InSight Bulletin: A Multidisciplinary Interlink International Research Journal
Peer Reviewed International, Open Access Journal.
ISSN : 3065-7857 / Website: https://ibrj.us / Volume-2, Issue-10 / October - 2025

Original Article

Biodegradable Polymers: Mechanisms of Degradation and Emerging Applications

Aarif Hanif Pinjari
Assistant Professor, Department of Chemistry, Govt College Harsud Dist Khandwa M.P

Manuscript ID:
IBMIIRJ -2025-021014

Submitted: 08 Sept. 2025

Revised: 12 Sept. 2025

Accepted: 10 Oct. 2025

Published: 31 Oct. 2025

ISSN: 3065-7857

Volume-2

Issue-10

Pp. 67-70

October 2025

Correspondence Address:
Aarif Hanif Pinjari
Assistant Professor, Department of Chemistry, Govt College Harsud Dist Khandwa M.P
Email: aarif.pinjari@gmail.com

OPEN ACCESS

Quick Response Code:

Web. https://ibrj.us

DOI: 10.5281/zenodo.17620922

DOI Link:
https://doi.org/10.5281/zenodo.17620922

Abstract

Biodegradable polymers have gained global attention as sustainable alternatives to conventional plastics due to their ability to degrade into environmentally safe products. They are broadly classified as natural polymers, such as polysaccharides, proteins, and polyhydroxyalkanoates, and synthetic polymers like polylactic acid (PLA), polyglycolic acid (PGA), and polycaprolactone (PCL). These materials combine biodegradability with tunable mechanical and thermal properties, making them valuable in biomedical fields, packaging, and agriculture. This review highlights their synthesis methods, degradation mechanisms, key properties, and diverse applications while addressing challenges such as cost, performance, and scalability, and exploring future prospects for sustainable material development. It also explores future prospects for sustainable material development through green chemistry, nanotechnology integration, and bio-based composites. The study emphasizes that biodegradable polymers hold immense promise in achieving environmental sustainability and reducing global plastic pollution.

Keywords: *Biodegradable polymers; degradation mechanisms; polylactic acid (PLA); polyhydroxyalkanoates (PHA); sustainable materials; hydrolytic degradation; enzymatic degradation; microbial degradation; green chemistry; nanocomposites; circular economy; environmental sustainability.*

Introduction

The growing consumption of petroleum-based plastics has resulted in severe environmental problems due to their persistence, accumulation in landfills, and contribution to global pollution. With increasing awareness of sustainability, biodegradable polymers have emerged as promising alternatives, offering the potential to reduce plastic waste while providing functional versatility. These polymers are designed to break down through microbial, enzymatic, or hydrolytic processes into non-toxic byproducts such as carbon dioxide, water, and biomass. Depending on their origin, biodegradable polymers are broadly classified into natural types, including polysaccharides, proteins, and polyhydroxyalkanoates, and synthetic types, such as polylactic acid (PLA), polyglycolic acid (PGA), and polycaprolactone (PCL). Their unique properties, including biocompatibility, tunable degradation rates, and adaptability, make them suitable for diverse applications ranging from biomedical engineering to food packaging and agriculture. This review aims to provide a comprehensive overview of their chemistry, synthesis, degradation mechanisms, applications, limitations, and future perspectives in sustainable development.

Classification of Biodegradable Polymers

1. Natural Biodegradable Polymers

Natural biodegradable products such as polysaccharides, proteins and polyhydroxyalkanoates are derived from plants, animals, or microorganisms, and are inherently biodegradable due to their natural origin and enzymatic susceptibility.

a. Polysaccharides

•**Starch:** It is one of the most abundant polymers. It is inexpensive and it has good film forming ability. It is used in packaging, drug delivery, and blends with PLA or PCL.

•**Cellulose:** Cellulose is the most abundant natural polymer. Modified derivatives of cellulose like cellulose acetate, carboxymethyl cellulose etc have very high solubility and processability

b. Proteins

•**Collagen and Gelatin:** They are biocompatible in nature. They are used in tissue engineering, wound healing, and drug release matrices.

How to cite this article:
Pinjari, A. H. (2025). Biodegradable Polymers: Mechanisms of Degradation and Emerging Applications. InSight Bulletin: A Multidisciplinary Interlink International Research Journal, 2(10), 67–70. https://doi.org/10.5281/zenodo.17620922

•**Silk Fibroin:** Silk fibroin has very strong mechanical properties therefore it is applied in biomedical implants and sutures.

c. Polyhydroxyalkanoates (PHAs)- These are the bacterial polyesters synthesized via microbial fermentation. They are biocompatible, thermoplastic, but relatively brittle. They are used in biomedical implants, packaging, and agricultural films.

Example: Polyhydroxybutyrate (PHB).

2. Synthetic Biodegradable Polymers

These are man-made polymers designed for controlled biodegradation, often via hydrolysis of ester, amide, or anhydride bonds. They may be aliphatic Polyesters, Poly anhydrides, Poly ortho esters or biodegradable blends and composites.

a. Aliphatic Polyesters

•**Polylactic Acid (PLA):** PLA is derived from lactic acid (corn/sugarcane fermentation). It has excellent strength. It is transparent and compostable in nature. It is used in packaging, disposable cutlery, and biomedical scaffolds.

•**Polyglycolic Acid (PGA):** It is highly crystalline in nature. It has excellent strength but brittle. PGA is widely used in absorbable sutures.

b. Poly anhydrides- These are hydrolytically unstable biopolymers. They degrade rapidly in aqueous media. They are used in controlled drug delivery where rapid release is needed.

c. Poly Orthoesters- These are hydrophobic, surface-eroding polymers. They are used in sustained drug delivery systems.

d. Biodegradable Blends and Composites- PLA/starch, PLA/PCL, and PHB blends improve mechanical properties and reduce costs. Nanocomposites with cellulose nanocrystals or clays enhance strength and barrier properties.

Degradation Mechanisms of Biodegradable Polymers

Biodegradable polymers undergo breakdown into smaller molecules through physical, chemical, enzymatic, and microbial processes, ultimately forming non-toxic products such as CO_2, H_2O, methane, and biomass. The degradation pathway depends on the polymer structure, crystallinity, molecular weight, hydrophilicity, and environmental conditions (pH, temperature, microorganisms).

Hydrolytic Degradation of Biodegradable Polymers

Hydrolytic degradation is one of the most important mechanisms through which biodegradable polymers break down. It is the cleavage of chemical bonds primarily ester, amide, urethane, or anhydride bonds by reaction with water molecules. It occurs without direct microbial or enzymatic involvement, though microbes may later metabolize the degradation products. It occurs when water molecules cleave the chemical bonds, particularly ester, amide, or urethane linkages, within the polymer backbone.

$$R–COOR' + H_2O \rightarrow R–COOH + R'–OH$$

Example- Hydrolytic degradation of PLA- The process generally takes place in two stages:

a) First, water penetrates the polymer matrix and causes random chain scission, leading to a gradual reduction in molecular weight.

$$[\text{-O-CH(CH3)-CO-}]n + H2O \rightarrow [\text{-O-CH(CH3)-CO-}]m + HO\text{-CH(CH3)-COOH}$$

b) In the second stage, the degraded fragments become sufficiently small and water-soluble, allowing them to diffuse out of the material and undergo further breakdown into carbon dioxide, water, or biomass.

$$[\text{-O-CH(CH3)-CO-}]m + mH2O \rightarrow mHO\text{-CH(CH3)-COOH}$$

$$C3H6O3 \rightarrow CO2 + H2O + Biomass$$

Factors such as the chemical structure of the polymer, degree of crystallinity, molecular weight, and environmental conditions like pH, temperature, and moisture strongly influence the rate of hydrolytic degradation. For example, aliphatic polyesters such as polylactic acid (PLA) and polycaprolactone (PCL) degrade primarily by hydrolysis of ester bonds, making them suitable for biomedical and packaging applications. This controlled and predictable degradation behavior is advantageous for designing polymers with tailored lifespans in specific applications.

Enzymatic Degradation

Enzymatic degradation involves the breakdown of polymers through the action of specific enzymes secreted by microorganisms, plants, or animal systems. Unlike hydrolytic degradation, which is a purely chemical process, enzymatic degradation is highly selective and occurs under mild physiological conditions like normal temperature and pH. Natural biodegradable polymers such as starch, cellulose, chitosan, proteins, and polyhydroxyalkanoates (PHAs) are especially prone to enzymatic attack, while some Synthetic polyesters such as polycaprolactone (PCL) and polylactic acid (PLA) can also be degraded by lipases and esterases. The process typically begins with enzyme adsorption on the polymer surface, followed by cleavage of specific chemical bonds such as glycosidic, amide, or ester linkages, producing oligomers and monomers that can be further metabolized by microorganisms.

For example, starch undergoes enzymatic hydrolysis in the presence of α-amylase, where the α-(1→4) glycosidic linkages between glucose units are broken:

$$(C_6H_{10}O_5)_n + nH_2O \xrightarrow{\text{Amylase}} nC_6H_{12}O_6$$

This reaction converts starch into glucose monomers, which can then be metabolized via glycolysis and the Krebs cycle. Similarly, cellulose is degraded by cellulase through cleavage of β-(1→4) linkages:

$$(C_6H_{10}O_5)_n + nH_2O \xrightarrow{\text{Cellulose}} nC_6H_{12}O_6$$

These degradation products, such as glucose and lactic acid, are eventually assimilated by microorganisms and converted into CO_2, H_2O, and biomass (in case of PLA). Enzymatic degradation is especially important in biomedical applications (e.g., wound dressings, sutures, drug delivery systems), where biocompatibility and controlled degradation under physiological conditions are essential.

Microbial Degradation

Microbial degradation is a biological process in which bacteria, fungi, or actinomycetes colonize polymer surfaces and secrete enzymes that break down the material into smaller fragments. These microorganisms use polymers as a carbon and energy source, first depolymerizing them into oligomers and monomers, followed by assimilation and mineralization into simple end-products such as carbon dioxide, water, methane (in anaerobic conditions), and biomass. The process involves two stages: (1) extracellular degradation, where enzymes such as esterases, lipases, proteases, and depolymerases break down high- molecular-weight polymers, and (2) intracellular metabolism, where the resulting monomers are absorbed by microbial cells and metabolized via pathways like glycolysis, the tricarboxylic acid (TCA) cycle, or fermentation.

For example, polyhydroxybutyrate (PHB), a natural polyester produced by microbes, is degraded by PHB depolymerase secreted by bacteria such as Pseudomonas lemoignei. The enzyme cleaves ester linkages to produce 3-hydroxybutyric acid (3-HB):

The 3-hydroxybutyric acid formed is then metabolized by microbes through the β-oxidation pathway, yielding acetyl-CoA, which enters the TCA cycle and is finally converted into CO_2, H_2O, and biomass:

Microbial degradation plays a vital role in waste management and composting, as it allows complete mineralization of bioplastics under natural environmental conditions. Moreover, in anaerobic environments (e.g., landfills, sediments), microbial degradation can lead to the formation of methane (CH_4), which can be captured as a bioenergy source.

Future Perspectives

Biodegradable polymers have shown great promise as alternatives to petroleum-based plastics, but significant challenges remain for their widespread adoption. Future research must focus on developing cost-effective and scalable production methods, particularly for synthetic biopolymers such as PLA and PCL, to compete with conventional plastics. Advances in microbial biotechnology and genetic engineering can enable the design of novel microbial strains with enhanced efficiency for producing polyhydroxyalkanoates (PHAs) and other biopolymers at industrial scale. Furthermore, nanotechnology-based modifications and polymer blending strategies can be employed to improve mechanical strength, barrier properties, and controlled degradation rates, thereby expanding their use in high-performance applications such as packaging, biomedical devices, and sustainable agriculture.

Another promising direction is the integration of biodegradable polymers with renewable resources, such as lignocellulosic biomass, to create fully bio-based and eco-friendly composites. In parallel, the development of smart biodegradable polymers that respond to environmental stimuli (pH, temperature, enzymes) will open new frontiers in controlled drug delivery and tissue engineering. Moreover, establishing global standards for biodegradability testing, along with supportive policies and circular economy strategies, will be essential for ensuring effective commercialization and public acceptance. Thus, the future of biodegradable polymers lies at the intersection of materials science, biotechnology, and sustainability policies, driving innovation toward a plastic-free and greener world.

Conclusion

Biodegradable polymers represent a promising solution to the growing environmental challenges posed by conventional plastics. Their ability to undergo hydrolytic, enzymatic, and microbial degradation into harmless end-products such as carbon dioxide, water, methane, and biomass makes them highly attractive for sustainable applications. Natural polymers like starch, cellulose, chitosan, and polyhydroxyalkanoates provide excellent biocompatibility, while synthetic biodegradable polymers such as PLA, PGA, and PCL offer tunable mechanical and degradation properties. Advances in synthesis strategies, including chemical modification, copolymerization, and microbial fermentation, have expanded their potential in diverse fields such as biomedical engineering, agriculture, packaging, and controlled drug delivery. Despite these advantages, limitations such as high production cost, limited mechanical strength, and dependence on specific environmental conditions remain challenges to large-scale commercialization. Future research must focus on developing cost- effective synthesis, enhancing degradation rates under real-world conditions, and integrating nanotechnology and green chemistry approaches. Thus, biodegradable polymers hold immense potential to drive sustainable development and reduce global plastic pollution.

Acknowledgment

The author expresses sincere gratitude to the Principal and Management of Government College, Harsud, District Khandwa (M.P.), for their continuous encouragement, academic support, and facilitation of a research-oriented environment that made this study possible.

Heartfelt thanks are extended to the Department of Chemistry for providing valuable academic inputs, laboratory resources, and motivation throughout the preparation of this paper.

The author also acknowledges the contributions of colleagues, researchers, and students for their constructive discussions and cooperation. Special appreciation is due to the scientific community and researchers whose pioneering studies on biodegradable polymers, sustainable materials, and environmental chemistry served as valuable references and inspiration for this work.

Finally, the author conveys deep appreciation to all those who are contributing to the advancement of eco-friendly materials and sustainable technologies, which form the foundation of a greener and more sustainable future.

Financial Support and Sponsorship

Nil

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

References

1. Chariyaporn, P., & Samir, J. (2022). Recent advances in biodegradable polymers for sustainable applications. Nature Reviews Materials, Article 41529-022-00277-7.
2. Shen, L., et al. (2022). A Review of Biodegradable Plastics: Chemistry, Applications, and Misconceptions. Chemical Reviews.
3. Mohanan, N., et al. (2020). Microbial and Enzymatic Degradation of Synthetic Plastics. PMC
4. / NCBI.
5. Siracusa, V., et al. (2019). Microbial Degradation of Synthetic Biopolymer Waste. Polymers, 11(6), 1066.
6. CAI, Z., et al. (2023). Biological Degradation of Plastics and Microplastics. PMC / NCBI.
7. Heris, Y. S., et al. (2024). Bacterial biodegradation of synthetic plastics: A review. BNRC / Springer Open.
8. Kaya Cakmak, O., et al. (2023). Biodegradable Polymers — A Review on Properties, Processing, and Degradation Mechanism. Springer / Circular Economy & Sustainability.
9. Recent Advances in Biodegradable Polymers and Their Biological Interfaces. (2022). PMC / NCBI.
10. Review of Bio-Based Biodegradable Polymers: Smart Solutions for Active Food Packaging. (2023). PMC / NCBI.
11. Biodegradable polymers and composites: Recent development and challenges. Polymers & Composites Review.
12. Biodegradable polymers — current trends of research and their applications: A review. (Čolnik et al.). Research Gate / Review Article.
13. Plastics: Environmental and Biotechnological Perspectives on Microbial Degradation. ASM Journals.
14. Designing Microbes and Polymers for Biodegradation. (2024). ACS Synthetic Biology.
15. Bio-based plastics, biodegradable plastics, and compostable plastics: biodegradation mechanism, standards and environmental implications. (2024). Elsevier / International Biodeterioration & Biodegradation.
16. Methods of Analyses for Biodegradable Polymers: A Review. (2022). MDPI / Polymers.