [27].

To summarize, 2G and 3G feedstock options hold promise to be used as feedstocks to produce LA and PLA. However, their widespread adoption will require continuing research, policy support, and innovation to overcome existing technical and economic barriers.

2.3 Properties of PLA and optimization

Depending on the ratio of *L*-lactide and *D*-lactide enantiomers used in the synthesis, PLA may exist both as highly crystalline and in an amorphous state. Therefore, the ratio of enantiomers can be used to tailor its mechanical properties, hydrophilicity, and bio-degradation rates [33]. The steric shielding effect of the side group makes PLA more resistant to hydrolysis compared to for example polyglycolic acid (PGA) and the degradation half-life typically varies from six months to two years depending on the ratio of *L*- and *D*-lactide (i.e., degree of crystallinity) [9], [10].

The melting temperature of PLA ranges from 150 to 200 °C. PDLLA is amorphous, i.e. it has no melting point [9]. The glass-transition temperature varies between 50 to 70 °C [9]. Physical properties of PLA in comparison to PP and PET are presented in Table 1.

Table 1. Physical properties of PLA, PLLA and PDLLA in comparison with commodity polymers from Taib et al., 2023; Casalini et al., 2019; Farah et al., 2016.

Property	**PLA**	**PLLA**	**PDLLA**	**PP**	**PET**
Melting temperature (°C)	150–160	170–200	-	160–170	250–260
Density (g/cm^3)	~1.25	~1.30	~1.27	~0.9	~1.4
Tensile strength (MPa)	21–60	15–150	25–50	190	205
Elastic modulus (GPa)	0.4–0.5	2.7–4.1	1.0–3.5	2400	3800
Elongation at break (%)	2–6	3–10	2–10	110	140

Like for most polymers, properties of PLA can be improved using additives, fillers, plasticizers, blending with other polymers, physical treatments etc. Examples of PLA modifications and their effects are presented in Table 2.

A review from Yin & Woo describes the use of different types of agricultural residues to modify PLA [3]. Here, the use of for example sugar palm crystalline nanocellulose, bamboo charcoal and mango seed waste to enhance properties such as water-barrier properties, mechanical, thermal and optical properties and mechanical and barrier properties, respectively are described.

Table 2. Examples of PLA film modifications and their effects, from Malek et al., 2021 (modified)

Approach	Type of modification	Observation
Additives	Emulsifiers, stabilizers	Improved physical properties (flow behavior and particle size)
Modifiers	Polyglycerol ester	Improved elongation at break
Fillers	Nanofillers (silica, metals etc.), Natural fibers (hemp, flax)	Improved antimicrobial and UV light scattering properties, improved elongation at break, improved mechanical properties
Plasticizers	Glycerol, polyethylene glycol (PEG)	Increased toughness, improved mechanical, thermal and barrier properties, enhanced biodegradability
Compatibilizer	PLLA-Polybutylene succinate (PBS) block copolymer	Improved adhesion between blended components
Blending with polymers	Natural biopolymers (starch, cellulose)	Lowers price, decreasing T_g, increasing biodegradability and transparency
Inclusion of active compounds	Essential oils, Nisin, Thymol	Improved mechanical and antibacterial properties, oils reduce water vapor permeability and moisture absorption
Bilayer and/or trilayer films	Using biopolymers	Improved mechanical properties, enhanced barrier properties
Physical treatment	Orientation	Improvement in tensile and impact strength
	Annealing	Increased toughness
	Aging	Increased T_g

3. Applications in food packaging

Food packaging typically requires high water resistance, gas and vapor-barrier properties, and a variability of mechanical properties (depending on the type of packaging). Additionally, antioxidant or antimicrobial properties may be desirable (see further section *3.2 Smart Packaging based on PLA*).

The use of PLA in food packaging is increasing, and has been commercially adapted for dry foods, fresh produce, ready-to-eat meals and bakery goods [30]. Transparency, processability, printability and heat-sealability (valid for PDLLA) are some of the advantages of PLA for food packaging applications [31]. PLA also provides good grease and aroma barrier [30]. Furthermore, PLA is regulated as "generally recognized as safe" (GRAS) by the US Food and Drug Administration (FDA) [32]. This means that PLA is considered safe for direct contact with food.

However, a high brittleness, >10% elongation at break, and low toughness restrict its wider application [8]. Another drawback is its poor melt strength and stability, which may complicate the processing of flexible films (processes will require stretching and orientation) [8]. Lastly, PLA is currently more expensive, US$2.92/kg (European market, January 2025), than for example PET (US$1.36/kg) or PP (US$1.46/kg) [33].

3.1 Films, trays and bottles

PLA films are highly transparent and are commonly used as laminates or biaxially oriented PLA in packaging materials [34]. Films made from PLA are stiff and can be sensitive to tearing, much like cellophane or PET films.

PLA based films are highly suitable for packaging of respiring products, such as fresh vegetables and fruits. Perforation of the film can be introduced to increase the water permeation to the required level [34]. On the contrary, PLA films, without any additional barrier material, are not suitable for packaging of water sensitive products which are stored for longer periods, for example cookies and crisps [34].

Trays made from PLA are comparable to polystyrene trays. Due to the lower barrier properties of PLA, PLA is more suitable for short shelf-lives storage for example for meats, dairy products and fresh vegetables and fruits. It is also used for takeout food containers. Here, both McDonald's and Burger King have used PLA containers for their salads and sandwiches [8].

Due to the higher water permeability of PLA, bottles for long-term storage will require optimization. However, bottles made of PLA could be used for short shelf-life drinks, such as fresh juices and dairy products. PLA could also replace PS in applications such as thermoformed cups for dairy products, such as yogurt [34].

Barrier layers could be used to enhance the water barrier properties. One example is a multilayer approach with inclusion of SiO_x and could potentially be used for carbonated drinks, although currently expensive [34].

3.2 Smart packaging based on PLA

According to the Commission Regulation (EC) No 450/2009 [35]:

> *“Active and intelligent materials extend the shelf-life by maintaining or improving the condition of packaged food, by releasing or absorbing substances to or from the food or its surrounding environment”.*

These substances are purposely added to the packaging material, to give a desired function. Generally, *active* materials maintain or improve the quality of the food, for example extending shelf life by adding antioxidants or antimicrobial substances. Whereas *intelligent* packaging can be used to trace the quality, using substances (i.e., markers) that detect and/or alert if the food is at risk of being spoiled. Additionally, intelligent and active packaging can be combined to form “*smart* packaging” [36].

In a review by Nasution et al. different modifications of PLA using natural extracts were covered. Modification of PLA with for example polyphenols, vitamin C, anthocyanins and beta carotene could be used as antioxidants, whereas for example chitosan, chitin, nisin, and essential oils could be used as antibacterial agents [37].

Smart packaging has the potential to reduce food waste and increase consumer satisfaction and safety. Challenges for implementing smart packing range from product cost, compatibility between the different components, possible issues in recycling, and in some cases issues in compliance with regulatory standards [37].

4. End-of-life

Despite numerous legislative and corporate initiatives worldwide, plastics recycling remains far from reaching its full potential. Currently, only about 10% of all plastic packaging globally is recycled, with 8% being repurposed into lower-grade applications and just 2% recycled in closed-loop systems [38].

Recycling of bioplastics is considered being the most sustainable end-of-life option, as compared to composting. However, bioplastics recycling is less established than for conventional plastics and bioplastics, such as PLA, require the development of new recycling systems. Sorting of mixed plastic waste becomes even more demanding with novel (non-drop-in) bioplastics by increasing the heterogeneity [6].

There are four main approaches to recycle plastic solid waste (see Figure 4 and Figure 5): i) closed-loop recycling (primary), ii) mechanical recycling (secondary), iii) chemical recycling into monomeric units (tertiary), and iv) energy recovery via incineration (quaternary) [39].

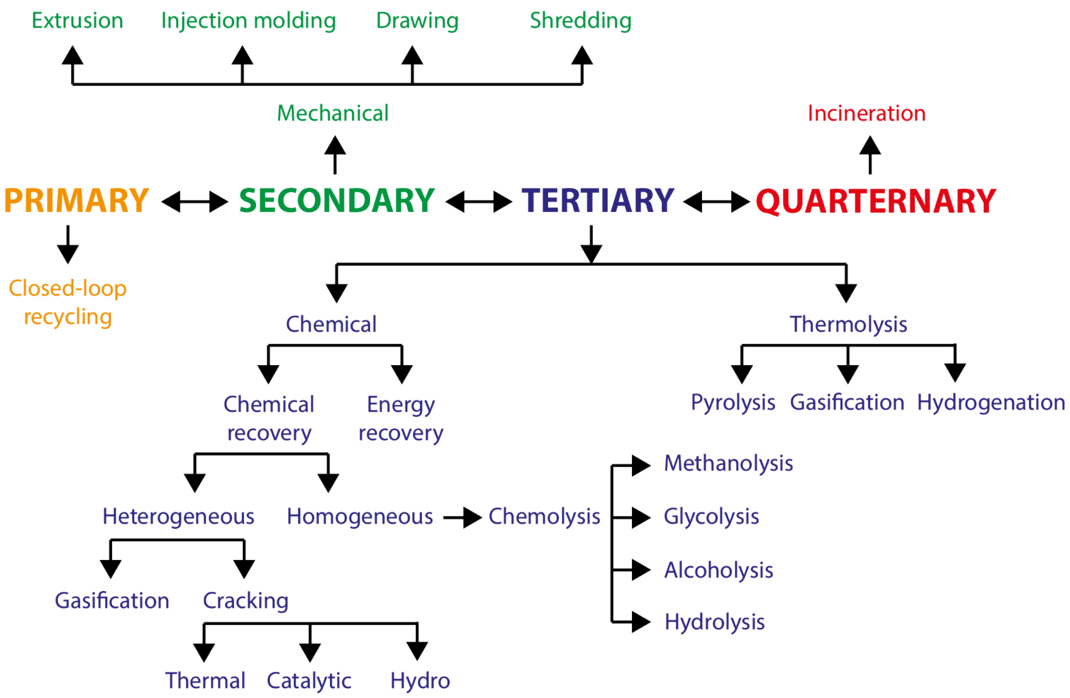

Figure 4. Various approaches for recycling of plastic solid waste [39].

4.1 Closed-loop recycling

Primary recycling refers to the closed-loop recycling of unused PLA, mainly from post-industrial polymer waste obtained during the injection or extrusion processes to generate new products. This method is widespread in industrial manufacturing to reduce waste and revalorize virgin material into high-quality products [40].

4.2 Mechanical recycling

Mechanical recycling on the other hand refers to end-of-life material where the PLA is reprocessed into new products. Such streams can be both contaminated, partially degraded and mixed with other materials and need to go through several recovery steps, such as collection, separation, shredding, washing to remove contaminants and drying before the granulation and final recasting into products [41], [42].

To facilitate plastic waste management and minimize contamination from other plastics, spectroscopic techniques such as near-infrared (NIR) scanners can be used to selectively identify bioplastics in the sorting process. It has been shown that PLA specifically, can be identified with 98% accuracy and PLA does not influence the sorting process of conventional plastics regarding detection and classification [43]. However, sorting of PLA is as of today not viable due to the small volumes in post-consumer plastic waste [44].

Mechanical recycling is considered being an energy and cost-efficient option but, compared to other polyesters, PLA degrades more easily during processing. High temperatures and moisture significantly reduce the quality, such as loss of tensile strength and molecular weight. Polymer degradation, in combination with the inability of mechanical recycling to effectively remove contaminants and additives, results in products that are generally ‘downcycled’ into goods of lower quality [6].

To improve the properties of mechanically recycled PLA, antioxidants and anti-hydrolysis agents can be added initially and chain extenders added during processing [45]. Chain extenders can, to some extent, recover the polymer chain length and other mechanical properties, making the recycled PLA more comparable with virgin PLA [46]. Currently, PLA can only be recycled up to three times before its molecular weight drops by over 50%, causing a severe decline in mechanical properties and ductility. Another option is to mix the recycled material with virgin PLA to allow for quality improvement.

4.3 Chemical recycling

A promising alternative to mechanical recycling is chemical recycling, in which PLA is broken down to the monomer building blocks. This method can handle partially degraded polymer, higher contamination levels and produces high-quality recycled material.

Chemical recycling is primarily performed through either solvolysis or thermolysis. In solvolysis, polymers with cleavable groups along their backbone, such as ester bonds in PET, PEF and PLA, can be subjected to solvent-based depolymerization processes including hydrolysis, pyrolysis, alcoholysis, and ammonolysis [6].

PLA is highly hydrolysable and can be hydrolyzed to 95% LA without a catalyst at 160–180 °C for 2 h with an energy demand 4 times lower compared to virgin LA production [47]. PLA can also be depolymerized to yield about 90% cyclic lactide monomers after 6 hours with the use of Zn transesterification catalysts, providing high-quality feedstock for plastic production [47]. However, the required chemicals and complex separation processes makes chemical recycling energy-intensive and costly, which limits its economic competitiveness compared to mechanical recycling. Consequently, chemical recycling is currently most viable in applications where high purity is essential [42].

TotalEnergies Corbion has launched the world’s first commercially available chemically upcycled PLA [48]. The product contains 20% chemically recycled PLA with the same properties as the virgin PLA and is food contact certified. In addition, NatureWorks’ manufacturing facility in Blair, Nebraska, has hydrolyzed over 17 million pounds (~ 7.7 million kg) of off-grade PLA waste and reused it to synthesize PLA resin [49].

4.4 Biodegradation and composting

Although PLA is a biodegradable polymer, the degradation rate is very slow in both soil and seawater in ambient conditions. After one year in a marine environment at 30 °C PLA only biodegrades by about 8% [45], i.e., PLA will not naturally degrade if left in the environment and should therefore be disposed in an appropriate manner.

In order to induce PLA biodegradation, a favourable environment of high temperature, humidity and in presence of appropriate microorganisms is essential.

The PLA degradation under composting conditions involves two-steps, i.e. i) hydrolysis (abiotic process), followed by ii) digestion to end-products by microorganisms (biotic process). The last step can be under aerobic or anaerobic conditions.

In household composting, which typically occurs at mesophilic conditions (~28 °C), the temperature is too low to efficiently initiate PLA hydrolysis and promote consumption by microorganisms. Industrial composting on the other hand, where the temperature is maintained at thermophilic conditions (~ 58 °C), PLA can fully degrade into CO_2 and H_2O within 90 days [42].

Although recycling may be more energetically favourable compared to composting for PLA products, composting could be more practical, as sorting and cleaning is not required [50].

As an alternative to composting, microorganisms and their hydrolyzing enzymes can be used for partial biodegradation where PLA is depolymerized into monomers, instead of CO_2, similar to chemical recycling [51]. Such biological processes are still underexplored but could potentially be a milder and cleaner option to the chemical approach.

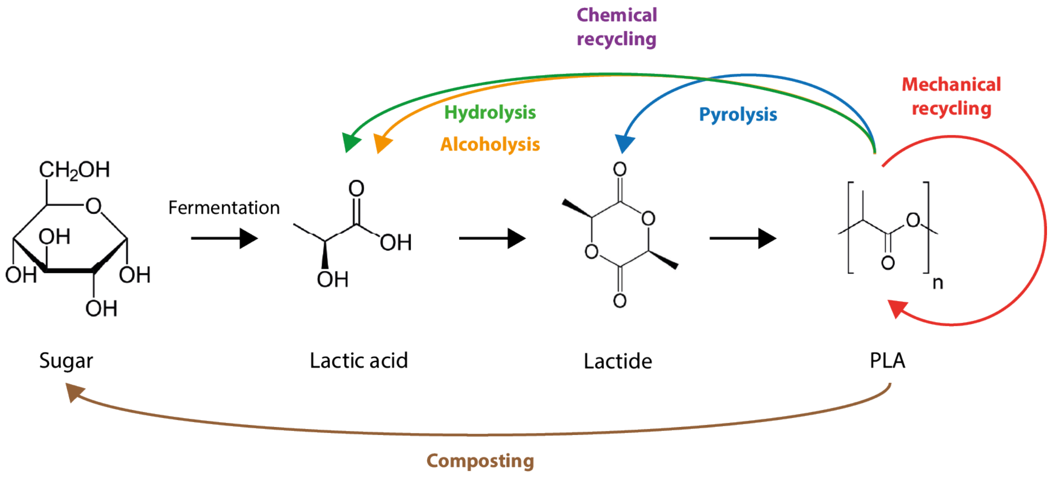

Figure 5. PLA formation and potential end-of-life scenarios [51].

5. Life cycle assessment

As sustainability is a major concern and one of the main arguments for an increased use of biobased plastics, many studies have focused on life cycle assessment (LCA) and comparisons between fossil-based and biobased polymers. However, it turns out that the complexity and the decisions made during the assessment makes it very difficult to draw reliable conclusions, which was shown, e.g., in a review where 39 fossil-based and 50 biobased case studies were compared. The results showed significant variation in impact between polymers across the seven impact categories (energy use, ecotoxicity, acidification, eutrophication, climate change, particulate matter formation and ozone depletion) for which sufficient data was available, both between fossil-based and biobased categories, between individual polymers within each category, and between different studies of the same polymer [52]. In the end, it was not possible to conclusively declare any polymer type as having the least environmental impact in any of the categories.

The large differences in LCA results are true also when looking specifically at PLA, which was concluded in a meta-analysis of over 80 LCA and carbon footprint studies of PLA [53]. The reason behind the discrepancies is mainly a result of how biogenic carbon is accounted for, as well as other choices made by the authors involving choice of feedstock, electricity mix, end-of-life option etc. When looking at cradle-to-gate scenarios, the median global warming potential (GWP) for PLA was 1.63 kg CO_2 eq./kg PLA, which is lower than the average fossil-based polymer. However, when looking at cradle-to-grave studies, the median value of PLA was 3.91 kg CO_2 eq./kg PLA, which is comparable to fossil-based polymers. It is worth to note that the version of the LCA database plays a significant role when evaluating PLA and other emerging biopolymers. As PLA processing is gradually becoming more efficient an older software version could overestimate the impact.

The most energy-demanding process step for PLA is the conversion from biomass to LA [54]. From a value chain perspective, the type of biobased resource (crop) will influence both the conversion process as well as other environmental impact categories, such as land- and water use. As an example, the Institute for Bioplastics and Biocomposites published some data for PLA, showing that wheat requires less feedstock compared to, e.g., sugar cane and sugar beet, however, requires a significantly larger amount of land and water [55].

In summary, the environmental assessments of PLA compared to other plastics are complex and largely dependent on decisions made by the evaluators, e.g., on which impact categories that are prioritized (most often primary focus is on GHG emissions). Thus, there is a need to further develop standardized protocols, such as the European Union Product Environmental Footprint (EU PEF) standards, to make the assessments more comparable.

6. Techno-economic analysis

The techno economics of producing PLA depends much on the type of feedstock used, i.e., 1G (starch- or sugar-based), 2G (lignocellulosic biomass), and even 3G (algae, CO_2 etc.) materials. The feedstock prices, conversion efficiencies, and economies of scale has a large impact on the market feasibility for each process.

1G, such as corn and sugarcane, are currently the ones used for commercial PLA production. These sources are rich in fermentable sugars and there are well-established technologies to convert these to LA. The process benefits from mature agricultural supply chains, however, some concerns have been raised about food security, land use, and GHG emissions associated with intensive farming practices [56]. While the production costs for PLA from 1G feedstocks are competitive, they are vulnerable to fluctuations in crop prices and policy shifts related to biofuels and bioplastics.

The process of developing techno-economic analysis (TEA) can be complex as input data to technoeconomic evaluation is often limited and there are no databases with average production costs for certain polymers. Thus, existing data are often based on individual case studies. Apart from the type of feedstock, other decisions in the technoeconomic evaluation, such as the system boundaries and the capacity/scale of production will have a large influence on the results, see for example the comparison of literature results below.

This report is more focused on 2G types of feedstocks, which do not directly compete with food production. These types of biomasses (e.g., agricultural residues, lignocellulosic biomass) often requires a pretreatment to break down the lignin and release fermentable sugars, which adds complexity and cost. As an example, a technoeconomic comparison between corn grains (1G) with corn stover (2G) using Monte Carlo simulations showed that despite higher energy requirements, it was estimated that corn stover-based PLA already was competitive with corn grain-based PLA in terms of variable costs, resulting from the lower costs of feedstock procurement. However, the fixed costs were much higher for corn stover and overshadowed the advantages of being a secondary resource [56].

There are more examples of where production of PLA from side-streams from food have shown both promising sustainability as well as techno economic feasibility. One study compared using corn glucose syrup, corn stover and sugar beet pulp (SBP) as feedstock for PLA and resulted in good values for a biorefinery using SBP as feedstock [57]. The minimum selling price for PLA in this case was estimated to 1.14 USD/kg PLA. Another study focused on the integration of PLA production with a typical Brazilian ethanol distillery, with sugarcane juice as feedstock [58]. The minimum selling price for PLA in this case ended up at 1.58 USD/kg, which also is well below the estimated market price. Another specific example investigated the techno economy of using food waste as a resource for making PLA for a hypothetical plant located in Hong Kong, producing 10 metric tons per hour and with a 20-year lifetime [59]. The process was found to be economically viable with a conversion yield for PLA of 1.3 tons/10 tons feedstock and with a minimum selling price of 3.33 USD/kg.

In summary, the more sustainable 2G feedstocks are desired and ongoing advancements with new types of thermal-chemical pretreatments and enzymatic hydrolysis improves the feasibility of utilizing these feedstocks. However, the scale of production remains limited as the capital investments costs are high and there are still challenges in achieving high yields of LA. Further development of technological processes (e.g., more efficient catalysts etc.) as well as integration with existing industrial infrastructure could help reduce costs in the future.

7. Concluding remarks

The growing demand for sustainable packaging solutions, combined with increasing regulatory pressure on single-use plastics, creates a strong market opportunity for bioplastics such as PLA. With its biodegradability, food safety certification, and versatility in applications such as films, trays, and bottles, PLA presents a viable alternative to conventional petroleum-based plastics. Additionally, advancements in material optimization, including the incorporation of additives, coatings, and multilayer structures, are enhancing PLA’s functional properties, making it more competitive in broader food packaging applications.

Despite its potential, commercial scalability remains a challenge due to the high production costs, limitations in barrier properties, and mechanical performance compared to traditional plastics. The reliance on first-generation feedstocks raises concerns over food security and land use, but ongoing research into second- and third-generation feedstocks, such as agricultural residues, food waste and seaweed, presents promising pathways for cost reduction and sustainability. Successful commercialization will depend on further investment in production infrastructure, supply chain optimization, and improvements in bioplastic recycling systems to support a circular economy.

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