Journal of Korea TAPPI
Vol. 57. No. 2, 2025, 5-19p
ISSN (Print): 0253-3200
Printed in Korea
https://doi.org/10.7584/JKTAPPI.2025.4.57.2.5

A Review of Biodegradation Mechanisms and Evaluation Methods for Biobased Materials: Polysaccharides, Lignin, and Biopolyesters

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Received April 8, 2025; Received in revised form April 17, 2025; Accepted April 18, 2025

ABSTRACT

With increasing concerns over plastic waste, biobased materials have emerged as promising alternatives due to their renewable origin and potential biodegradability. However, biodegradation varies significantly depending on material composition, structural properties, and environmental conditions. This review explores the biodegradation characteristics of biobased materials, focusing on the key factors influencing their degradation processes. The discussion covers the general biodegradation mechanisms of biobased materials and the role of microbial and enzymatic activity. Structural properties such as crystallinity and polymer composition play a crucial role in determining degradation rates. Additionally, environmental factors, including temperature, moisture, and microbial communities, further impact biodegradability. A comprehensive understanding of these aspects is essential for optimizing material performance and sustainability. This review is expected to provide insights that support the development of biodegradable biobased materials for applications in packaging, textiles, and other sustainable industries.

Keywords: *Biobased materials, lignocellulose, biodegradation, biodegradation mechanisms*

1. Introduction

The global plastic crisis has become increasingly severe over recent decades, with more than 7 billion tons of plastic waste produced between 1950 and 2017, and only about 10% of it effectively recycled.[1-3] This persistent accumulation of plastic waste has led to growing environmental concerns, including microplastic contamination in oceans and greenhouse gas emissions from plastic production and incineration. By 2019, an estimated 6.1 million tons of plastic waste had entered marine ecosystems, severely impacting biodiversity and food safety.[4] The proliferation of microplastics has raised health concerns globally, with studies detecting synthetic particles in aquatic species and even in human lung tissue.[5,6]

In response to these environmental challenges, attention has turned to sustainable material alternatives—particularly biobased and biodegradable materials. While often used interchangeably, the two terms refer to distinct concepts. Biobased materials are derived from renewable

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biological resources but are not necessarily biodegradable.[7] In contrast, biodegradable materials are defined by their ability to be broken down by microorganisms, regardless of whether the material originates from fossil or biological sources.[7] This distinction yields four classifications:[7] (1) biobased and biodegradable, (2) biobased but non-biodegradable, (3) fossil-based but biodegradable, and (4) fossil-based and non-biodegradable. Despite this broader classification, the current study is limited to biobased biodegradable materials.

Biobased materials originate from a variety of sources, making it difficult to define typical properties for these materials. Similarly, even among biodegradable biobased materials, their biodegradability and biodegradation mechanisms can vary significantly. Therefore, to better understand the biodegradability and underlying degradation mechanisms of biobased materials, it is necessary to further classify biodegradable biobased materials—either by their sources or by their chemical structures.

Biobased materials are often classified according to their sources. For example, they can be grouped into agropolymers (originating from agricultural resources), microorganism-derived polymers, and bio-derived synthetic polymers. However, when it comes to understanding biodegradation mechanisms, it is more effective to classify them based on their chemical structures. For example, the degradation mechanism of a polymer depends on its backbone structure, which in turn determines which enzymes or microbial species can effectively break it down.[8-10] Furthermore, even among polymers with the same backbone, substitution groups and crystallinity can significantly affect biodegradation behavior. A notable case is cellulose acetate, a derivative of cellulose where the degree of acetyl substitution (DS) directly affects its biodegradability in aqueous environments.[11] Therefore, in the present study, biodegradable biobased materials are investigated within the following groups: polysaccharides (e.g., cellulose, hemicellulose, chitin, chitosan), lignin, and biopolyesters (e.g., polylactic acid (PLA), polycaprolactone (PCL), and polyhydroxyalkanoates (PHAs)), which represent the most prevalent biodegradable structures encountered in the field.

Environmental conditions also play a key role in biodegradation of biobased materials. PLA, a widely used biobased polyester, has high biodegradability under industrial composting conditions but degrades very slowly in marine or ambient soil environments.[12-21] Similarly, PCL has shown differential degradation rates depending on whether the system is aerobic or anaerobic.[14,22-24] These observations suggest that evaluating the biodegradability of materials requires not only material-level analysis but also a detailed understanding of microbial and enzymatic activity under varied environmental conditions.

This review aims to provide a comprehensive overview of the biodegradability of biobased materials by exploring their degradation mechanisms, the influence of chemical and physical structures on degradation behavior, and current evaluation methodologies. By identifying key factors that affect biodegradation, the review intends to offer insights that may inform the design of materials that maintain functional durability during use while enabling effective degradation after disposal. Particular attention is given to lignocellulosic materials such as pulp and paper products, which are among the most widely used biobased materials. These insights are anticipated to support ongoing research and development efforts toward next-generation biobased materials that combine reliable performance with environmental sustainability.

2. General Biodegradation Mechanisms

2.1 Definition and biodegradation process

Biodegradation is a process in which organic materials are chemically broken down by microorganisms such as bacteria, fungi, and algae.[25,26] Generally, high-molecular-weight polymers cannot be directly absorbed by microorganisms due to their size. Instead, microbes secrete extracellular enzymes that cleave polymer chains into smaller molecules. These lower-molecular-weight fragments are then taken up by the microbial cells and further

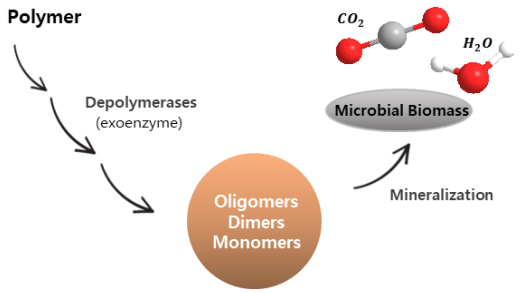

Fig. 1. General biodegradation process.

metabolized by intracellular (endo-)enzymes into inorganic compounds. In aerobic conditions, the end products are primarily carbon dioxide (CO_2) and water (H_2O), whereas in anaerobic conditions, methane (CH_4) is also produced.[8,10,27] Thus, biodegradation is essentially an enzymatic depolymerization process. Fig. 1 illustrates this general pathway.

When analyzing the biodegradation of biodegradable materials, the process is generally characterized by three distinct phases.[28] The lag phase is a preparatory stage during which microbial communities adapt to the surrounding environment and attach to the polymer surface. This is followed by the biodegradation phase, the active stage in which enzymatic hydrolysis or oxidation breaks down polymer chains into oligomers and monomers, which are subsequently metabolized by microorganisms. Finally, the plateau phase marks a decline in the degradation rate, often due to the depletion of accessible degradable components or the accumulation of inhibitory byproducts. These phases can vary significantly depending on polymer type, morphology, and environmental conditions.[29]

2.2 Key physicochemical factors

The biodegradation of biobased materials is not determined by a single intrinsic property, but rather by a combination of structural characteristics and environmental conditions that collectively influence enzymatic accessibility and microbial colonization. Several key physicochemical parameters contributing to this process are as follows: polymer backbone structure, crystallinity, molecular weight and polydispersity, substitution groups, hydrophilicity and surface wettability, and so on (Fig. 2).

The chemical nature of the main chain strongly influences its susceptibility to enzymatic cleavage. Ester and glycosidic linkages, which are hydrolyzable, are more amenable to microbial degradation than stable carbon-carbon bonds.[7-10,29-32] In addition, functional groups such as acetyl, methyl, or carboxyl groups can either hinder or promote biodegradation depending on their steric and electronic effects. For instance, cellulose acetate's biodegradability decreases with higher degrees of substitution.[33-35] On the other hand, biodegradability of biopolyesters, such as PHAs can be increased with the longer side chains due to increased chain mobility and accessibility of enzymes to the polymer chains.[29]

Crystallinity plays a critical role in the biodegradation of polymeric materials. Polymers with highly crystalline regions are generally more resistant to biodegradation, primarily due to reduced water permeability and limited accessibility to enzymatic attack.[7,9,36,37] In contrast, amorphous regions are more susceptible to microbial degradation, and materials with lower overall crystallinity tend to degrade more readily. Notably, studies on biobased polyesters have reported an inverse relationship between crystallinity and biodegradability.[29]

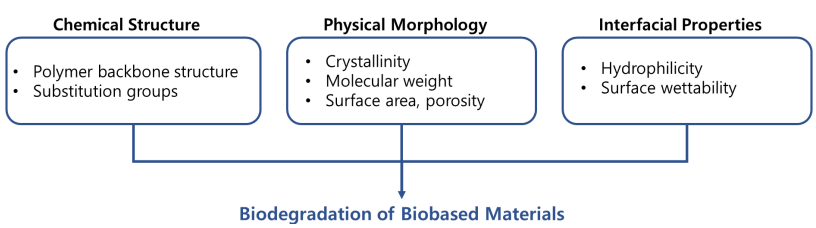

Fig. 2. Physicochemical factors affecting biodegradation of biobased materials.

Materials that absorb water more readily tend to facilitate faster microbial colonization and enzymatic activity. Surface hydrophilicity influences not only the initial adhesion of microorganisms but also subsequent enzymatic hydrolysis. One study reported that the onset of biodegradation in biobased polymers was closely related to their surface hydrophilicity, particularly during the initial phase of water absorption.[29)]

2.3 Environmental conditions and biodegradation behavior

A wide variety of microorganisms—including fungi, bacteria, and algae—are capable of breaking down polymeric materials. However, the population and composition of these microbial communities vary significantly depending on environmental factors such as temperature, pH, and oxygen availability. As a result, biodegradation is highly environment-dependent, and the mechanisms involved may differ even for the same material.

Due to these variations, direct comparison of biodegradability across different studies can be challenging unless environmental conditions and microbial inocula are clearly specified. Therefore, biodegradation assessments are generally reported along with detailed information on testing conditions, such as temperature, medium, pH, oxygen presence, and microbial source.[28)]

Numerous studies have demonstrated that the degradation rate of biobased and biodegradable polymers varies greatly depending on these conditions. For instance, PLA shows negligible degradation at ambient temperatures, but significant degradation at elevated temperatures: 29–49% biodegradation at 37°C and up to 82% at 55°C have been reported.[12-21,29)] Most studies that demonstrate PLA degradation use test environments above 30°C, with faster rates observed under alkaline conditions.

PCL, another widely studied biodegradable biopolyester, also exhibits environment-dependent behavior. In marine conditions, complete degradation has been observed within two months, whereas in saline solutions, only a 20% weight reduction was noted after ten weeks.[22)] In contrast, PCL showed a 95% weight loss when incubated with compost-derived microbes, a 90% loss in aerobic activated sludge, and a 22% loss under anaerobic sludge conditions.[14,23,24)]

Among natural polymers, lignin is known to be particularly recalcitrant, primarily due to its complex aromatic structure and the limited number of microbial species capable of degrading it—mainly certain fungi and a few bacterial strains.[10,38,39)]

These findings underscore the importance of considering environmental context when evaluating the biodegradability of biobased materials. To obtain meaningful and comparable results, it is crucial to assess materials under conditions that reflect their intended end-of-life scenarios, and to standardize test parameters when comparing across different materials.

3. Biodegradation of Biobased Materials

3.1 Biodegradation of polysaccharides

Polysaccharides are the most abundant natural polymers on Earth and can be derived from a wide range of biological sources, including plants, animals, microorganisms, algae, and insects. As polysaccharides serve as essential energy sources for many organisms, over 100 types of glycosyl hydrolases capable of degrading them have been identified.[40)] Although polysaccharides are often found in association with peptides or lipids, this review focuses on simple polysaccharides that are not chemically bound to proteins, peptides, or lipids.

The biodegradation of polysaccharides typically involves the hydrolysis of O-glycosidic linkages. This hydrolysis can be classified into exo- and endo-type processes, depending on the types of enzymes involved.[40)] Exo-type enzymes act on the non-reducing ends of the polysaccharide chains, progressively releasing dimers, which are further broken down into monomers. In contrast, endo-type enzymes cleave internal glycosidic bonds, resulting in the formation of lower molecular weight fragments such as oligosaccharides.

Hydrolysis of glycosidic bonds can occur via two distinct catalytic mechanisms: retaining and inverting, depending on the stereochemical outcome at the anomeric carbon.[40-42] In the retaining mechanism, the stereochemistry of the anomeric carbon is preserved (e.g., α → α or β → β), whereas in the inverting mechanism, the configuration is reversed (e.g., α → β or β → α). Similar to the distinction observed between endo- and exo-acting enzymes, different glycoside hydrolase families are associated with each mechanism, reflecting differences in catalytic residues and active site architecture. Despite their mechanistic differences, both mechanisms share fundamental catalytic steps. The glycosidic oxygen is protonated by a catalytic acid residue, facilitating the departure of the aglycon moiety. This is followed by a nucleophilic attack on the anomeric carbon—either by a catalytic residue forming a covalent intermediate (retaining), or by an activated water molecule (inverting)—ultimately leading to cleavage of the glycosidic bond (see Fig. 3).

Cellulose is the most abundant polysaccharide in nature,

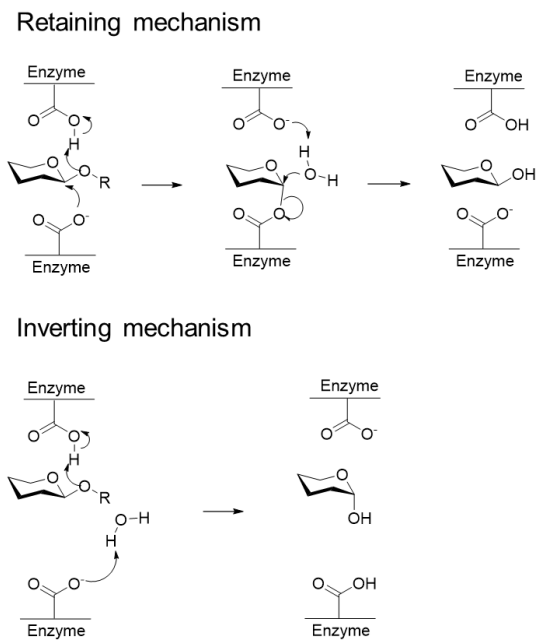

Fig. 3. Enzymatic hydrolysis mechanisms of glycosidic bonds: retaining vs. inverting.

mostly synthesized by plants and algae. It is a linear homopolysaccharide composed solely of glucose monomers and is degradable by various microorganisms, including bacteria and fungi.[43,44] The main enzymes involved in cellulose biodegradation are endoglucanases and cellobiohydrolases (also known as exoglucanases), which act through similar mechanisms as described above.[43-45]

Most cellulose contains tightly packed crystalline regions that hinder enzymatic accessibility. While crystalline domains resist degradation, amorphous regions are more readily attacked.[44,45] Indeed, a strong relationship was already reported between the degree of crystallinity and enzymatic hydrolysis efficiency.[46] As glycosidic bonds are often embedded within cellulose aggregates or crystalline domains, cellulose undergoes a preliminary process known as “amorphogenesis,” involving fibril dispersion, delamination, and reduction in crystallinity.[47,48] Many carbohydrate-hydrolyzing enzymes contain carbohydrate-binding modules (CBMs) that assist in this process.[48-50]

Hemicellulose is a class of amorphous carbohydrates with diverse sugar compositions and branched structures, which vary depending on the plant source. Biodegradation of hemicellulose requires a combination of enzymes that break down heteropolysaccharides into monosaccharides and acetic acid.[10,32,51,52]

Chitin and chitosan, like cellulose, are naturally abundant polysaccharides. Their degradation is catalyzed by chitinases, chitosanases, and a range of glucosyl hydrolases, which cleave the β-1,4-linkages between sugar units.[41] Unlike typical polysaccharide hydrolysis, the acetamide group of N-acetylglucosamine—the main hydrolysis product of chitin—acts as a nucleophile, participating directly in the hydrolytic reaction mechanism.[41,53-55]

3.2 Biodegradation of lignin

Lignin is an amorphous and highly aromatic polymer, which makes it particularly resistant to biodegradation under both aerobic and anaerobic conditions. This structural feature contributes to the durability of lignocellu-

losic biomass and serves as a key factor in the biological resistance of wood fibers.[10,46,56)]

Among the various microbial systems studied for lignin degradation, fungi, such as white-rot fungi, have received the most attention.[32,57-59)] The key enzymes identified in these fungi include lignin peroxidase (LiP), manganese peroxidase (MnP), and laccase, all of which are classified as phenol oxidases.[60,61)] These enzymes initiate lignin degradation through oxidative reactions. The enzymatic breakdown of lignin typically involves three main stages: (1) oxidation of β-O-4 linkages, (2) cleavage of the aromatic ring via the β-ketoadipate pathway, and (3) formation of cyclic carbonate structures resulting from ring cleavage[62-64)] (see Fig. 4).

Peroxidases, including LiP and MnP, catalyze oxidation reactions in the presence of hydrogen peroxide, which serves as an electron acceptor.[65,66)] LiP catalyzes the one-electron oxidation of non-phenolic aromatic units by abstracting an electron from the π-system, thereby generating an aryl cation radical. This highly unstable intermediate facilitates bond cleavages, such as the C_α-C_β bond (cf. Fig. 4a). Following C_α-C_β bond cleavage, the resulting carbocation at the C_α position rearranges to form an aldehyde, while the radical at the C_β position may undergo further reactions due to its high reactivity. Meanwhile, resonance structures that delocalize the

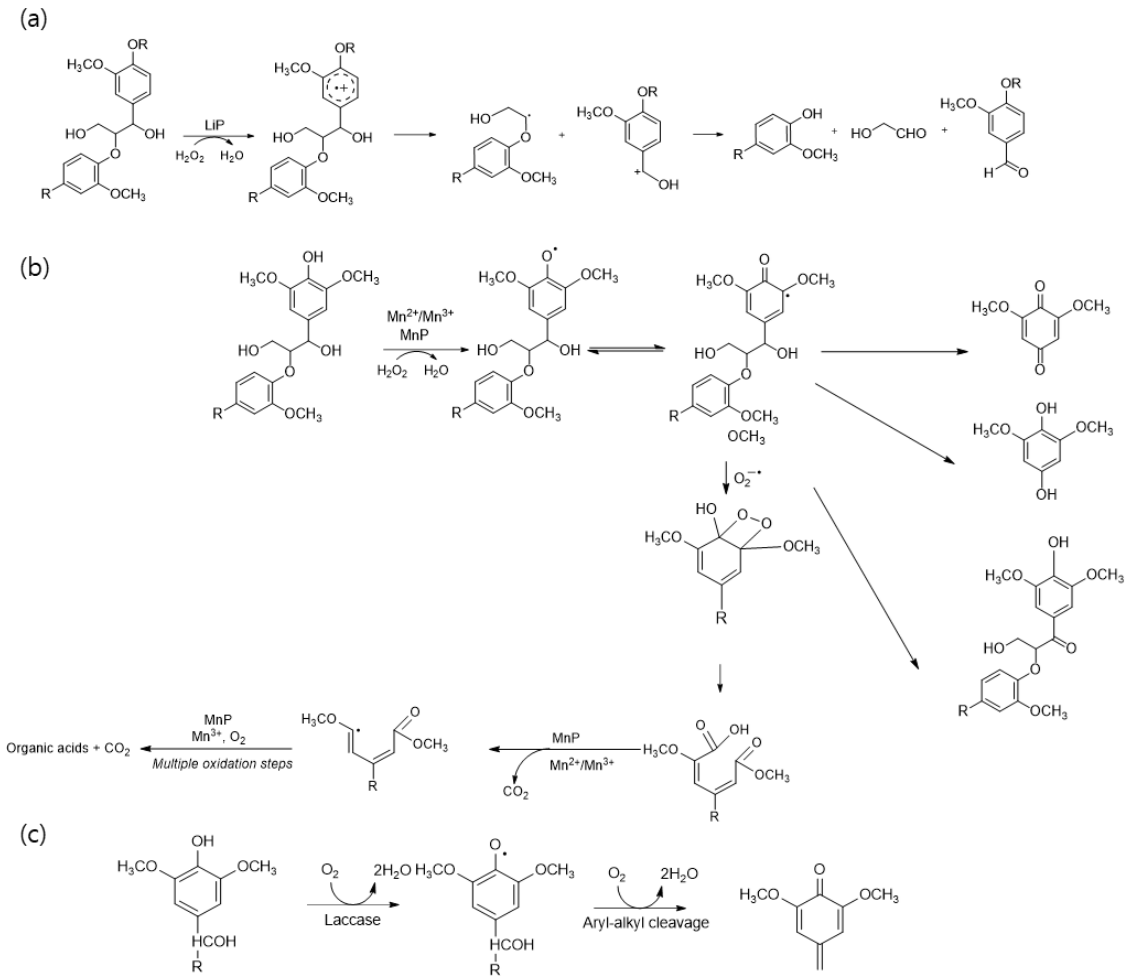

Fig. 4. Example of lignin degradation reaction mechanisms by LiP (a), MnP (b), and laccase (c).[60-72)]

positive charge and radical across different positions of the aromatic ring, can lead to alternative cleavage sites.

MnP initiates its catalytic cycle by reacting with hydrogen peroxide, but it requires Mn^{2+} as an essential electron donor.[61,67,68] MnP primarily oxidizes phenolic lignin compounds into phenoxy radicals via chelated Mn^{3+}, which is formed through the oxidation of Mn^{2+} after MnP interacts with hydrogen peroxide (cf. Fig. 4b). These phenoxy radicals can undergo further transformations, including C_α–C_β cleavage, C_α oxidation, and alkyl-aryl cleavage of syringyl-type dimers. Moreover, it has been suggested that through multiple oxidation steps, MnP can ultimately degrade lignin into CO_2.[69,70]

Laccase primarily oxidizes phenolic units in lignin by generating phenoxy radicals through a single-electron transfer mechanism, similar to that of MnP but without requiring Mn^{2+} as a redox mediator.[71,72] The resulting phenoxy radicals are stabilized through resonance across the conjugated aromatic structures of lignin and can trigger subsequent reactions, including cleavage of interunit linkages such as C_α-C_β bonds and β-O-4 linkages and alkyl-aryl bonds. These cleavage events contribute to the depolymerization of the lignin polymer. Notably, some degradation products of lignin, such as vanillin and p-hydroxybenzoic acid, may act as secondary mediators in the laccase-catalyzed system, further facilitating oxidative bond cleavage and enhancing delignification efficiency.

Bacterial degradation pathways have also been reported.[38,39] Healy and Young demonstrated the potential for anaerobic degradation through in vitro microbial treatments,[38] while Raj and co-workers showed that a single bacterial species could degrade lignin under aerobic conditions.[39] Furthermore, recent studies have shown that bacteria are capable of producing oxidative enzymes, including laccases and dye-decolorizing peroxidases (DyPs), which allow them to degrade lignin in a manner similar to fungi.[73-75] However, it is generally recognized that bacterial lignin degradation is less efficient than fungal degradation.[10] This is largely due to the limited variety and lower catalytic complexity of ligninolytic enzymes in bacteria. Unlike fungal enzymes, bacterial enzymes tend to be structurally simpler, reflecting the limited protein synthesis capacity of bacterial systems.[73]

3.3 Biodegradation of lignocellulosic materials

Pulp- and paper-based materials are typically derived from wood or non-wood plant fibers. Among these, wood fibers are composed of a complex matrix of cellulose, hemicellulose, and lignin, whose chemical composition and structural features vary depending on the type of raw material and the specific mechanical or chemical treatment applied during manufacturing. Due to their natural origin and polymeric structure, lignocellulosic materials are generally regarded as biodegradable and are widely utilized in eco-friendly product applications across various industries.

During the papermaking process, fibers undergo a series of physical and chemical treatments and are often combined with additives such as fillers and strength agents. The choice of raw material and processing conditions depends on the intended use of the final product and significantly affects the chemical and physical characteristics of the final products. For example, corrugated cardboard contains a relatively high lignin content, whereas bleached pulps used for printing paper or food packaging have much lower lignin levels. Products like linerboard and newsprint may incorporate not only virgin pulp but also recycled fibers, which often contain additional components such as chemical additives.

Lignocellulosic biodegradation is a multistep, synergistic process that requires various enzymes, as the three major components—cellulose, hemicellulose, and lignin—are tightly bound within a polymer matrix.[10,32,76] Microorganisms employ two principal extracellular enzymatic systems to degrade lignocellulose: a hydrolytic system, which breaks down cellulose and hemicellulose using hydrolases, and a ligninolytic system, which depolymerizes lignin through oxidative reactions.[32]

A wide range of studies have investigated the biodegradation of lignocellulosic fibers, revealing various aspects

of the underlying mechanisms.[77-90] Under anaerobic conditions, lignin content has been identified as a key factor influencing the rate and extent of degradation.[85,91] Anatomical analyses have shown that biodegradation in anaerobic environments often begins at the center (lumen) of the fiber cell and progresses outward.[80] In contrast, Wang et al.[84] reported cavities on the fiber surface, suggesting that composting microbes may initiate degradation through a tunneling process. These findings indicate that microbial or enzymatic attack typically starts at accessible areas such as the lumen or outer fiber surface. In addition, recent studies have explored various strategies to improve the biodegradation efficiency of lignocellulosic materials, including microbial engineering, the use of surfactants, and the identification of effective microorganisms and enzymes.[43,86,90,92-94]

While composting[78,79,88] and anaerobic digestion[77,80,85,95] have been the main focus of lignocellulosic biodegradation studies, several reports have also examined aerobic conditions.[91,96] Notably, some studies suggest that wood-based materials degrade more effectively in aerobic environments.[91] Furthermore, high lignin content has been correlated with reduced biodegradability and slower initial degradation rates.[96] Structural characteristics such as fiber morphology and degree of crystallinity also influence biodegradation. For example, highly crystalline cellulose limits enzymatic accessibility and slows down degradation, whereas amorphous hemicellulose tends to be more readily degraded.[96] Therefore, a comprehensive assessment of lignocellulosic biodegradability should consider not only chemical composition but also structural features and environmental conditions.

3.4 Biodegradation of biopolyesters

Many biodegradable polymers of biological or microbial origin fall under the category of polyesters. Polyesters are characterized by repeating ester linkages, making them particularly susceptible to enzymatic and hydrolytic degradation. The ester linkages in these polymers increase their hydrophilicity, rendering them more responsive to moisture and enzymatic attack. These ester bonds act as primary sites for enzymatic cleavage during biodegradation.[97] Thus, the degradation of polyesters typically begins with the enzymatic cleavage of ester bonds.[98,99] While many biodegradable polyesters are synthetically produced, some are biosynthesized by microorganisms or derived from renewable biobased monomers.[100] To date, more than 30 biobased aliphatic monomers have been developed,[97] and more are expected to follow.

Based on their polymer backbone structure, polyesters are generally classified as either aliphatic or aromatic. Most biodegradable biopolyesters—such as PHAs, including polyhydroxybutyrate (PHB), poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), and poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) (PHBH), as well as PLA and polybutylene succinate (PBS)—belong to the aliph-

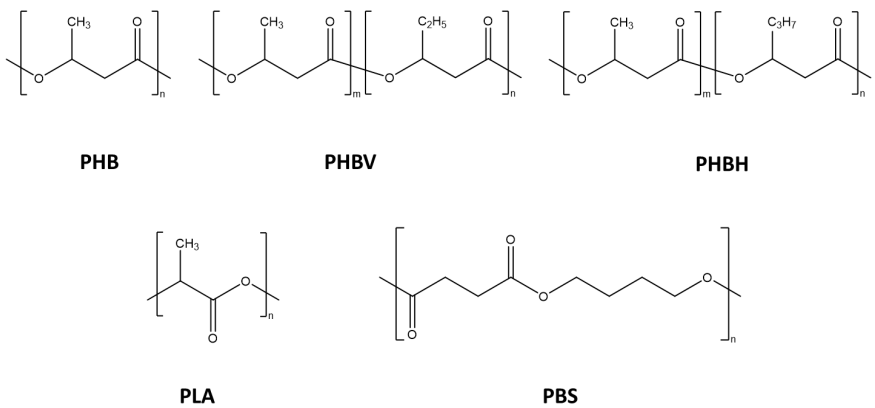

Fig. 5. Examples of biobased polyesters.

atic category. Consequently, current research efforts are primarily focused on aliphatic biobased polyesters. Fig. 5 illustrates the typical molecular structures of biobased and microbially derived aliphatic polyesters.

Various enzymes are involved in polyester biodegradation, and the mechanisms differ depending on the enzyme type and polymer characteristics. Satti and Shah summarized key polyester-degrading enzymes, including lipases, esterases, proteases, cutinases, catalases, ureases, and glucosidases.[98] These enzymes exhibit substrate specificity, suggesting that each polyester requires an optimized enzymatic system depending on its molecular structure and properties.

Among these enzymes, esterases play a central role in polyester degradation. The activity of esterase can be related to the chain length of biopolyesters. For example, studies using activated sludge revealed that esterase activity decreases as the length of the aliphatic chain increases,[101] which may account for the relatively slower degradation observed in long-chain polyesters like PBS and PCL. A similar trend was reported by Kwon et al.,[29] who observed delayed degradation in polyesters with longer carbon chains.

PLA is one of the most widely studied biodegradable biobased polyesters. However, its biodegradability remains a topic of debate due to inconsistent degradation behavior under varying experimental conditions, including differences in the enzymes involved. While some studies have reported that lipases and proteases are capable of degrading PLA under specific conditions,[102] others have shown that high-molecular-weight PLA is resistant to degradation, particularly in acidic or neutral environments.[17,102-104] Nevertheless, enzymes such as Proteinase K and subtilisin have demonstrated the ability to degrade PLA, although few enzymes have been identified with such activity, and the degradation rate is significantly slower than that observed for other polyesters such as PHB, PCL, and PBS.[104,105]

In a comparative study the enzymatic degradation of various aliphatic polyesters, including PLA, PCL, and PHB, was investigated using several types of enzymes: lipases, esterases, proteases, and proteinases.[106] They found that Proteinase K showed the highest activity, followed by proteases, esterases, and lipases. The study also revealed that enzyme specificity plays a key role—for instance, PLA was degraded by lipases, while PHB was not. These findings underscore the importance of selecting enzyme systems tailored to the specific structure of each polyester in order to optimize biodegradation efficiency.

4. Biodegradation Testing and Limitations

The biodegradability of materials is commonly assessed through standardized protocols such as ISO 14851 (aerobic aquatic), ISO 14855 (compost), and ISO 15985 (anaerobic digestion) (Table 1). These tests typically monitor CO_2 evolution or weight loss over time under controlled

Table 1. Examples of international standards for biodegradability testing

Standard	Test environment	Target material	Maximum test period	Biodegradation requirement	Measurement index	Test temperature
ISO 14851	Aerobic, Aqueous	Plastics	Up to 6 months	N/A	Amount of oxygen consumed	25 ± 2°C
ISO 14855	Aerobic, Composting	Plastics	Up to 6 months	≥90% within 180 days	Amount of carbon dioxide generated	58 ± 2°C
ISO 15985	Anaerobic, High-solids digestion	Plastics	Up to 6 months	>70% after 15 days	Amount of biogas generated (CH_4 + CO_2)	52 ± 2°C

laboratory conditions using inoculums like activated sludge or compost. Depending on the intended end-use environment—soil, marine, or industrial compost—different test conditions apply. For instance, while PLA exhibits poor degradation in aquatic environments, it shows relatively better performance under high-temperature industrial composting.[12-17,29] This highlights the importance of selecting test conditions that reflect the real-world disposal context of the material. Failure to align laboratory tests with actual environmental conditions may lead to misleading conclusions about a material's environmental fate.

Despite the utility of such evaluations, several limitations remain. First, biodegradability observed under laboratory conditions does not necessarily translate to effective degradation in natural environments. Factors such as temperature fluctuations, microbial diversity, moisture levels, and oxygen availability vary widely in real-world contexts and can significantly affect degradation rates. Second, chemical additives, surface coatings, or processing aids may modify the surface energy or hydrophobicity of a material, potentially hindering microbial colonization and enzymatic activity. These modifications can lead to incomplete degradation, leaving behind microplastic residues or harmful byproducts. Moreover, biodegradability does not inherently imply environmental benignity. A material that degrades slowly but leaves no toxic residues may be more sustainable than one that degrades rapidly while releasing hazardous intermediates. Therefore, biodegradability should be evaluated in conjunction with other sustainability metrics such as toxicity, carbon footprint, and resource efficiency. Given these limitations, there is a growing need for complementary assessment methods, including long-term field studies, ecotoxicological evaluations, and life cycle assessment (LCA), to gain a more comprehensive understanding of a material's environmental impact. When integrated with LCA, biodegradation testing provides a more holistic framework for evaluating not only the degradation behavior of materials but also their broader environmental trade-offs across the entire life cycle.

5. Conclusion

The growing concern over plastic pollution has prompted increased attention toward biobased materials as sustainable alternatives. However, not all biobased materials are inherently biodegradable or environmentally benign. Their biodegradability is influenced by a complex interplay of chemical structure, crystallinity, molecular architecture, and environmental conditions. This review examined the biodegradation behavior of various biobased materials—including polysaccharides, lignin, lignocellulosic composites, and biopolyesters. The findings emphasize that biodegradation outcomes vary not only by material type but also by testing methods and environmental settings, highlighting the importance of standardized and context-relevant evaluation protocols. To ensure the sustainable application of biobased materials, future research must aim to predict and control their degradation behavior, while balancing functional durability with post-use degradability. Design strategies should consider surface properties, enzyme accessibility, and potential environmental impacts of degradation byproducts, such as microplastics or toxic intermediates. Moreover, biodegradability should be assessed alongside broader sustainability metrics, including life cycle impact, ecotoxicity, and resource efficiency. A multidisciplinary approach that integrates material science, environmental engineering, and ecological evaluation is essential for developing next-generation biobased materials that are both high-performing and environmentally responsible. Through such informed development, biobased biodegradable materials can make a meaningful contribution to reducing plastic pollution and advancing a circular, sustainable materials economy.

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