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Research
Recycling of Polymeric Materials—Review

Reframing Biodegradable Plastic as an Effective, Chemically Recyclable Resource for a Circular Economy

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ABSTRACT

Plastics play a pervasive role in contemporary society and serve a wide range of purposes. However, widespread accumulation of plastic waste has become a serious environmental concern. Traditional disposal techniques, such as incineration and landfill disposal, have exacerbated ecological problems, including air, water, and soil pollution. A crucial strategy for promoting sustainability is the adoption of biodegradable plastics as green alternatives to traditional plastics along with the implementation of mechanical and chemical recycling approaches. However, the recycling of biodegradable plastics remains understudied because of prevalent biases and misconceptions. This review aims to address this knowledge gap by assessing common misconceptions regarding biodegradable plastics and emphasizing the merits of their recyclability. Furthermore, this review explores the trends and methods for chemically recycling biodegradable plastics and highlights innovative practices. It endeavors to show that the environmental impact of accidental spills can be minimized by transitioning from a linear economy—focused on the disposal of biodegradable plastics—to a circular economy that emphasizes sustainable chemical recycling. The structural properties of biodegradable materials require less activation energy for decomposition than conventional plastics, facilitating effective chemical recycling. This review highlights the need to develop advanced recycling technologies and encourage further research and societal action to support the transition to a circular economy.

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1. Introduction

The escalating problem of plastic waste has emerged as a major environmental concern, with millions of tonnes of plastic waste accumulating each year. Plastic waste causes significant destruction of ecosystems, human health hazards, and increased pollution from landfills and microplastics [1,2]. Microplastics, defined as particles less than 5 mm in diameter, pose a particular threat as they infiltrate diverse ecosystems, including oceans, soil, air, and the food chain, endangering both human and wildlife health [3–5]. Furthermore, the accumulation of plastic waste in landfills presents critical challenges related to space management, uncontrolled long-term decomposition, and potentially toxic chemical emissions that may harm the surrounding ecosystems [6,7].

To address the escalating environmental issues associated with plastic waste, biodegradable plastics have been proposed as potential solutions because they are designed to naturally decompose over time. Research on biodegradable plastics is advancing actively. Despite their potential benefits, biodegradable plastics have been criticized for their effectiveness and sustainability. They often degrade sub-optimally in natural environments and poorly in marine environments. Moreover, they can have negative environmental impacts when mixed with conventional petroleum-based

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plastics or incinerated [8,9]. Biodegradation also results in the emission of CO_2, which contributes to climate change. Although carbon emissions are a natural part of the degradation process, their long-term implications must be considered for the widespread adoption of biodegradable plastics. A common misconception is that biodegradable plastics have little to no recycling value, which can undermine the goals of traditional green research. Effective communication is essential to correct the public and marketplace perceptions of biodegradable plastics. The optimal approach to the end-of-life (EoL) of biodegradable plastics is to consider them within the context of a circular economy rather than a linear economy represented by landfills and incineration.

Therefore, the concept of "efficient, chemically recyclable plastics" has been proposed to reorient the discourse [10]. By shifting the focus toward the efficient chemical recycling of plastics and emphasizing proper recycling methods, the challenges associated with biodegradable plastics can potentially be overcome, and their benefits can be realized. This review underscores the importance of recycling biodegradable plastics and their potential advantages, such as obtaining high-quality raw materials [11].

In contrast to traditional polyolefins such as high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polypropylene (PP), which consist of C–C bonds that require considerable energy to break down, most biodegradable plastics are polyester-based [12]. The disparity in the energy required for the decomposition of biodegradable and traditional plastics highlights the potential sustainability and recyclability of biodegradable plastics. Efficient recycling processes can help reduce the relatively high costs associated with biodegradable plastics [13]. Establishing a circular economy for these materials can maximize their value and offset financial barriers. Importantly, effective recycling can reduce CO_2 emissions. Notably, even if biodegradable plastics are improperly disposed, they decompose considerably faster than non-biodegradable petroleum-based plastics, thus mitigating long-term plastic pollution and reducing landfill burdens.

This new perspective on biodegradable plastics provides a comprehensive understanding of their role in addressing plastic waste. Although the effectiveness and sustainability of biodegradable plastics has been debated, refocusing on the importance of proper and efficient plastic recycling could help address these issues. This approach encourages a comprehensive understanding of the role of biodegradable plastics in addressing plastic waste problems and highlights the advantages of their recyclability. With the continued development of recycling technologies and infrastructure, the environmental benefits of biodegradable plastics can be maximized, ultimately contributing to a significant paradigm shift in plastic waste management (Fig. 1).

2. Terminology

2.1. Biodegradable plastics

Plastics permeate every facet of modern life; however, their environmental implications have raised global concerns. Consequently, in recent years, the development of sustainable alternatives has become a priority. In this context, we categorized different types of plastic materials based on two crucial criteria: their source (biomass or petrochemicals) and biodegradability. This approach identifies four distinct types of plastics, each with unique attributes, applications, and environmental impacts (Fig. 2).

Type 1: Biodegradable plastics derived from biomass, including polylactic acid (PLA), polyhydroxyalkanoates (PHA), and starch-based plastics. These materials are primarily derived from renewable resources such as corn starch, sugarcane, and cassava. They offer a potential solution to the growing problem of plastic waste as they can decompose in the environment, making them promising substitutes for conventional petroleum-based plastics. However, their performance, cost, and availability require further investigation.

Type 2: Biodegradable plastics synthesized from petroleum resources, such as polybutylene adipate-*co*-terephthalate (PBAT), polycaprolactone (PCL), and polybutylene succinate (PBS). These materials combine the desirable properties of traditional plastics with biodegradability. However, their production relies on non-renewable resources, raising concerns about their long-term sustainability. To address this, studies have explored producing these polymers from biomass. For instance, PBS can be synthesized not only from petroleum feedstocks but also from biomass. Mitsubishi Corporation in Japan has commercialized bio-polybutylene succinate (bio-PBS) using succinic acid [14].

Type 3: Non-biodegradable plastics made from biomass, including bio-polyethylene terephthalate (bio-PET), bio-polyethylene (bio-PE), bio-polypropylene (bio-PP), bio-polytrimethylene terephthalate (bio-PTT), and isosorbide-based plastics. These materials provide sustainable alternatives to traditional petroleum-based plastics. While bio-PET, bio-PE, and bio-PP have the same chemical structure as their petroleum-based counterparts and are partially derived from biomass, they are not biodegradable. Although these materials can contribute to a reduction in greenhouse gas (GHG) emissions, they still pose environmental risks similar to traditional plastics due to their non-biodegradable nature.

Type 4: Non-biodegradable plastics originating from petroleum, such as polyethylene (PE), PP, polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polystyrene (PS). These materials have been extensively used across various industries. Despite their versatility and low cost, their environmental persistence and associated ecological impacts emphasize the urgent need for the development and promotion of sustainable alternatives.

Biodegradable plastics can be classified into two categories, that is, types 1 and 2. Bioplastics are categorized into types 1, 2, and 3. Biodegradable plastics degrade through the action of microorganisms, such as bacteria, fungi, and algae. This multistage process involves the breakdown of polymer chains into simpler compounds, such as water, CO_2, and biomass. The biodegradation rate is influenced by factors such as the chemical structure of the plastic, environmental conditions (e.g., temperature), and the presence of suitable microorganisms [15,16]. Biodegradation also affects the biomechanical morphology of plastics, leading to structural changes [17,18]. Mechanical properties such as tensile strength and elasticity are altered as the polymer chains break down, with observable signs of degradation such as discoloration, embrittlement, and the appearance of cracks and pores. Understanding these biomechanical changes is crucial for designing biodegradable plastics with optimized degradation rates and performance characteristics.

2.2. Mechanical and chemical recycling

Plastic recycling is recommended as an EoL option to achieve economic and environmental sustainability. There are two major methods for recycling plastics: mechanical and chemical [19].

Mechanical recycling, also known as mechcycling or physcycling, involves the collection, sorting, cleaning, and disintegration of plastics into flakes that are then heated and remolded into new items. It is popular because of its simplicity and cost effectiveness. However, the physical properties of plastics can degrade during melting, leading to crystallization, decreased molecular weight, and reduced mechanical properties [20–22]. These issues are particularly problematic in applications requiring high quality standards, such as food-grade plastics. The primary drawback of mechanical recycling is the requirement of uncontaminated,

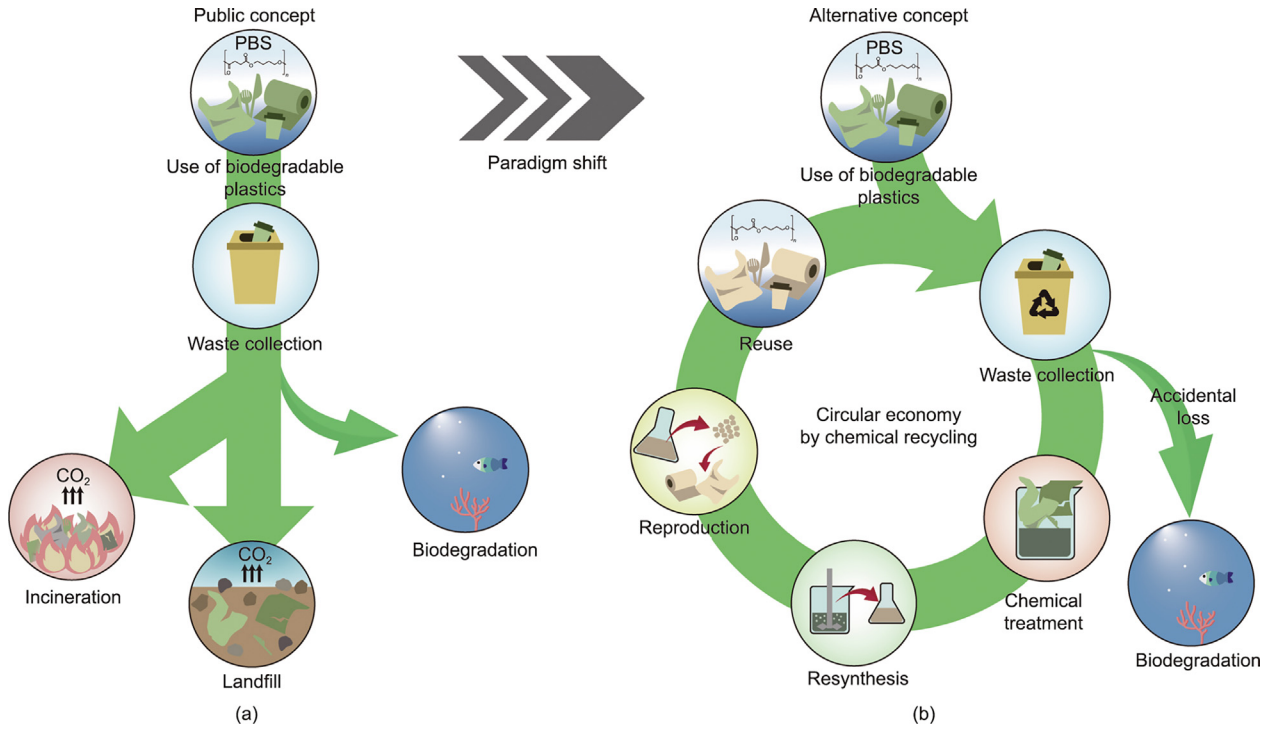

Fig. 1. Paradigm shift in the use of biodegradable plastics: from (a) a linear economy to (b) a circular economy. PBS: polybutylene succinate.

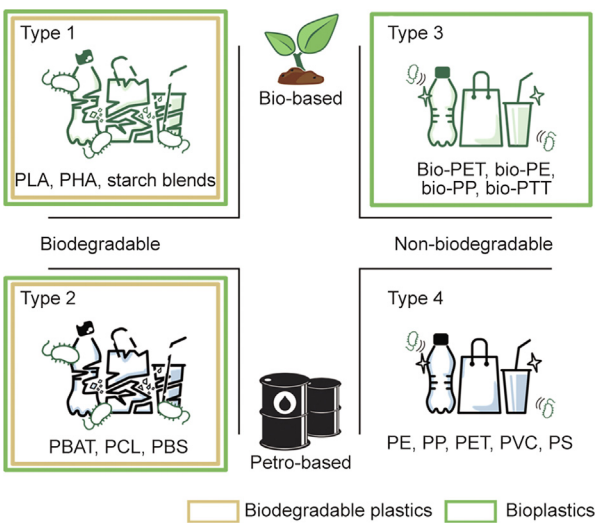

Fig. 2. Classification of plastics based on their source and biodegradability. PLA: polylactic acid; PHA: polyhydroxyalkanoates; PBAT: polybutylene adipate-*co*-terephthalate; PCL: polycaprolactone; PBS: polybutylene succinate; bio-PET: bio-polyethylene terephthalate; bio-PE: bio-polyethylene; bio-PP: bio-polypropylene; bio-PTT: bio-polytrimethylene terephthalate; PE: polyethylene; PET: polyethylene terephthalate; PVC: polyvinyl chloride; PS: polystyrene.

homogeneous, high-quality plastic waste, which is often scarce. Furthermore, toxic substances have been detected in postconsumer resin products obtained through mechanical recycling, leading to restrictions on the use of recycled materials in food packaging in some regions, such as the Republic of Korea.

Chemical recycling, also known as chemcycling, decomposes plastic waste into fundamental monomers or other valuable chemicals using methods such as pyrolysis, gasification, and chemical depolymerization [23,24]. The monomers produced can be repolymerized to create new plastic materials. The main advantages of chemical recycling include its ability to handle mixed and contaminated plastic waste and its potential to produce high-quality virgin-like plastics. However, chemical recycling is generally more complex and energy-intensive than mechanical recycling, and its efficiency can vary depending on the structure and purity of the plastic. Chemical recycling, particularly pyrolysis, is a suitable method for processing waste polyolefins and their mixtures [25]. However, pyrolysis requires the removal of non-polyolefin plastics and other impurities to avoid complications [26]. For example, PET pyrolysis can produce phthalates that degrade oil quality and clog piping systems, whereas PVC pyrolysis generates chlorinated hydrocarbons and hydrogen chloride, leading to reactor corrosion and halogenated oils [27,28]. In addition, the high energy requirements for the decomposition of non-biodegradable plastics make this process economically less viable, thereby limiting its application primarily to PET chemolysis.

The global plastic recycling rate is less than 10%, and chemical recycling has become a crucial strategy for addressing this issue. To prevent deterioration, mechanical recycling is limited to plastics in good condition, whereas chemical recycling has great potential because it can utilize lower-value products. Studies have demonstrated the environmental advantages of chemical recycling over landfills and plastics [29–31]. Chemical recycling consumes less energy than raw materials [32]. For example, the life cycle energy consumption of recycled LDPE is 38% lower than that of the virgin material [33]. Large-scale operations are required to make chemical recycling processes effective. This requires significant investment in large processing plants and robust plastic waste collection systems to ensure a steady supply of materials [34]. The importance of differentiating between "downcycling" and "upcycling" has also gained attention in recent years. While downcycling refers to the production of lower-value materials, upcycling aims to enhance the quality, performance, and economic/environmental value of recycled products. Whenever possible, closed-loop recovery (i.e., "recycling") is preferred to ensure that waste

polymeric materials are effectively reutilized without material loss within a fully circular system through physical or chemical recycling [35]. Based on these advantages, Plastics Europe has pledged to invest 2.6 billion and 7.2 billion Euros in chemical recycling technologies by 2025 and 2030, respectively [36,37].

3. Criticisms and prejudice against biodegradable plastics

As the term "biodegradable plastic" implies, these materials are designed to break down into smaller components after disposal, potentially providing a solution to the global problem of plastic waste. Biodegradable plastics are primarily composed of bio-based ingredients, which can reduce fossil fuel reliance and, consequently, lower the carbon footprint associated with traditional plastics. Nevertheless, certain misconceptions about biodegradable plastics may discourage their use. The following subsections address these misconceptions and emphasize the importance of recycling in maximizing the benefits of biodegradable plastics (Fig. 3).

3.1. Incomplete decomposition in nature

A common criticism of biodegradable plastics is their incomplete decomposition in the natural environment, particularly in aquatic environments such as rivers and oceans [34]. While these materials are designed to degrade over time, truly effective biodegradation requires specific conditions such as higher temperatures, adequate moisture, and active microbial communities. These conditions are reliably met in industrial composting facilities, but vary widely in natural ecosystems.

Under real-world conditions, biodegradable plastics degrade at different rates, generally in the following order: composting facilities > soil > freshwater > seawater. The slower decomposition in oceans is of particular concern because these environments are already severely affected by plastic pollution, absorbing millions of tonnes of plastic waste each year [38]. Lower temperatures and reduced microbial densities in marine environments can slow down the degradation of biodegradable plastics, raising concerns about their potential contribution to "ghost fishing," in which partially degraded fishing gear continues to capture marine organisms [39,40]. Critics also worry that incomplete degradation may produce microplastics or nanoplastics [41].

Despite these concerns, research shows that biodegradable plastics can degrade 100–200 times faster than non-biodegradable plastics in the same environment, even under less than ideal conditions [17]. In particular, small fragments of biodegradable plastics degrade more rapidly. In addition, while complete degradation may require prolonged exposure to microorganisms and compost-like conditions, the mechanical strength of biodegradable plastics declines relatively quickly, reducing the risk of long-term entanglement ("ghost fishing"). As a result, even under less than optimal conditions, these plastics offer significant advantages over their conventional counterparts in mitigating persistent plastic pollution.

3.2. CO_2 emission during biodegradation

Some researchers argue that biodegradable plastics emit CO_2 as they degrade, potentially contributing to climate change [42]. Indeed, any organic material decomposing in nature, whether plant-derived biomass or biodegradable plastic, releases CO_2. However, when these plastics are derived from renewable, bio-based feedstock, the carbon they release is part of a natural cycle—plants absorb CO_2 through photosynthesis, and this carbon is later returned to the atmosphere during degradation [43]. Advocates of biodegradable plastics therefore argue that this cyclical process contrasts with the fossil carbon released by conventional plastics, which adds to atmospheric levels of CO_2 without compensating uptake.

Nevertheless, the production of biodegradable plastics can still generate some GHG emissions through the consumption of energy, which may be derived from fossil fuels. Petroleum-based biodegradable plastics also do not offer the same closed-loop carbon benefit as purely bio-based options. To accurately evaluate these trade-offs, life cycle assessments (LCAs) are critical for analyzing the cumulative energy use, CO_2 emissions, and other

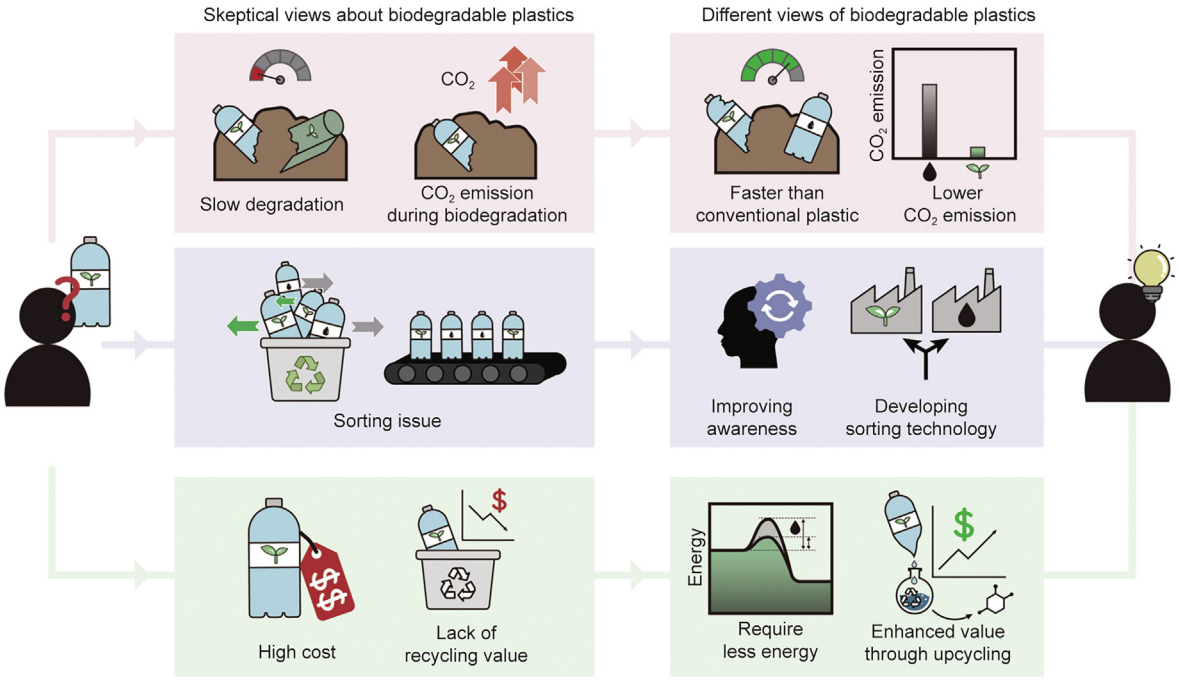

Fig. 3. Illustration of skeptical views and alternative perspectives on biodegradable plastics.

environmental impacts of plastics. Several LCA studies suggest that biodegradable plastics often have a lower net carbon footprint than traditional plastics when their entire life cycle is considered [44,45].

3.3. Contamination with petroleum-based plastics

Another concern is that biodegradable plastics contaminate recycling streams when mixed with conventional petroleum-based plastics. Recycling plastics that are composed of a single material is simple and environmentally beneficial. On the other hand, mixing biodegradable plastics with non-biodegradable plastics can complicate waste separation and sorting, reducing recycling efficiency [46]. Introducing biodegradable polymers into mechanical recycling processes can cause thermal degradation or discoloration of the material stream [47], and some of the chemical reactions that occur during mixing can make these blends more difficult to recycle or degrade [48].

However, the low recycling rates of conventional plastics are not inherently caused by biodegradable plastics, but rather by improper sorting and limited consumer awareness [49]. Similarly, if properly sorted, biodegradable plastics do not necessarily undermine existing recycling systems. The challenge is to develop improved waste management and recycling infrastructure that can efficiently separate biodegradable plastics from conventional plastics. Thus, improved facility technologies and public policies can help biodegradable plastics reach their full environmental potential without disrupting existing recycling processes.

3.4. Lack of recycling value

A widespread misconception is that biodegradable plastics have little or no recycling value because they are designed for degradation. They were initially developed to reduce microplastic pollution and curb plastic waste rather than to reduce GHG emissions. However, the idea that they cannot contribute to a circular economy overlooks the potential of chemical recycling and upcycling strategies.

The recycling of biodegradable plastics can reduce the environmental impact of plastic waste by diverting it from landfills to ecosystems. Chemical recycling, including depolymerization, can break down biodegradable plastics into monomers with significant market value [50]. For example, PBAT can be chemically recycled to produce terephthalic acid, which can then be used to produce PET. These monomers, which typically cost between 0.35 and 4.71 USD·kg^{-1} (Table 1) [52–57], can then be reused to synthesize new biodegradable plastics or other polymer families such as polyesters and polyamides [10,57]. In addition, the production of new monomers can generate between 0.87 and 4.87 kg of CO_2 ($kgCO_2$) per kilogram of monomers produced; hence, the recovery and reuse of these monomers also helps to reduce emissions [51,52]. Thus, with the right facilities and incentives, biodegradable plastics can participate in recycling loops that reduce overall carbon and resource demand.

3.5. Cost concerns

Despite their environmental promise, biodegradable plastics are sometimes considered prohibitively expensive compared to traditional petroleum-based plastics. Costs remain high for several reasons: Small-scale production, specialized feedstocks, and specialized processing techniques can deter manufacturers and consumers. As a result, biodegradable plastics currently account for only about 1% of total global plastic production [58]. However, advances in synthetic biology and growing market demand are helping to narrow the price gap. Fluctuating oil prices can periodically benefit biomass-based materials, and as the technology matures, their production methods become more efficient.

A historical parallel can be seen in materials such as PET and nylon, which were initially expensive but became more affordable as production expanded. In the same way, biodegradable plastics will benefit significantly from economies of scale. For example, the "Plastic Ban and Plastic Restriction Order" in China has already increased global PBAT production capacity to about 500 000 t per year and reduced its market price from about 4.6 to 3.1 USD·kg^{-1} [59–61]. Although still about three times higher than PET, such reductions illustrate how policy-driven demand, technological improvements, and larger scale production can make biodegradable plastics increasingly cost-effective.

Recycling and upcycling of biodegradable plastics can contribute to cost competitiveness and sustainability through monomer reuse. In addition, the environmental costs associated with traditional plastics, which ultimately affect their affordability, must be considered. The cost of plastic waste management and environmental cleanup is a burden that biodegradable plastics can help alleviate, offsetting their initial cost.

4. Changing perspectives on biodegradable plastics

4.1. Redefining biodegradable plastics as efficiently recyclable

To effectively address the global plastic waste crisis, we must shift our perspective on biodegradable plastics. Redefining them as "efficiently recyclable plastics" rather than merely materials destined for degradation will be crucial. This paradigm shift will facilitate the transition to a circular economy, where biodegradable plastics are subjected to chemical recycling processes, and the materials obtained through upcycling are reused to minimize waste and conserve resources. Therefore, the development of technologies and infrastructure for recycling and upcycling

Table 1
Price and GHG emissions from monomer preparations, and their major applications for biodegradable plastics.

Monomer	Price (USD·kg^{-1})[a]	GHG emission ($kgCO_2$·kg^{-1})	Application for plastics	Refs.
Succinic acid	2.37	0.87–1.39 (bio) 1.94 (petro)	PBS	[51,52]
Lactic acid	2.12	0.30–1.20 (bio)	PLA	[53]
Ethylene glycol	0.63	1.09 (bio) 1.50 (petro)	Bio-PET, PET	[54]
Terephthalic acid	0.35	1.21 (petro)	PBAT, PET	
Adipic acid	1.28	4.87 (bio) 12.81 (petro)	PBAT	[55]
Caprolactone	4.71[b]	1.56 (bio) 3.00 (petro)	PCL, polyurethane	[56]

[a] Referenced from the Korea International Trade Association (December 2023).
[b] Based on PCL.

biodegradable plastics is important for realizing their full environmental benefits.

The price competitiveness and CO_2 reduction associated with the recycling of conventional plastics highlight the viability of recycling biodegradable plastics. Literature evidence from cradle-to-gate LCA indicates that recycled polyethylene terephthalate (rPET), whether recycled mechanically or chemically, results in 25%–30% fewer GHG emissions compared to virgin PET [62,63]. As more global food and apparel corporations mandate the use of rPET, this environmentally friendly alternative increasingly competes with virgin PET in terms of cost-effectiveness. These results suggest a parallel opportunity for biodegradable plastics, which, if approached with a similar recycling mindset, can also achieve meaningful reductions in both waste and emissions.

4.2. LCA insights

LCA is a systematic methodology for evaluating the environmental impact of a product throughout its life cycle from raw material extraction to manufacturing, use, and disposal. By quantifying resource consumption, emissions, and waste, an LCA provides a comprehensive assessment of environmental impacts, including those related to climate change, acidification, and toxicity to humans and ecosystems. It is a decision-making tool widely used across various industries to promote sustainable development and minimize environmental impacts.

Regarding the EoL options for biodegradable plastics, research has indicated that mechanical recycling generally achieves the best environmental and economic performance, particularly in terms of eco-efficiency [64]. These findings challenge the traditional belief that composting is a viable EoL solution for biodegradable plastics. An LCA study compared the environmental impacts of PLA disposal methods, such as composting, chemical recycling, and mechanical recycling, on climate change, human toxicity, and fossil fuel depletion. Composting showed the highest environmental impact, set at 100%, whereas chemical recycling reduced these impacts to 10%–30%; mechanical recycling achieved even lower impacts of 5%–10% [65].

From an energy perspective, composting 1 kg of PLA (kgPLA) requires approximately 43 MJ of fossil energy, which is nearly 11 and 6 times higher than the energy required for mechanical recycling (4 MJ) and chemical recycling (9 MJ), respectively [65]. Moreover, composting does not enable material recovery, meaning that the production of additional virgin PLA compensates for this loss. It also does not contribute to energy recovery or material circularity because the fixed carbon contained in PLA is emitted as CO_2 during the composting process. Although PLA is derived from biomass, and the carbon emitted can eventually be reabsorbed by plants, reconversion to stable carbon stocks takes time. However, recycling circumvents the environmental burdens associated with biomass cultivation, such as land use, fertilizer application, and transportation, offering clear advantages in terms of land occupation, eutrophication, and acidification. Although composting remains a valid option when recycling is not feasible, recycling has been shown to be more sustainable and circular in PLA EoL management.

Recent LCA results for PLA demonstrate that chemical recycling is significantly more energy efficient than other methods, with −1.67 t of CO_2 equivalent (tCO_2-eq) per tonne of recycled PLA. This is in contrast to composting and incineration, which have ratios of 125 and 451 kg of CO_2 equivalent ($kgCO_2$-eq), respectively [66]. Mechanical recycling, while also efficient with −1.75 tCO_2-eq, is less effective owing to the degradation of PLA quality during the process.

In addition, an LCA analysis conducted by Corbion indicated that the lactic acid used to produce PLA acts as a carbon sequestrator, showing −0.22 $kgCO_2 \cdot kgPLA^{-1}$, which means more carbon is absorbed than emitted during production [67]. From a cradle-to-gate perspective, PLA has a global warming potential (GWP) of just 0.5 $kgCO_2 \cdot kgPLA^{-1}$, which is about 75% lower than that of most conventional plastics. The shift from negative to positive GWP was likely due to the energy inputs during polymerization and processing; however, biomass-based plastics still offer substantial carbon offsets. If the lactic acid from PLA is chemically recycled, the GWP can be further reduced, potentially in the range of −0.22 to 0.50 $kgCO_2 \cdot kgPLA^{-1}$. Although a few LCAs have addressed this specific scenario, currently available data strongly indicate its potential for significant carbon savings.

4.3. Comparing decomposition energies: Biodegradable vs conventional

Although PET constitutes only 8% of global plastic production, it represents 50%–60% of the recycled plastic market [68]. This substantial market presence is largely attributable to the value-driven monomer PET, in which end products, such as bottles, are prevalent in households and easy to collect. Likely contributing to this recycling ease is the fact that PET, unlike polyolefins, contains ester bonds that are readily degradable. In chemical recycling, the magnitude of the activation energy is directly related to the efficiency of the recycling process, making PET a favorable candidate. The recyclability of PET is enhanced by the ester bonds, which are easier to degrade than the robust C–C bonds in polyolefins.

Most commodity plastics are olefin-based polymers such as LDPE, HDPE, and PP. These polymers pose a significant challenge for recycling or upcycling through chemical processes, primarily pyrolysis, because their polymer chains are composed of robust C–C covalent bonds, necessitating high activation energies (150–250 $kJ \cdot mol^{-1}$) and advanced catalysts [69]. Olefin-based polymers are typically produced at a relatively low cost from olefin monomers (e.g., ethylene and propylene), which are primarily derived from petroleum (via naphtha cracking), coal, and shale gas. Owing to their low production costs, recycled polyolefins have limited economic value and are primarily used as fuel, resulting in recycling rates that generally remain below 10% [70]. The energy-intensive decomposition of polyolefins not only contributes to their long-term environmental impact but also poses challenges for recycling [31,57,71,72]. Recycling polyolefins requires considerable energy input to break down the materials and process them into new products compared with biodegradable plastics, as shown in Fig. 4 and Table 2 [69,73,74,78–89]. This high energy demand limits the overall sustainability of polyolefin recycling in terms of GHG emissions.

On the other hand, PET, a condensation polymer with an ester-based polymer chain, can be readily decomposed through hydrolysis and alcoholysis with relatively low activation energy (> 100 $kJ \cdot mol^{-1}$) [75,77]. This indicates that the upcycling and recycling of PET via hydrolysis and alcoholysis are relatively straightforward. For instance, Rubio Arias et al. [87] reported activation energies of 131.4 $kJ \cdot mol^{-1}$ for PET and 68.6 $kJ \cdot mol^{-1}$ for polycarbonate (PC), reflecting the varying challenges of bond cleavage in these polymers. While PET can partially degrade at 120 °C within 1 min, complete depolymerization requires raising the temperature to 130 °C. In contrast, lower activation energy of PC allows for full depolymerization in just 1 min at 120 °C, highlighting the impact of activation energy on recycling efficiency.

Biodegradable plastics, with their ester and aliphatic structures, exhibit even lower activation energies than PET or polyolefins, typically below 100 $kJ \cdot mol^{-1}$, which enhances their recycling potential via hydrolysis or alcoholysis. As a result, biodegradable plastics offer enhanced recycling efficiency compared with their conventional counterparts. Beyond recycling, the low activation energies of biodegradable plastics imply that when released into the environment, they can break down more readily [88].

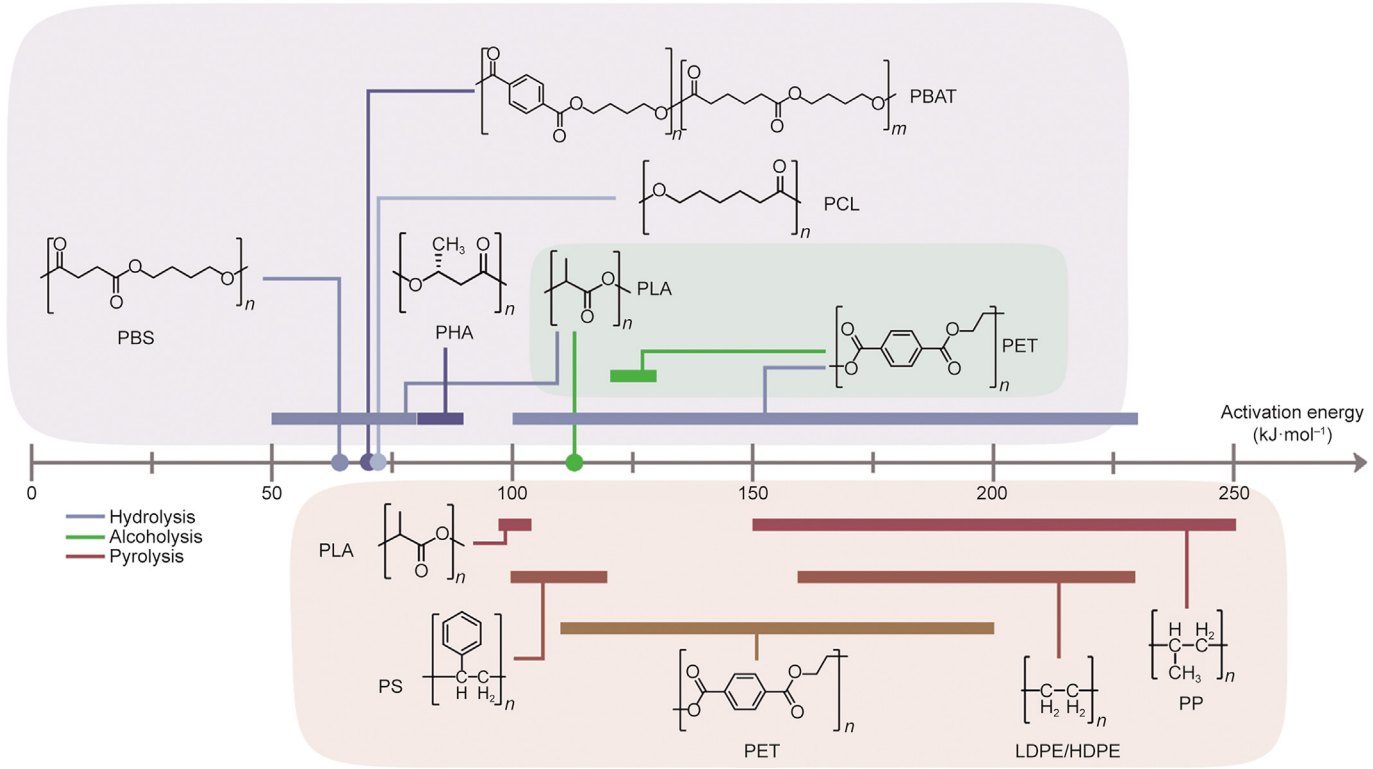

Fig. 4. Activation energy of various polymers for different depolymerization methods. The red scale represents pyrolysis, the green scale represents alcoholysis, and the blue scale represents hydrolysis.

Table 2
The activation energy of various polymers for different depolymerization methods.

Polymer type	Activation energy (kJ·mol^{-1})	Method	Refs.
LDPE	160–230	Pyrolysis	[73]
HDPE	160–230	Pyrolysis	[73]
PP	150–250	Pyrolysis	[69]
PS	100–120	Pyrolysis	[74]
PET	110–200	Pyrolysis	[74]
	100–230	Hydrolysis	[75,76]
	120–130	Alcoholysis	[77]
PLA	97–104	Pyrolysis	[78]
	50–80	Hydrolysis	[79,80]
	113	Alcoholysis	[81,82]
PBAT	70	Hydrolysis	[83]
PBS	64	Hydrolysis	[84]
PHA	80–90	Hydrolysis	[85]
PCL	72	Hydrolysis	[86]

Considering enzymatic breakdown, biodegradable plastics outperform most other plastic types, including PET, which is the most enzymatically degradable traditional plastic. Nonetheless, the discovery of an efficient PET degradation enzyme is a significant scientific achievement owing to the scarcity of diverse and effective enzymes [89]. In contrast, biodegradable plastics are compatible with existing digestive enzymes and are easily broken down. The various enzymes capable of facilitating the biodegradation of these plastics are summarized in Table 3 [90–118].

5. Sustainable strategies for biodegradable plastics

5.1. Case studies of chemical recycling

Compared to traditional plastics, the chemical recycling of biodegradable plastics is an attractive EoL option due to the lower activation energy required for depolymerization. However, the process is not yet mature, largely because biodegradable plastics are often assumed to decompose naturally after use, leading to an underestimation of their recyclability [119]. Nevertheless, chemical recycling of biodegradable plastics can play an important role in carbon sequestration and energy efficiency. Case studies on the chemical recycling of biodegradable plastics are shown in Fig. 5.

The hydrolysis, alcoholysis, and depolymerization processes enable waste plastics to be recycled into monomers or upcycled into other useful compounds. Numerous studies have investigated these processes, particularly for PLA, and identified optimal conditions and key factors.

Tsuji et al. [80,120] demonstrated that hydrolysis of PLA at 180–350 °C resulted in 90% lactic acid yield at 250 °C within 20 min. Their results suggest a bulk erosion mechanism where degradation occurs uniformly throughout the material.

Piemonte and Gironi [121,122] analyzed the hydrolysis kinetics of PLA at 140–180 °C and observed the independence of the reaction from the PLA concentration. They proposed a two-phase reaction mechanism and an autocatalytic effect, achieving complete degradation within 90 min under certain conditions. Iñiguez-Franco et al. [123,124] studied the effect of water–ethanol mixtures on PLA hydrolysis. They estimated that although 41 h would be required to achieve a 95% lactic acid yield at 90 °C, the formation of oligomers suitable for repolymerization would only take approximately 29 h.

Acidic and basic conditions provide different hydrolysis mechanisms for PLA depolymerization [125,126]. Under acidic conditions, hydrolysis is dominated by chain-end scission, whereas, under basic conditions, random chain scission occurs via backbiting. The nature of the hydroxyl terminus affects the kinetics of this process.

Song et al. [127] found that ionic liquids such as 1-butyl-3-methylimidazolium acetate ([Bmim][OAc]) act as both solvent

Table 3
Enzymes involved in the breakdown of biodegradable plastics.

Plastic	Enzyme	Microorganism	Conditions	Refs.
PLA	Esterase	*Pseudomonas aeruginosa*	37 °C, pH 8.0	[90]
		Alcanivorax borkumensis	30–37 °C, pH 9.5–10.0	[91]
		Rhodopseudomonas palustris	55–60 °C, pH 9.5–10.0	[91]
	Proteinase K	*Tritirachium album*	37 °C, pH 7.4–8.6	[92–95]
	Alcalase	*Bacillus licheniformis*	60 °C, pH 9.5	[96,97]
PBS	Cutinase	*Fusarium solani*	37–40 °C, pH 7.2–8.0	[98,99]
	Esterase	*Pseudozyma antarctica*	25 °C, pH 8.5	[100]
		Paraphoma sp.	25 °C, pH 7.2	[100]
	Lipase	*Candida antarctica*	45 °C, pH 7.2	[99]
		Burkholderia cepacia (*Pseudomonas cepacia*)	37 °C, pH 7.2–7.4	[101]
			50 °C, pH 6.0	[102,103]
		Thermomyces lanuginosus	50 °C, pH 6.5	[104]
PBAT	Cutinase	*Thermobifida fusca*	70 °C, pH 9.0	[105]
		Fusarium solani	37 °C, pH 7.2	[106]
			30 °C, pH 6.0	[107]
	Esterase	*Pseudomonas pseudoalcaligenes*	65 °C, pH 7.0	[108]
		Clostridium botulinum	60 °C, pH 7.0–8.0 (Cbotu_EstA); 40 °C, pH 7.0 (Cbotu_EstB)	[109]
	Lipase	*Candida antarctica*	45 °C, pH 7.2	[110]
PHA	Depolymerase	*Bacillus megaterium*	40–45 °C, pH 8.0–8.5	[111]
		Ralstonia pickettii	37 °C, pH 7.4	[112]
		Thermus thermophilus	70 °C, pH 8.0	[113]
		Paucimonas lemoignei	40 °C, pH 8.0–9.0	[114]
	Lipase	*Bacillus subtilis*	40 °C, pH 8.0	[115]
PCL	Cutinase	*Fusarium solani*	37 °C, pH 7.2	[116]
	Lipase	*Candida antarctica*	45 °C, pH 7.2	[116]
		Pseudomonas hydrolytica	40–50 °C, pH 9.0–10.0	[117]
	Lipase–cutinase	*Thermomyces lanuginosus* and *Thielavia terrestris*	40 °C, pH 8.0	[118]

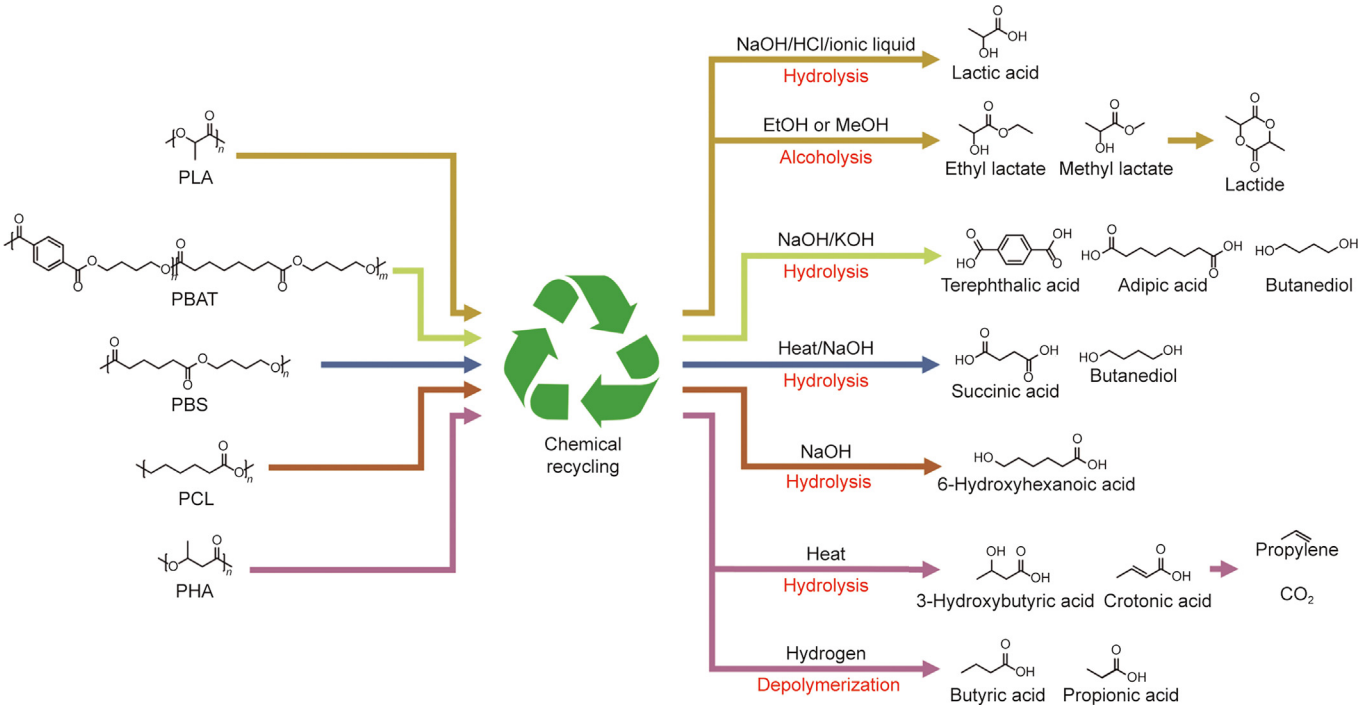

Fig. 5. Chemical recycling processes and products of five different biodegradable plastics.

and catalyst for PLA hydrolysis, achieving high lactic acid conversion at relatively low temperatures.

PLA alcoholysis produces alkyl lactates, such as methyl lactate or ethyl lactate which can serve as green solvents or precursors for other chemicals. Various catalysts have been studied, including acid catalysts [128], basic catalysts [129], metal salts [130], organocatalysts [131], ionic liquids [132], and discrete metal complexes [133].

Remarkably, the stereochemistry of the lactates is often retained, allowing these products to be reused for block copolymers or reconverted to lactides for new PLA production [134,135]. Majgaonkar et al. [136] devised an eco-friendly

recycling model for PLA waste using solvent-assisted transesterification to produce valuable lactate ester. The study evaluated the impact of solvent, nucleophile, and catalyst systems, achieving an 80% ethyl lactate yield with preserved stereochemistry. This model adheres to the principles of green chemistry and sustainable engineering, focusing on managing PLA waste and producing lactate esters while addressing environmental challenges. The strategy simplifies downstream processing, retains market value, and promotes a circular economy for other plastics.

Yang et al. [137] presented a "polymer-to-polymer" chemical recycling approach for PLA, avoiding material performance loss. Using their approach, a PLA polymer chain (approximately 18 000 $g{\cdot}mol^{-1}$) is controlled and cleaved to a lower molecular weight (approximately 4000 $g{\cdot}mol^{-1}$) via transesterification and then participates with methanol. The oligomer is subsequently re-polymerized to PLA (approximately 18 000 $g{\cdot}mol^{-1}$) by adding lactide. This method bypasses the intricate processes of degradation, separation, purification, and repolymerization during PLA recycling.

The natural degradation rates of the five major biodegradable plastics rank in the following order: PHA > PCL > PBS/PBAT > PLA [138]. While PHA degrades rapidly in marine environments, PLA degrades extremely slowly due to the absence of effective microorganisms and thus abiotic hydrolysis is predominant [139,140]. In the literature, PLA remains largely stable in soil, with only about 1% degrading over a span of 100 years [141]. Thus, one can reasonably infer that PHA, PBS, and PBAT possess lower hydrolysis activation energies than PLA. However, research on their chemical recycling, including hydrolysis and polymerization, remains limited compared to PLA. This discrepancy may be related to their respective market shares, which are approximately 40% for PLA, 36% for starch, 9% for PBAT, 8% for PBS, 1.8% for PHA, and less than 1% for PCL [58]. Below, we present hydrolysis studies on biodegradable plastics other than PLA.

Shen et al. [142] established an efficient process for the alkaline hydrolysis of PBAT using potassium hydroxide in ethanol and H_2O solutions. A PBAT degradation ratio exceeding 99% was achieved at 80 °C within 50 min. The diacid salts were recycled through precipitation, and the butanediol monomer was recovered through mild distillation.

Zheng et al. [143] presented a sustainable recycling method for PBS via selective hydrolysis using succinic acid as a catalyst. This method yielded monomers and oligomers in water and achieved a complete hydrolysis yield of 100% at 150 °C, with 79% succinic acid recovery.

Tsuji and Ishizaka [144] conducted the alkaline hydrolysis of PCL films, subjecting them to 4 $mol{\cdot}L^{-1}$ NaOH at 30 °C for up to 96 h. They found enzymatic hydrolysis differed from alkaline hydrolysis, with enzymes primarily targeting chain ends, whereas alkaline treatment resulted in random chain scission. This conclusion was supported by observing a short induction period during time-dependent weight loss screening, followed by a consistently increasing weight loss rate during alkaline hydrolysis.

The hydrolysis of PHA at high temperatures of 175–220 °C has been comprehensively studied [145]. Hydrolysis yields 3-hydroxybutyric and crotonic acids, which are subsequently converted into propylene and CO_2 via dehydration and decarboxylation. In addition to hydrolysis, PHA can be aminolyzed using aqueous methylamine or ethylamine solutions [146].

Wang et al. [147] developed a method for poly(3-hydroxybutyrate) (PHB) alcoholysis using zinc bis[bis(trimethylsilyl)amide] ($Zn(HMDS)_2$) as a catalyst via a coordination–insertion mechanism. The process selectively depolymerizes PHB into alkyl 3-hydroxybutanoate under mild, solvent-free conditions, achieving high yield and purity.

Several studies have illustrated the hydrogenative depolymerization of biodegradable plastics. Krall et al. [148] converted PHA into butyric and propionic acids using Ru complexes as catalysts via hydrogenative depolymerization. Westhues et al. [149] demonstrated the successful degradation of PLA, PCL, and PET through a hydrogenolysis-based process by utilizing a molecular Ru catalyst to derive alcohols. Tang et al. [150] reported an efficient method for recycling polyester wastes, such as PLA, PBS, and PCL, into valuable diols using a Ru–Mo dual-atom catalyst supported on TiO_2. This catalyst enabled the complete hydrogenative depolymerization of diols under mild conditions (160 °C, 4 MPa H_2) with 100% selectivity. Lehnertz et al. [151] demonstrated a hydrogenative depolymerization process for the bioplastics PHB and PLA, using Ru/CeO_2 as a catalyst. They effectively converted PHB and PLA to their respective monomers 3-hydroxybutyric acid and lactic acid with yields of 79% and 94%, respectively. Moreover, selective depolymerization of PHB and PLA into monomers was achieved even in the presence of PET, with comparable PLA yields under both pure and mixed conditions. These findings demonstrate the potential for effective chemical recycling of biodegradable polymers in conjunction with petroleum-based polymers, highlighting the feasibility of recovering valuable monomers despite the heterogeneous nature of the waste.

5.2. Additional EoL approaches

Biodegradable plastic waste can be recycled using other methods owing to its degradability and structural characteristics (Fig. 6). These characteristics offer a wider range of options than conventional plastic waste, underscoring their sustainability. The following subsections discuss four illustrative examples.

5.2.1. Compost

The biodegradability and compostability of plastics ensure their appropriate decomposition and utilization after serving their initial intended purpose. This characteristic is particularly useful for agriculture, where recovery is difficult, and in food waste bags, where separating organics from plastics is challenging [119,152]. Although biodegradation and composting both involve microbial degradation of polymers, they differ in decomposition conditions and final products. Biodegradation converts organic materials into CO_2, new microbial biomass, and inorganic salts under aerobic conditions, whereas composting produces high-value fertilizers for soil enrichment. Various studies are exploring these properties under different decomposition environments and with different plastic compositions, with ongoing efforts to standardize practices in this field.

Pilot-scale composting tests on PLA have shown that the resulting compost had no negative effects on plant germination or growth, demonstrating its safety and quality [153]. Moreover, biodegradable plastics have been found to reduce ammonia (NH_3) gas emissions during composting, which is a major cause of odors in the process. As PCL decomposes, it can neutralize and bind NH_3 produced during organic matter decomposition, acting as a reserve acid and mitigating odor issues [154]. A composting study by Altieri et al. [155] on mixtures of poly(butylene succinate-*co*-adipate) (PBSA) and hydrolyzed collagens showed that adding hydrolyzed collagens to PBSA accelerates the composting of mixtures containing organic nitrogen, demonstrating its potential as a fertilizer in agricultural settings, similar to mulch films. In addition, a study on composting food waste with biodegradable bags showed that bags made of PLA and PBAT can accelerate the decomposition of organic matter, increase the temperature, and alter the richness and diversity of bacterial communities in compost [156]. Research on composting is increasingly being recognized as a vital part of a sustainable circular economy and can contribute to resolving the issue of unrecycled biodegradable plastic waste.

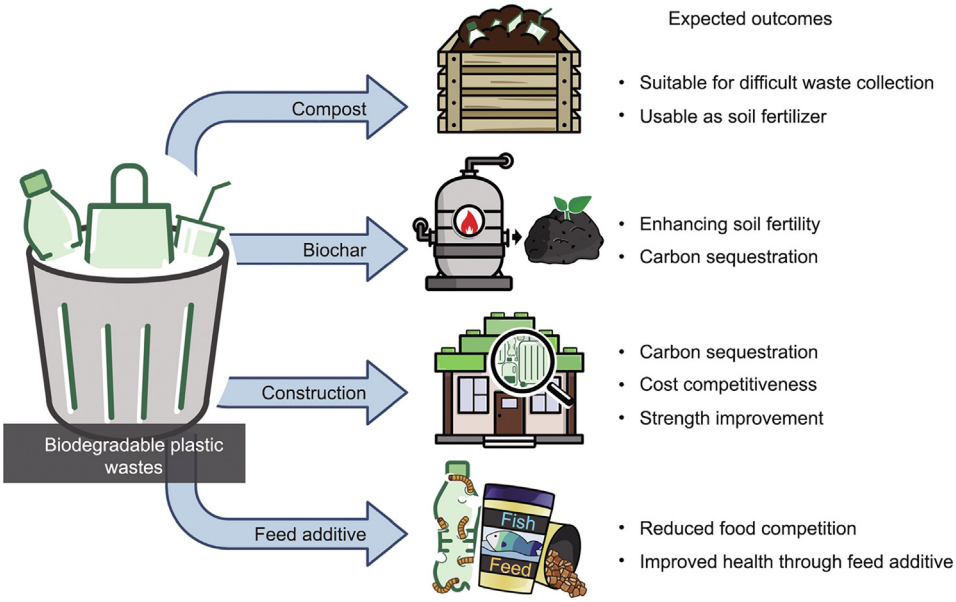

Fig. 6. Alternative methods for recycling biodegradable plastic waste for EoL management and their expected outcomes.

5.2.2. Biochar and pyrolysis

The conversion of biodegradable polymers into biochar offers a sustainable environmental management and waste treatment alternative to traditional recycling methods. Biochar is primarily produced through the pyrolysis of biomass in an oxygen-free environment, enhancing soil fertility and contributing to carbon sequestration, thus playing a crucial role in sustainable agriculture and carbon cycling [157,158].

Currently, biochar production from biodegradable polymers is in the early stages of research, likely due to the relatively small market share of biodegradable plastics. However, considering the potential of biochar and the growing market for biodegradable plastics, further research and development in this area are essential. The recovery of biochar from plastic waste could be instrumental in improving plastic-contaminated environments [159].

According to existing biochar research, the co-conversion of biomass and plastics can produce biochar at higher yields from many components in municipal solid waste, thus facilitating waste management [160–162]. Biomass, with its low carbon and high oxygen content, produces oxygen-rich pyrolysis oil, while traditional plastic waste, with its high carbon and low oxygen content, produces hydrocarbon-based pyrolysis oil. Co-processing these materials increases charcoal formation as the additional carbon from plastics enhances the carbon supply [160,161]. Biodegradable plastics, similar to other plastics, can be mixed with biomass for biochar production to balance the carbon and oxygen contents. Moreover, crosslinked post-consumer resins from biodegradable plastics with relatively high thermal stability can form more stable carbon structures in biochar [163,164].

5.2.3. Construction materials for carbon sequestration

By 2015, plastics used in building and construction materials represented 19% of the total plastic industry, second only to packaging materials, which accounted for 42% [165]. As a building material, plastic offers several advantages: It is lightweight, durable, processable, thermally insulating, and economical, and it can diversify building appearances through various colors and designs. While the expected lifespan of packaging materials is around 0.5 years, plastics used in construction can last for 30–40 years, suggesting their potential for carbon sequestration, especially when using biomass-derived plastics.

In parallel, wood waste has been explored as a building material for carbon sequestration. Similarly, bio-derived biodegradable plastics are being explored for use in construction as a sustainable alternative to traditional plastics, offering environmental benefits and carbon sequestration potential similar to natural materials such as wood [166]. These bio-derived plastics could mitigate environmental impacts such as GHG emissions associated with traditional non-biodegradable plastics. However, since the decomposition of biodegradable plastics releases CO_2, the development of coating technologies that inhibit degradation during their lifetime or provide antimicrobial properties is essential [167,168].

In line with these trends, the UK design firm ecoLogicStudio is engaged in the Hydro Organism Responsive to Urban Stimuli project, which aims to innovate in the field of building materials by fusing different types of biomass (e.g., microalgae), with plastics derived from biological sources (e.g., PLA), or plastics that have been recycled (e.g., rPET) [169–171]. This method introduces a new perspective on the utilization of sustainable materials in construction and is drawing attention as an inventive approach for achieving eco-friendly and sustainable architectural designs.

The incorporation of waste plastics into building materials presents an effective strategy for reducing plastic waste. These mixtures not only offer cost competitiveness but also enhance the physical properties of construction materials, including cohesion, compressibility, and shear strength [172,173]. By integrating plastic waste into construction materials, the environmental impact is further minimized, as this approach extends the effective lifespan of the waste, reducing the need for landfill space and contributing to more sustainable waste management practices [174].

5.2.4. Feed and additives for living organisms

The discovery that certain insect larvae can ingest plastics offers a promising new approach to plastics biodegradation. These insect larvae have digestive tracts that contain microorganisms and enzymes capable of degrading polymers, allowing them to survive on a diet that includes plastic. This suggests a potential method for biological upcycling of plastic waste [175,176].

For example, when mealworms were fed on PLA supplemented with 20% bran, the ingested PLA was not only biodegraded, but also used for growth and development [177]. Notably, the biodegradation rate of biodegradable plastics by larvae is faster than that of

conventional plastics. When mealworms were fed on PLA, PS, and PVC, the highest biodegradation and survival rates were observed for PLA, followed by PS and PVC, indicating a correlation between biodegradability and survival rate [178]. In another case, when the diet of mealworms was supplemented with 10% PBAT, the survival rate was 96% and weight gain was approximately 40% [179]. Although supplementing biodegradable plastics with bran improves the survival rate of mealworms compared to those on a 100% plastic diet, competitive digestion sometimes limits polymer degradation. Interestingly, a recent study found that mealworms fed on only PBS had greater weight gain and protein intake than those fed on only bran [180].

Certain biodegradable plastics can be effectively used as feed additives for animals. For example, PHA are particularly effective as a water-insoluble feed supplements in aquaculture. PHA not only provides a source of energy but also inhibits pathogen growth and strengthens the immune systems of aquatic organisms [181,182]. This suggests that PHA waste can serve as a valuable alternative to conventional feed, enhancing both animal health and sustainable waste management [183].

While concerns remain regarding the long-term effects of plastic exposure and ingestion on living organisms, studies have shown promising results. For example, larvae fed on PBAT exhibited higher growth rates in the second generation, suggesting potential benefits of using biodegradable plastics as feed [184]. However, the potential toxicity of plastic waste, especially when contaminated or containing additives, should be carefully considered. Despite these risks, using biodegradable plastic waste as feed presents an efficient and sustainable solution for waste management. Moreover, this approach reduces competition with human food resources, thereby further enhancing the sustainability of waste management practices.

6. Paths toward a sustainable society with biodegradable plastics

6.1. Closed-loop strategy for designing biodegradable polymers

Because biodegradable polymers are based on the assumption of degradation, research has focused on optimizing their bio-based raw materials, mechanical strength, thermal stability, and processability. However, a paradigm shift is underway, as researchers increasingly recognize that EoL management must extend beyond degradation and composting. Recent research has highlighted that designing polymers for efficient chemical recycling is essential for achieving true circularity and driving the development of new polymer structures that enhance performance while enabling closed-loop resource recovery [185].

Recent studies highlight the benefits of this integrated approach. For example, Yan et al. [186] demonstrated that poly(γ-butyrolactone)-*b*-poly(*p*-dioxanone) (PγBL-*b*-PPDO) undergoes sequential depolymerization at 120 °C without catalysts, achieving over 95% monomer recovery, thereby establishing a low-energy recycling pathway. This process begins with the breakdown of poly(γ-butyrolactone) (PγBL) due to its lower thermal stability, followed by the decomposition of poly(*p*-dioxanone) (PPDO) at a significantly lower temperature than its homopolymer. In a complementary approach, Zhang et al. [187] demonstrated that a Brønsted–Lewis acidic ionic liquid system can convert PPDO to its monomer in only 8 min with 99.9% purity, effectively halving the activation energy required compared to conventional methods. Li et al. [188] introduced a novel seven-membered benzodioxepinone lactone (BDXO) that enabled the formation of polymerized BDXO (PBDXO), which can be chemically recycled with over 92% efficiency under mild conditions, while maintaining robust mechanical properties and biocompatibility. Shi et al. [189] developed a strategy using a bifunctional lactone/epoxide monomer to synthesize both polyester and CO_2-based PC, which could be simultaneously depolymerized back to the original monomer under mild conditions, eliminating the need for complex separation processes. These advances show that next-generation biodegradable polymers with novel structural innovations can improve closed-loop cycles, reduce energy consumption, and establish a foundation for a sustainable circular polymer economy.

6.2. Conceptual scenario with biodegradable plastics in marine

The implementation of a circular system for biodegradable plastics is particularly relevant for fishing gear and marine tools. As marine plastic pollution continues to worsen, the loss or disposal of products such as fishing nets, fishing gear, buoys, and ship ropes contributes to serious environmental issues such as ghost fishing and microplastic pollution [39]. According to a report by the Food and Agriculture Organization and United Nations Environment Program (UNEP), approximately 640 000 t of fishing nets are discarded into the oceans globally. Fishing lines, ropes, and nets, particularly those made of nylon 6 and buoys made of PS, do not degrade easily and persist in marine environments for long periods [190].

To address these issues, global companies, such as Patagonia and Samsung, have made advances in recycling discarded fishing nets into clothing and electronic components. For example, ECONYL, a brand of Aquafil, has developed technology to produce high-quality nylon threads similar to virgin nylon from discarded fishing nets. ECONYL technology saves approximately 65 100 t of carbon dioxide emissions per 10 000 t of nylon produced, reducing the global warming impact by up to 90% compared to petroleum-based nylon [191]. While these strategies for recycling conventional materials are important, the development and application of biodegradable materials are even more essential in situations where recycling is difficult or impossible.

Among the biodegradable plastics, PBS has recently emerged as a promising fiber to replace nylon. PBS is environmentally friendly and offers a mechanical strength comparable to that of nylon. The tensile strength of fishing net twines made from PBS-based random copolymers is 510 MPa, which is comparable to that of nylon (492 MPa) [192]. In addition, core–sheath structural fibers using PBAT and PBS also exhibit a strength of 3.5–4.2 g·denier^{-1} (1 denier = 1.111 × 10^{-4} g·m^{-1}), which is close to that of nylon fibers (4–6 g·denier^{-1}) [193,194]. In terms of carbon footprint, PBS shows clear advantages over nylon. Nylon resin emits 8.638 $kgCO_2$-eq·kg^{-1}, compared with 6.6 $kgCO_2$-eq·kg^{-1} for fossil-based PBS and 5.19 $kgCO_2$-eq·kg^{-1} for food waste-based bio-PBS, indicating an even lower environmental impact [194,195]. In particular, recycling biodegradable materials offers additional environmental benefits because it can significantly reduce the carbon footprint of raw material production [196]. In addition, biodegradable plastics lose their mechanical strength relatively quickly in marine environments, significantly reducing the risk of long-term ghost fishing caused by traditional materials [197]. This indicates that the implementation of a closed-loop biodegradable polymer system is an effective strategy for maximizing environmental sustainability.

In conclusion, the use of biodegradable plastics in marine products is an effective way to simultaneously reduce marine pollution and carbon emissions from production and disposal. The use of biodegradable materials and establishment of closed-loop recycling systems can significantly improve sustainability not only in marine plastic management, but also in the plastics industry as a whole.

Table 4
International policies to reduce plastic pollution and promote biodegradable plastics.

Country/region	Policy or regulation	Implementation year	Key objectives	Refs.
European Union	Single-Use Plastics Directive	2021	Ban on selected single-use plastics (e.g., cutlery, plates, straws, and food containers)	[198]
	Packaging and Packaging Waste Regulation	By 2028	All packaging must be sustainable by 2028	[199]
Italy	Plastic Tax & Compostable Packaging	Since 2020	Tax exemption for certified biodegradable packaging; mandatory compostable fresh-food bags	[200]
France	Biodegradable Packaging & Plastic Phase-out	By 2040	Complete elimination of single-use plastics by 2040; promotion of biodegradable alternatives	[201]
United States (California)	Senate Bill 54	By 2032	25% reduction in single-use plastic packaging; 100% packaging recyclable or compostable	[202]
China	Biodegradable Plastic Promotion	Since 2020	Ban or restriction on non-biodegradable plastic bags in major cities	[203]
India	Single-Use Plastic Ban & Compostable Exemption	2022	Ban on single-use plastics; compostable plastics exempted	[204]
Malaysia & Vietnam	Conventional Plastic Bag Phase-out	By 2025	Complete ban on single-use plastic bags in retail, hospitality, and tourist sectors by 2025	[205,206]
Republic of Korea	Plastic-Free Roadmap	By 2030/2050	End use of single-use plastic bags by 2030; switch entirely to biodegradable plastics by 2050	[207]

6.3. Global policy frameworks and agreements for biodegradable plastics

Addressing the global challenge of plastic pollution and effectively adopting biodegradable plastics require coordinated efforts at both national and international levels. Since 2020, major economies have implemented significant policies to reduce plastic pollution and promote the adoption of biodegradable plastics (Table 4) [201–210]. These initiatives address pressing environmental concerns related to plastic waste and actively support the transition to a circular economy. Especially, global cooperation has further accelerated efforts to adopt biodegradable plastics. In 2022, 175 countries at the United Nations Environment Assembly (UNEA) agreed to establish a legally binding global plastic pollution treaty by 2024, with the goal of standardizing criteria and labeling for biodegradable plastics [208]. Similarly, the Group of Twenty (G20) Osaka Blue Ocean Vision in 2019 called for the elimination of marine plastic waste by 2050, with an emphasis on biodegradable alternatives [209]. In addition, the New Plastics Economy Global Commitment, led by UNEP and supported by more than 500 companies, mandates that all plastic packaging be reusable, recyclable, or compostable by 2025 [210].

Given the global scale and transboundary nature of plastic pollution, both national action and international cooperation are important. Standardization and the development of efficient collection and treatment systems are essential to ensuring the sustainability of biodegradable plastics. Global organizations such as UNEP and the International Organization for Standardization must unify certification standards and eliminate trade barriers, facilitating broader adoption of biodegradable plastics.

7. Conclusions

Biodegradable plastics are emerging as promising alternatives to traditional petroleum-based plastics because of their potential to alleviate the global plastic waste crisis and reduce the associated environmental impacts. However, as this review demonstrates, fully realizing the benefits of biodegradable plastics requires shifting beyond the simple perception that they merely "decompose" upon disposal. Redefining biodegradable plastics as "efficiently recyclable materials" allows active consideration of EoL strategies, such as chemical recycling, and highlights their potential value within a circular economy, rather than a linear, disposal-oriented system.

Biodegradable plastics are primarily polyester-based, and they significantly reduce the activation energy required for chemical degradation. Consequently, they are more susceptible to processes such as hydrolysis, alcoholysis, and pyrolysis than polyolefin-based materials such as PE and PP. This enhanced reactivity leads to reduced processing requirements and improved recycling efficiency, rendering biodegradable plastics more economical and environmentally beneficial alternatives. Various studies, including LCA, have shown that chemical recycling can recover monomers in high yields, reduce waste, and significantly diminish resource consumption and GHG emissions. Furthermore, considering these plastics as resources rather than disposable materials provides them with a comparative advantage over traditional petroleum-based polymers.

To achieve this, the following key priorities must be addressed: First, the public misconception that biodegradable plastics do not need to be recycled hinders the wider adoption of closed-loop recycling practices. Second, with new environmental regulations and international initiatives, coordinated efforts at national and global scales are more crucial than ever. Issues such as high initial costs and contamination risks in mixed waste streams further highlight the need for robust policy frameworks and strong infrastructures for sorting, collection, and reprocessing. Finally, continued innovation and interdisciplinary collaboration in the recycling of biodegradable plastics have significant potential to reduce plastic pollution and carbon footprint, ultimately playing a pivotal role in advancing a sustainable circular economy.

CRediT authorship contribution statement

Sungbin Ju: Writing – original draft, Visualization, Data curation. **Seonghyun Chung:** Writing – original draft, Visualization. **Sung Bae Park:** Funding acquisition, Data curation. **Jun Mo Koo:** Writing – review & editing. **Giyoung Shin:** Validation, Funding acquisition, Formal analysis. **Hyeonyeol Jeon:** Writing – review & editing, Validation. **Jeyoung Park:** Writing – review & editing, Conceptualization. **Dongyeop X. Oh:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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