# Biodegradable Polymers, Blends and Biocomposites
## Trends and Applications

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# Chapter 11
# Circular Economy on Bioplastics and Biobased Polymers



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# 11 Circular Economy on Bioplastics and Biobased Polymers

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## 11.1 INTRODUCTION

The annual increase in world population poses challenges to global food security and environmental issues, both of which have an impact on the feasible development targets (Talan & Tyagi, 2020). The use of non-renewable resources to generate energy depletes natural resources and contributes to the release of greenhouse gases, which harms the environment. As a result, these global challenges necessitate an immediate solution, with the circular bioeconomy playing a major part in a low-carbon economy that will undoubtedly aid in the resolution of these issues (Leong et al., 2021).

Plastics manufacturing surged from 245 million metric tonnes in 2008 to 359 million metric tonnes in 2018 and is anticipated to triple by 2050, accounting for over a fifth of world oil usage (Chia et al., 2020). Despite the enormous manufacture of plastics ever since 1950s, no viable strategy for dealing with the disposal challenges caused by plastic waste has been implemented. Plastic recycling rates are poor when compared to the amount of plastic produced, with the majority of it ending up in landfills. Plastics are the most difficult to decompose when compared to aluminium, papers, fruits, and leathers. This is due to the persistence of plastics in nature for centuries before degrading (X. Chen & Yan, 2020).

Inadequate active solid-waste management to identify plastic waste results in serious environmental, human, and animal health problems. As a result, there is a lot of interest in the development of bioplastics, which are biodegradable and derived from plant, animal, and microbial sources (Kalia et al., 2000).

Biobased resources for plastic production are an alternative to fossil-based resources. The benefits of using biobased plastics include the conservation of fossil resources and the elimination of carbon dioxide emissions. Biobased plastics, in comparison to fossil-based plastics, have the possibility for a closed-loop in a truly circular economy because the biogenic carbon taken up by a plant is released back into the atmosphere after use (Spierling et al., 2018).

Bioplastics, also known as "biopolymers" have been the subject of significant research and debate on a global scale for quite some time. The scarcity of fossil fuels drives the development of biobased products, while the potential to reduce pollution and ease organic waste collection stimulates the development of biodegradable and compostable plastics (Di Bartolo et al., 2021). Bioplastics are already being used

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in the market as packaging, compost bag, and carriers; they are also used in agriculture and horticulture industries, as well as the automotive and electronic industries. Bioplastics are critical for increasing sustainability, which can be defined as a balance between a firm's economic, environmental, and social aspects and can be applied to a wide range of disciplines (Yadav et al., 2020).

To increase the efficiency of resources and management of wastes, it is essential to elevate and follow a circular economy. In place of fossil fuels, alternatives such as biomass, municipal waste streams, and industrial waste streams can provide a sustainable carbon supply (Yadav et al., 2020). It will not only benefit the environment by lowering the waste disposal expenditure and wastes, but it will also help cut overall production expenses by using wastes as substrates (Jiang et al., 2012). The usage of non-renewable materials and the production of wastes are reduced in a circular economy, while the reprocessing and regeneration of the materials are enhanced (Rosenboom et al., 2022).

This chapter mainly concentrates on the detrimental effects of using conventional plastics and the role of bioplastics and biobased polymers in a circular economy. The different biobased polymers are also discussed, along with the end-of-life treatment options for bioplastics.

## 11.2 DETRIMENTAL EFFECTS OF USING CONVENTIONAL PLASTICS

In today's world, one of the most serious environmental issues that humans face is uncontrollable plastic pollution caused by the production of numerous plastic wastes. The varieties of plastic products that are available in the market are made up of imperishable materials, mainly polyethylene and polypropylene. These two materials are the dominant polyolefins in the market (Plastics Europe, n.d.). In 2017, about 8300 metric tons of plastics were generated globally. Plastics that are chemically synthesised do not degrade and thus end up in landfills (Geyer et al., 2017). According to the reports of the United Nations Environment Programme (UNEP), out of all the plastics generated, about 9% of the plastics are recycled while 12% of the plastics are ignited (UNEP, 2016). The remaining plastics are dumped into the environment and thereby polluting the land as well as the marine environment.

The most prevalent cause of garbage generation in the world is packaging, which generated 146 million tonnes of waste in 2015. Out of 146 million tonnes, 141 million tonnes of waste were not recycled (96.6%). Additionally, the operating life of any industrial plastic component is the shortest for packaging (Geyer et al., 2017). Single-use plastics may only have a brief shelf life of a few minutes. Around 80% of the plastic trash that ends up in the ocean originates on land, usually from kerbsides and poorly maintained landfills that are destroyed by wind and sea tides (Gallo et al., 2018; Jambeck et al., 2015). Every year, almost 2 million tonnes of plastic garbage is washed into rivers in both developing and developed countries, due to a lack of effective collection and waste treatment infrastructure (Jambeck et al., 2015; Lebreton et al., 2017; Schmidt et al., 2017).

Plastic waste is highly persistent in the natural environment, mainly in seawater it is expected to take hundreds to thousands of years to break down (Gallo et al., 2018;

UNEP, 2016). Plastic waste in marine has a significant and negative impact on the ecology (Gregory, 2009). Plastic trash, with its extended half-life and hydrophobic nature, provides ideal circumstances for the expansion of different microbial species, thereby generating a "plastisphere" ecosystem. The plastic wastes are converted into minute residual forms called microplastics through UV-light degradation, microbial action, heat, and mechanical stress (Andrady, 2011). These microplastics are available in enormous amounts to wildlife, birds as well as numerous aquatic organisms (Andrady, 2011). Subsequently, these microplastics enter the food chain and, thus, pose a high threat to human health (Rochman et al., 2015; Smith et al., 2018).

Because of the microplastics particulate nature, these particles have the potential to absorb and carry pollutants such as hydrophobic organic chemicals like polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and microplastics transport pathogens from one location to another (Ziccardi et al., 2016). Most marine microplastics (98%) arise from soil sources, notably from washing textile clothing (especially from Asia) and stripping of car tyres (predominantly from North America) (Boucher & Friot, n.d.; Henry et al., 2019; Jan Kole et al., 2017). Although there are now too little microplastic fragments in freshwater to cause harm, but increasing levels can have negative consequences (Ziccardi et al., 2016). When exposed to increased quantities of microplastic particles, freshwater organisms such as worms, amphipods, oysters, and crabs showed decreased development, inflammation, and cognitive function (Crump et al., 2020; Straub et al., 2017; Von Moos et al., 2012). The sources of information regarding the trophic transmission of microplastics include measurements of the amount of microplastics in field-collected species and controlled feeding experiments that aimed to replicate the transfer of microplastics through a synthetic food chain (Carbery et al., 2018). In some sea-floor ecosystems, gravitational sinking and bottom currents result in localised and concentrated deposits of microplastics (Kane et al., 2020).

To solve plastic pollution, we can increase the recycling and reusing processes of already manufactured plastics. Moreover, we can replace several classes of plastic items, particularly single-use products, with recyclable alternatives. A shift in our society's mentality and habits is also important factor to curb plastic pollution. At the same time, fossil resources are limited, and their consumption results in greenhouse gas emissions. Plastics made from renewable resources have been proposed as a way to reduce carbon emissions by absorbing carbon dioxide during their growth and to reduce the economy's reliance on fossil fuels. As part of technological advancement in the bioeconomy, the use of biodegradable plastics in specialised domains such as soil cover films, carrier bags, and single-use packaging is also suggested.

## 11.3 CIRCULAR ECONOMY

The circular economy, in broad terms, is an economic and production model that aims to maximise resource reuse and recycling, thereby extending product life cycles while minimising waste. The model was conceived as retaliation to the traditional economy, the linear economy, in which resources are used to generate products which are used and discarded as waste. The circular economy is a viable alternative to the classic linear economy model of manufacture, use, and discard. In the circular economy, resources are kept in use for as long as possible in order to maintain product,

component, and material effectiveness and value at all times. Businesses can get the most value out of the things their customers use if they do it this way. The product and materials can then be recovered and regenerated after their maximum value has been attained. The circular economy is designed to be redeemable and regenerative, mirroring the biological world. Natural materials disintegrate into simple building elements, which can then be repurposed for new purposes.

A true circular economy is determined by renewable sources such as raw supplies and renewable energies and not by fossil resources (European Bioplastics, n.d.). In context of plastics, the aim of circular economy should be to utilise resources that are non-polluting in nature. The plastic items should be recycled more, and the post-use treatment of plastics should be based on reuse, recycling, and other environmentally acceptable disposable methods.

The European Commission's Circular Economy Action Plan, which was released in 2020, defines the main directions in which the economic model is evolving. Few main points of the document are briefly summarised here—Reusability and recyclability should be considered while designing products, which means they should be more durable, repairable, and recyclable. Packaging will be reduced, limited to certain applications, and made recyclable. Single-use item manufacture will be limited, and the disposal of unsold objects will be prohibited. Finally, importance will be given to the biobased sector because it enables greater circularity in plastic industry. However, it should be noted that sourcing, labelling, and use of biobased, biodegradable, and compostable plastics are emerging challenges for which the European Commission will develop a policy framework in the coming years.

The three components of the circular economy are preserving and enhancing natural capital, optimising resource outputs, and fostering system effectiveness (Di Bartolo et al., 2021). These three elements are the foundations of the circular economy's success. To protect and increase natural capital, society must regulate the use of finite resources while also balancing and promoting the rise of renewable resources. Resources must be carefully chosen and then processed utilising cost-effective technologies and procedures. These methods promote the flow of nutrients throughout the system, resulting in better regeneration conditions.

Within the circular economy, optimising resource yields entails the cycling of high-value products, components, and materials for both technical and biological cycles. It also entails going beyond Design for Manufacturing methods to include refurbishment and recycling in the design process. When manufacturers adopt these design principles, their products have a longer lifespan and are more suited for reuse. Businesses, governments, and consumers must manage land use, as well as water, air pollution, and climate change, in order to enhance system effectiveness—the final tenant of the circular economy. Managing these externalities helps to protect renewable feedstocks while also limiting the use of scarce resources.

## 11.4 BIOPLASTICS AND BIOBASED PLASTICS

The word "bioplastic" is regularly used interchangeably with the term biodegradable. Some bioplastics are biodegradable; however, now no longer they all are. Bioplastics are described as polymers that meet either one of the criteria: they may be biodegradable or they may be biobased (Tokiwa et al., 2009). The term "biobased" refers

to a polymer which is made completely or in part from biomass, which includes any type of organic renewable material of biological source as well as organic waste. The term "biodegradable" refers to a material that can be broken down by microbes into natural substances such as biomass, water, and carbon dioxide. A biodegradable plastic, in a more particular sense, is a plastic substance that meets certain official biodegradability requirements, where a certain percentage of decomposition must be scientifically observed within a set length of time and under specific conditions. A biodegradable plastic, meanwhile, undergoes biodegradation in industrial composting facilities and must adhere to strict guidelines. Thus, bioplastics can be divided into three categories: biobased and biodegradable, solely biobased, and only biodegradable. Polylactic acid (PLA) (Garlotta, 2001; Madhavan Nampoothiri et al., 2010), biobased polybutylene succinate (bio-PBS) (Xu & Guo, 2010), and polyhydroxyalkanoates (PHAs) (Chanprateep, 2010) are few examples of bioplastics having both biobased and biodegradable nature. Apart from this, plastics made from starch, chitosan, cellulose, and lignin are other examples of biobased and biodegradable bioplastics. Biobased polyamides (bio-PP), polyethylene terephthalate (bio-PET), and polyethylene (bio-PE), are examples of bioplastics that are biobased but not biodegradable (Siracusa & Blanco, 2020). Bioplastics such as polycaprolactone (PCL) (Labet & Thielemans, 2009), polybutylene adipate terephthalate (PBAT) (Ferreira et al., 2019), PBS, and polyvinyl alcohol (PVA) (Aslam et al., 2018) are procured from fossil resources but are biodegradable in nature (Figure 11.1).

Polyethylene and other conventional polymers are fossil-based and long-lasting. It is also important to differentiate biobased plastics into two types – drop-in types and chemical unique types. Drop-in kinds are biobased plastics, such as bio-polyethylene terephthalate (bio-PET) or Bio-PE, that have the same chemical structure as their traditional counterparts and change solely in terms of feedstock (Di Bartolo et al., 2021). As a result, the processing of plastic products as well as the recycling procedures are

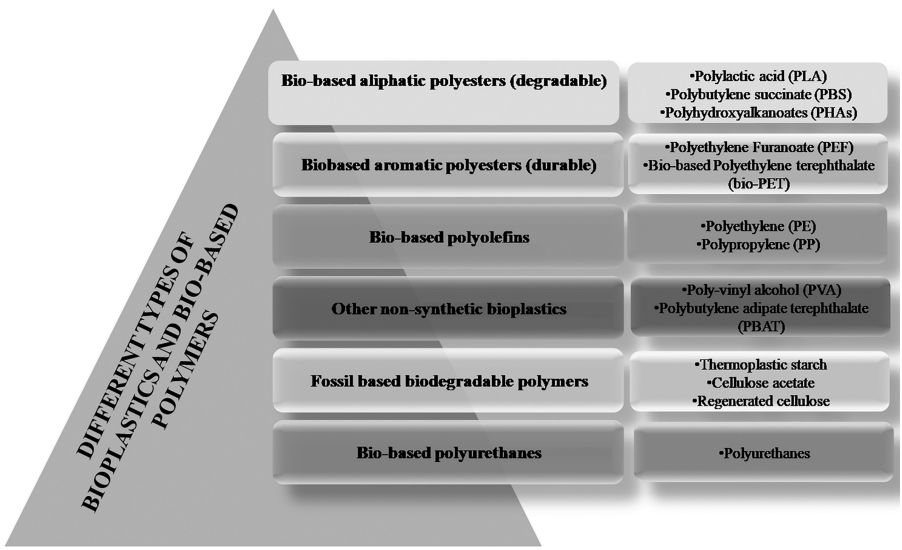


**FIGURE 11.1** Different types of bioplastics and bio-based polymers.

the same for drop-ins, and the conventional infrastructure can be used in the same way. Chemical novel kinds such as PHA and PLA have no direct conventional counterparts and have their own set of features. As a result, they are typically unable to be integrated into current traditional recycling systems (Di Bartolo et al., 2021).

To date, the scientific community has developed four scientific methods for producing these environmentally friendly, sustainable, and biobased plastics. The methods are (i) partial alteration of naturally occurring polymers (starch, cellulose, pullulan); (ii) fabrication of bioplastics by growing and adapting microbial colonies isolatedfrom natural environments or developed through genetic engineering (PHA, PHB) (Mohanrasu et al., 2018; Nikodinovic-Runic et al., 2013); (iii) Monomers are made by de novo or fermentation methods from raw materials using traditional chemical procedures, with polymerisation occurring later (PLA, polyethylene); (iv) manufacturing of bioplastics by using polymers which are partially biodegradable such as PBS, PBAT, etc. (Rosenboom et al., 2022).

When compared to the size of the conventional plastics sector, the volume of bioplastics produced today is rather small. According to European Bioplastics, global bioplastic output was roughly 2 Mt in 2018, whereas global plastic production was around 360 Mt. Simultaneously, the global market for bioplastics is expected to increase rapidly over the next five years, increasing in volume by roughly 40%. Various types of bioplastics are already on the market and are manufactured by firms in Europe, the United States, and Asia. Corbion N.V. (Netherlands), Tianjin Guoyun (China), BASF (Germany), CJ Cheil Jedang (Korea), NatureWorks LLC (USA), and Novamont (Italy) are the most prominent manufacturers of bioplastics. Cellophane™ made from regenerated cellulose by Futamura Chemical Company (UK), and Nylon-11, made from castor oil by various producers, are two historically successful examples (Di Bartolo et al., 2021).

Building and construction, as well as flexible and rigid packaging, are among the application fields of bioplastics. Biobased plastics, such as bio-PET, account for the majority of the overall market share. Short-life uses, such as flexible and rigid packaging, currently account for around 70% of all applications. Long-term uses such as construction and building make up a minor portion of the total. Long-term applications are said to be hindered. The end-of-life possibilities of biobased plastics, as well as the application of the circular economy idea, are significant due to the focus on packaging and short life cycles.

## 11.5 TYPES OF BIOPLASTICS AND BIOBASED POLYMERS

### 11.5.1 Biobased Aliphatic Polyesters (Degradable)

The ester groups in the backbones of the aliphatic polyesters are easy to be cleaved by enzymatic activity or hydrolysis process. This helps in quickly degrading the aliphatic polyesters. PLA, polybutylene succinate (PBS), and polyhydroxyalkanoates (PHAs) are the most prevalent biobased aliphatic polyesters.

PLA is an aliphatic homopolymer with a production capacity of about 250,000 tonnes per year, making it the most cost-effective synthetic bioplastic (Chafran et al., 2019; Hottle et al., 2017; Morão & de Bie, 2019). PLA is commonly manufactured by lactic acid polycondensation, which is generated from sugar fermentation,

or by ring-opening polymerisation of lactide, which is a cyclic dimer of lactic acid (Dusselier et al., 2015; Penczek et al., 2003). PLA is optically clear and has been used as a substitute for polyolefin films and polystyrene foams, as well as in single-use goods. PLA, on the other hand, is brittle and difficult to crystallise due to its small repeat unit and methyl side group. Before being treated, PLA is usually changed and mixed (for example, with additional biodegradable polymers or nucleating agents) (X. Chen & Yan, 2020).

Compared to other aliphatic copolyesters, PBS has a more adaptable molecular structure than PLA due to its longer hydrocarbon repeat units. As a result, PBS has similar material properties to polyolefins, such as reduced glass transition temperature and increased elongation at break (>500%) (Rosenboom et al., 2022). Although the feedstocks used to make PBS are often non-renewable, but the monomers of PBS, that is, butanediol and succinic acid, can be derived from sources which are environmentally friendly and renewable in nature. The generation of succinic acid from lignocellulosic sugars is being researched, and hydrocracking of starches and sugars yields butanediol (Dechent et al., 2020; Xu & Guo, 2010).

In the coming years, it is anticipated that the commercial market for PHAs, a novel class of biodegradable aliphatic polyesters, will increase to more than 100,000 tonnes annually (Tullo, 2021). PHAs may be produced by a variety of bacteria, including *Pseudomonas* and *Ralstonia*strains, as well as algae, rather than chemical synthesis (Mendhulkar & Shetye, 2017; Mohanrasu et al., 2018, 2020, 2021). PHAs are stored intracellularly by these microbes at up to 80% of their cell capacity (Künkel et al., 2016). Various carbon-rich feedstocks, such as affordable food scraps and liquefied plastic wastes, can be employed for culture, demonstrating the biological PHA production process' use in permitting circularity (Medeiros Garcia Alcântara et al., 2020; Nikodinovic-Runic et al., 2013). Most PHAs decay faster than PLA, making them appealing for applications that need biodegradation.

### 11.5.2 Biobased Aromatic Polyesters (Durable)

Polyethylene furanoate (PEF), a high-performance plastic similar to PET, is expected to enter the market in the coming years. The slightly altered semi-aromatic structure of PEF results in a higher glass transition temperature, gas diffusion barrier, and tensile strength, which could be beneficial for long- term storage packing (Loos et al., 2020). PEF, on the other hand, is more thermally sensitive and thus requires more care during processing (Burgess et al., 2014; Rosenboom et al., 2018). Under particular industrial composting settings (within nine months), PEF biodegrades faster than PET but is otherwise regarded as an equally durable polymer with less biodegradation in the environment (Loos et al., 2020). PEF is made by polycondensing the bio-derived monomers monoethylene glycol and 2,5-furandicarboxylic acid in the same way that PET is made (Rosenboom et al., 2018).

Alternately, cyclic PEF oligomers can be converted into PEF using ring-opening polymerisation, which can speed up reaction times and enhance molecular weight control (Carlos Morales-Huerta et al., 2016; Fleckenstein et al., 2018; Rosenboom et al., 2018). To optimise the glass transition temperature, mechanical strength, and

degradability of PEF (Righetti et al., 2020; Terzopoulou et al., 2017), various molecular modifications and copolymerisations are being investigated. However, producing the monomer 2,5-furandicarboxylic acid at a low cost remains a challenge (Sajid et al., 2018).

PET with a bio-derived drop-in variation is known as bio-PET. Because of its similar qualities, it may be used directly in the textile (two-thirds) and beverage (one-third) markets (Pudack et al., 2020), as well as in PET recycling processes. PET can be manufactured by esterification of terephthalic acid with ethylene glycol. The terephthalic acid can be generated by microbes from biomass via. intermediates like para-xylene and 2,5-furandicarboxylic acid (Sajid et al., 2018).

### 11.5.3 Biobased Polyolefins

Polyolefins, such as PE and PP, account for more than half of all worldwide plastics production and more than 90% of all packaging materials (Hees et al., 2019). Because of their superior chemical stability and tailorable mechanical qualities, they are widely used. Chemically, biobased PE is similar to PE, thereby making it useable and recoverable on the current technologies as well as future recycling methods like thermolysis (Hees et al., 2019). Ethylene can be produced by number of methods such as conversion of methanol to olefins, ethanol dehydration from sugarcane and biomass steam cracking (Harmsen et al., 2014; Wang et al., 2020).

### 11.5.4 Fossil-Based Biodegradable Polymers

PVA is a widely used water-soluble polymer(1.2 Mt per year). Ethylene, used to make PVA, is commonly extracted from fossil energy but can also be derived from bioethanol. PVA is a single vinyl polymer that degrades quickly by the process of hydroxyl groups being converted to diketones, which are subsequently hydrolysed and cleaved (Ben Halima, 2016; Kawai & Hu, 2009; Matsumura et al., 1993).

PBAT is a biodegradable aromatic, aliphatic copolyester supplied by BASF (BadischeAnilin & Soda Fabric AG) Company (Germany) as Ecoflex and by many Asian vendors under various brand names. It is utilised in agricultural mulch films, which can take up to nine months to breakdown in the soil (Künkel et al., 2016; Zumstein et al., 2018).

Several biomedical applications have been explored for degradable fossil-derived polymers. Polycaprolactone is a biodegradable and biocompatible polymer commonly utilised in sutures and implantable pharmaceutical delivery systems (Kawai & Hu, 2009; Matsumura et al., 1993). In humans, polycaprolactone hydrolyses nonenzymatically in years and is biodegraded in seawater by fungi and bacteria in weeks (Labet & Thielemans, 2009; Woodruff & Hutmacher, 2010).

The simplest aliphatic ester is polyglycolic acid. The excellent gas barrier and fast industrial and marine breakdown rates make it a promising candidate for plastic packaging. Polyglycolic acid's manufacturing volumes are insignificant from a commodities standpoint, despite its large economic market dominance in the biomedical sector (Jem & Tan, 2020; Lamberti et al., 2020).

### 11.5.5 Other Non-synthetic Bioplastics

Polymers can be extracted directly from biomass, which is a very simple and cost-effective approach. Starches, which make up a significant amount of food waste, are the primary component of non-synthetic starch-based bioplastics, which are made by converting starch into films (Zhang et al., 2014). In second-generation biorefineries, lignin extracted from biowastes is largely (98%) burnt for power generation. The complicated phenolic structure of lignin, on the other hand, has generated interest in using it as monomers, polymer grafts, or polymer additives for specific polymers (Schutyser et al., 2018; Wang et al., 2020).

The most common natural polymer is cellulose which is derived from plant biomass or particular cellulose-producing bacteria. It is employed in food packing constituents or as a nano-filler additive with additional bioplastics to increase barrier characteristics and tensile strength (Azeredo et al., 2019; Vilarinho et al., 2018). Despite the fact that cellulose is eco-friendly, about 60% of sea-bed microplastics account for regenerated cellulose, that is used to make "viscose" or "rayon" textile fibres (Henry et al., 2019). Cigarette filters, made from a similar substance called cellulose acetate, are a major source of litter. Because of its acetylation, which makes the material hydrophobic, cellulose acetate degrades very slowly (Robertson et al., 2012).

### 11.5.6 Biobased Polyurethanes

Polyurethanes (PU) are used commercially on a scale of more than 18 million tonnes, primarily in the form of flexible and rigid foams. Major health concerns have emerged due to the usage of poisonous phosgene and cancer-causing isocyanate monomers during the production of conventional polyurethanes (Cornille et al., 2017). Non-isocyanate bioPUs can be produced instead using cyclic carbonates and diamines from vegetable oils (Blattmann et al., 2016; Harmsen et al., 2014; Rokicki et al., 2015). The cycloaddition of epoxides with $CO_2$ can also form cyclic carbonates.

## 11.6 LIFE CYCLE ASSESSMENT OF BIOPLASTICS

The major method through which scientists and policymakers can analyse the merits and disadvantages of adopting bioplastics instead of traditional plastics is life cycle assessment (LCA). LCA is a systematic technique for analysing the environmental and socio-economic effects of the production and utilisation of a specific good (Di Bartolo et al., 2021). The general standards of LCA are ISO 14040 and ISO 14044 (Rosenboom et al., 2022). At the worldwide level, there are various LCA standards in use, as well as guidelines that are applicable in the European Union. The total LCA of bioplastics must examine a number of impact areas, including environmental, social, and economic impacts, as well as several options for end-of-life possibilities of the product. The cradle-to-gate and cradle-to-grave assessments are the two basic approaches to a product's LCA, depending on the system boundaries (Finkbeiner, 2013). Cradle-to-gate refers to a review that takes place from the beginning of the

resource extraction process (cradle) to the end of production (factory gate). In the case of biobased products, this includes crop cultivation and biomass pre-processing, as well as any transportation involved (Di Bartolo et al., 2021).

The cradle-to-grave assessment considers the product's whole life cycle, from raw material extraction to end-of-life management. This comprises all parts of the cradle-to-gate evaluation, as well as the sale, storage, and usage by consumers of the product, as well as its disposal (Di Bartolo et al., 2021).

Environmental influence categories are often considered in LCA studies, but social and economic factors are also important. The social life cycle assessment examines how the extraction or production of raw materials, as well as the manufacturing, distribution, use, and disposal of items, might have negative societal consequences (Spierling et al., 2018). When used in conjunction with LCA, life cycle costing (LCC) is referred to as environmental LCC (E-LCC) (Spierling et al., 2018). E-LCC encompasses all expenses associated with a life cycle of the product, regardless of who is responsible for them. Environmental cost elements are taken into account, like ecological taxes and emissions control expenditures. The LCA of bioplastics is essential to realise the principle of circular bioeconomy in relation to bioplastics and their long-term durability. Bioplastics are made from low-cost or residual carbon sources, but economic studies are necessary to confirm the feasibility of bioplastics production procedures (Talan et al., 2020).

## 11.7 END-OF-LIFE TREATMENT OPTIONS OF BIOPLASTICS AND BIOBASED POLYMERS

Plastic leakage into the environment is a major problem caused by poor End-of-life management (Geyer et al., 2017; Jambeck et al., 2015). Bioplastic recycling is often recognised as the most environmentally beneficial end-of-life alternative, and it is preferred over ordinary composting. Bioplastic recycling streams, on the other hand, are less well-developed than those for conventional plastics (Hottle et al., 2017; Morão & de Bie, 2019). The presence of additives in practically every finished plastic product complicates plastic and bioplastic recycling (Geyer et al., 2017). This section examines the end-of-life alternatives for bioplastics, taking into account the existing and future recycling options.

## 11.8 MECHANICAL RECYCLING

The easiest, most affordable, and most popular type of recycling is mechanical recycling (Hong & Chen, 2017). It entails separating plastic waste from polymeric material, eliminating tags, rinsing, manual tearing, melting, and rebuilding into new shapes. Re-extrusion has been done in the literature; however, mechanical recycling of bioplastics is not yet commercially viable. PLA and PHA are mechanically recycled, which results in quality degradation like tensile strength and molecular weight loss (Lamberti et al., 2020; Vu et al., 2020). Due to mechanical recycling inability to efficiently remove impurities and additives from polymer waste, as well as the inherent thermal and mechanical stress, the products are typically "downcycled" into

lower-quality commodities. Additional challenges include coloured or low-density substances (films, foams), as well as therapeutic pollutants, which can make products non-recyclable (Bucknall, 2020; Hong & Chen, 2017). As a result, food-grade recycled plastic is difficult to achieve (Briassoulis et al., 2013).

To improve the quality of reused polymers, virgin polymers are frequently combined with recyclates (Chanda & Roy, 2006; Hong & Chen, 2017). Mechanical recycling, on the other hand, is frequently considered as the most suitable end-of-life alternative due to its deviation from virgin resources. Mechanically recycled plastic often has a lesser impact on the environment than virgin plastic. For example, recycled PET (rPET) has a twofold lower environmental effect than fresh PET (GHG emissions from transportation and process energy usage), while recycled PE and PP (rPE and rPP, respectively) have a threefold lower environmental impact than virgin materials (Gu et al., 2017). However, there is relatively little recycling for this type of recycling: Around 10% of high-density PE and PET are recycled globally, compared to closer to zero for PP and polystyrene. Recyclable textiles and fibre products are also uncommon (Geyer et al., 2017). PET from soft drink bottles is the most widely processed recycled plastic. Its performance as a polycondensation polymer can be enhanced through solid-state post-polymerisation (essentially, eliminating volatile by-products of polymerisation by warming recycled particles under pressure), which raises the molecular weight of recyclates for industrial applications.

## 11.9 CHEMICAL RECYCLING

Chemical recycling, as opposed to mechanical recycling, can produce high-quality polymers from waste, a process known as "upcycling." Depolymerisation of plastic products yields their monomeric components, which can subsequently be repolymerised using methods that allow for regulated polymerisation to yield preferred polymers (like those with regulated molecular weight). Low-molecular-weight fibre polyesters, for example, can be easily broken down into monomers and subsequently polymerised into the longer-chain polyesters needed for bottles (Park & Kim, 2014; Pudack et al., 2020). Impurities and colour can be eliminated as well. Solvolysis and thermolysis are the most common methods for chemical recycling.

Solvolysis is a solvent-based depolymerisation process in which polymers containing cleavable groups throughout their backbone, like ester linkages in PET, PEF, and PLA, are exposed to hydrolysis, glycolysis, or methanolysis (Demarteau et al., 2020; Hong & Chen, 2017; Pudack et al., 2020). Aromatic polyesters are more hydrolysable than aliphatic polyesters like PLA, PBS, or PHAs. PLA can be hydrolysed to 95% lactic acid production devoid of a catalyst around 160°C–180°C for two hours with a four-times lower energy requirement (Lamberti et al., 2020). It can be depolymerised to 90% cyclic lactide monomers after six hours using Zn transesterification catalysts (Alberti & Enthaler, 2020). The resultant monomers can be used to make high-quality polymers as a feedstock. Chemical recycling, on the other hand, is more costly and less economically viable than mechanical recycling due to the requirement for chemicals and more complicated separation machines. Chemical recycling makes up less than 1% of all recyclable plastic. Several significant chemical companies are working on ways to make chemcycled polymers globally viable

with virgin polymers. In plastic applications, chemically recoverable polymers can be configured and used to address enduring end-of-life issues and support a circular materials economy (Coates & Getzler, 2020; Hong & Chen, 2017). With this method, monomers for high-quality condensation polymers, like polyesters and polyamides, can be produced.

Thermolysis is the process of pyrolyzing polyolefins that do not have hydrolysable functional groups at temperatures ranging from 200°C to 800°C (based on the catalyst utilised and also, polymer used) in lack of oxygen. In these circumstances, the C–C linkages disintegrate, converting the polymer either back into hydrocarbon oil or gas as feedstock or straight into olefin monomers.Conventional refineries and polymerisation companies can then use this feedstock (Anuar Sharuddin et al., 2016; Hees et al., 2019; Zhao et al., 2020).

## 11.10 COMPOSTING AND BIODEGRADATION

Composting and biodegradation is referred as the digestion of compounds by different microorganisms and physiological transition of polymeric substances into water, carbon dioxide, and other inorganic compounds by many recognised species (Künkel et al., 2016). Physical techniques are frequently utilised to support this process, particularly those that help with particle size reduction and fragmentation. Micronization or extrusion, for example, can amorphise crystalline structures into semi-crystalline plastics, making them more prone to enzymatic degradation (Austin et al., 2018). Microbial enzymes, acids, or bases can accelerate hydrolysis, which breaks vulnerable linkages in permeable amorphous portions of a polymer, usually aliphatic esters. UV radiation photodegrades tertiary and aromatic C–C bonds, often resulting in brittle and discoloured material. Metallic catalysts embedded in the polymer can improve this reaction (Sivan, 2011). Metals can also cause oxo-degradation (decomposition by oxidation); however, this can result in fragmentation into microplastics and inadequate digestion. As a result, oxo-degradation has been prohibited in the European Union and Switzerland.

Because the pace of biodegradation is strongly influenced by the elemental composition of a polymer, stabilising additives, environmental factors (such as the availability of $H_2O$ and $O_2$), and any microorganisms employed, biodegradation is not an easy process (Lambert & Wagner, 2017). In industrial composting facilities, home compost, and even in open water, these parameters are frequently not met. Biodegradable plastics, like PLA shopping bags and cutlery, are frequently rejected by composters because the required decomposition timeframes are longer than the average composting duration of six to eight weeks (X. Chen & Yan, 2020).

## 11.11 INCINERATION

In the United States, 20% of end-of-life plastic waste is burnt; in Europe, 40% of end-of-life plastic garbage is incinerated. Emission of carbon dioxide are total zero when solely carbon/hydrogen/oxygen-containing renewable substance is burnt, while a portion of the generated thermal energy can be reclaimed for energy generation. Nevertheless, the burning of N-, S-, and Cl-containing polymers, on the other hand,

creates poisonous NOx, SOx, and HCl. Similarly, additives in polymers can produce a variety of harmful chemicals when they are burnt, necessitating potentially costly capture and treatment (Chanda & Roy, 2006; Harding et al., 2007). Moreover, there are issues about a "locking-in" effect, in which high incineration facility investment costs and the necessity for ongoing garbage intake may hinder the development of recycling technologies.

## 11.12 BIOLOGICAL RECYCLING

Alike chemical recycling and as an alternative to complete biodegradation, microbes and their hydrolytic enzymes can be utilised to break down condensation polymers into smaller sub-units, that is, monomers (Jarerat et al., 2006). These biological mechanisms are still being researched, but they have the potential to be greener than the synthetic approach. Aromatic polyesters are often resistant to enzymatic hydrolysis, whereas aliphatic esters are easily hydrolysed. At ambient temperatures, however, *Ideonellasakaiensis 201-F6*, a bacterium identified in a Japanese recycling facility, can depolymerise PET in 40 days (Yoshida et al., 2016). The PETase enzyme, interestingly, is only effective in the degradation of aromatic polyesters and unsuccessful in the breakdown of aliphatic polyesters (Austin et al., 2018). To improve substrate specificity and thermal stability, leaf compost cutinase can be genetically engineered. At temperatures around the glass transition of PET (75°C), the improved enzyme can depolymerise 90% of micronised, amorphous PET into monomers in ten hours (Tournier et al., 2020). The amorphous chain mobility increases at this temperature, making it more susceptible to microbial destruction. The terephthalic acid monomer obtained can be utilised to make bottle-grade PET (Wei et al., 2019). PEF has also been depolymerised using this approach (Pellis et al., 2016; Weinberger et al., 2017).

Polyurethanes are substantially less biodegradable than polyesters due to the strength of the urethane linkages. Fungi and soil bacteria, on the other hand, can assist hydrolyse the ester groups in polyester-containing polyurethane (Espinosa et al., 2020; Russell et al., 2011). Improved understanding of enzyme activity and gene editing to improve microorganism selectivity could actually boost polyurethane biorecycling.

Polyolefin materials are very hard to degrade biologically because they lack breakable functional groups throughout their backbones. They are very hydrophobic in nature, have a high molecular weight, and contain stabilising additives (C. C. Chen et al., 2020; Gewert et al., 2015). Some organisms are thought to metabolise small fragments of less than 5,000 Da; but the molecular weight of most polyolefin polymers exceeds millions of daltons. Waxworm bacteria and *Pseudomonas* strains have been found to partially biodegrade PE films (5%–20%) over a period of one to two months (Gajendiran et al., 2016; Jaiswal et al., 2020; Santo et al., 2013; Yang et al., 2000).

## 11.13 LANDFILL

Landfills are still the most common method of garbage disposal in many countries: in the United States, 58% of waste is disposed of in landfills (2014), and in Europe, 27.3% of waste is disposed of in landfills (2017) (Geyer et al., 2017). Landfills that are

poorly maintained and permeable are a major source of pollution in the environment. Biodegradable polymers also should be restricted out of landfills since they can decompose anaerobically into $CH_4$, which has a greenhouse gas impact >20 times greater than $CO_2$. In 2006, it was projected that just 10% of $CH_4$ produced in landfills was trapped worldwide, which is a strategy that provides the option for energy efficiency while also enhancing the climate and public health (Anenberg et al., 2012; Themelis & Ulloa, 2007). Landfilling taxes, according to the UN, might make recycling more cost-effective.

## 11.14 ANAEROBIC DIGESTION

In a methanisation "biogas" factory, regulated fermentation (which takes place without oxygen) converts biodegradable polymer waste into methane. Following the capture and burning of the methane, which results in the production of carbon dioxide and water, heat and energy can be retrieved for use. This technique produces energy and generates a total zero-carbon residue for the bioplastic waste (Hobbs et al., 2019; Stagner, 2015). By including components like a "bioreactor landfill," which cycles water to increase microbial activity for methane yield, anaerobic digestion efficacy can be enhanced (Themelis & Ulloa, 2007). At rising temperatures, numerous polymers, including PLA, polycaprolactones, PHAs, and thermoplastic starch, can be digested anaerobically.

## 11.15 CONCEPT OF BIOPLASTICS AND BIOBASED POLYMER IN A CIRCULAR ECONOMY

Bioplastics, or materials that are biobased, biodegradable, or both biobased and biodegradable, have several advantages: they benefit our economy, society, and environment. They represent an economically creative sector that is developing between 20% and 100% each year, with a current share of roughly 1% of the worldwide plastics market (European Bioplastics, 2016). In Europe, investment in bioplastics production and R&D is contingent on a long-term legislative framework that encourages the use, reuse, and recycling of these materials. The development of a strong and resilient bioplastic requires a favourable legislative framework for the circular and biobased economy throughout the value chain.

Achieving circular economy in case of plastics presents substantial obstacles. This is because our existing techniques for plastic generation, usage and disposal generally fails to meet most of the circular economy's concepts. The prevalence of fossil fuels as polymeric feedstocks, for example, obviously defies a core circular economy premise of solely using renewable resources. Other inconsistencies can be noticed in the present state of plastics after they have been used. Despite recent improvements in recycling processes, the majority of end-of-life plastics are still consigned to landfill or increasingly burnt for energy recovery, both of which contribute to environmental damage in different ways and constitute a significant loss of a valuable resource.

Significant changes to current practices will be required to achieve the circular economy of plastics. This changes include new and sustainable approaches to eco-design, reuse, maintenance and repair, renting and sharing, recycling,

and chemical conversion of plastics. (Iaquaniello et al., 2018). In addition to this, necessary social and economic changes are also required to attain circular economy of plastics. Several governments, including the European Union, local governments, and private businesses, have implemented laws to support the circular economy in an attempt to balance environmental concerns with economic growth. If completely implemented, a circular plastics economy would not only keep plastics in use for a wide range of applications, but it would also lessen the environmental harm caused by plastic waste. Current estimates suggest that the circular economy might contribute US$ 1 trillion annually to the global economy, suggesting that the economic benefits could be considerable (Korhonen et al., 2018).

## 11.16 CONCLUSION AND FUTURE PERSPECTIVES

The utilisation of renewable resources does not guarantee long-term viability. Sustainability is mostly determined by the process of making the material, the place to be used and the recycling process, rather than the substance's constituent parts. Bioplastics, on the other hand, have the potential to transform various plastic-intensive sectors towards a circular economy as technology progresses. Almost every fossil-based application has a biobased equivalent; however, they are typically in limited and expensive quantities, and they do not necessarily have significant environmental benefits.The ability to assess, analyse, and compare the long-term viability and environmental impact of fossil- and biobased materials is critical. Although there are hazards (consumption of fertilisers, societal risks, etc.) associated with the adoption of biobased plastics, it is clear that it provides an alternative to fossil-based production and may thus become a requirement in the future.

To offer polymer building blocks in a cost-effective and sustainable way, biorefinery processes must, however, become more efficient and follow concepts of "green" chemistry, such as employing non-toxic chemicals and conserving energy. A possible method for boosting microorganism productivity in the consumption of biomass, the polymerisation of bioplastics (particularly PHAs), and biological depolymerisation for recycling is gene editing.

LCA is the primary tool; however, to make LCAs increasingly transparent, uniform, and comparative, methodology principles need to be standardised. Existing bioplastic labels must be updated for use on both global and local levels. The labels should be able to convey globally accepted quality standards and yet, still reflect the end-of-life of plastics in the domestic market.

If compostable or biodegradable plastics are not separated from recycling streams, they may cause difficulties. Nonetheless, applications such as compost bags have advantages because the bag and contents can be co-digested, avoiding the need for separation and generating energy and compost. During the "usage" phase, materials should be created to ensure rapid degradation without producing technological concerns while maintaining mechanical qualities. Another claimed benefit is the use of biodegradable plastics to reduce pollution caused by leaks in open environments; however, this appears to be unduly hopeful at the moment. The size and density of the plastic waste, as well as agglomeration with other materials, might influence the outcome in natural ecosystems, which differ dramatically between geographic

regions and seasons. Furthermore, employing biodegradable alternatives does not eliminate the economic loss caused by plastic trash. In this regard, stronger laws, the promotion of an environmentally friendly culture, and early investment in sustainability-focused education could prove to be a more efficient use of resources.

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