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Biodegradable Polymers, Synthesis Properties and Applications

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Abstract

People's perceptions about biodegradable materials have steadily changed as science and technology have advanced. Biodegradable materials often have a high percentage of polymers, many of which may be synthesised chemically. The manufacturing method is straightforward, and certain basic ingredients are inexpensive to get. The synthesis properties, applications, and perspectives of biodegradable polymers are the subject of this article, which reviews the related literature. This review highlights that biodegradable polymers such as PLA, PHA, PCL, PBS, and PBAT derived from renewable resources offer sustainable alternatives to petroleum-based plastics. Advances in synthesis techniques, including enzyme-catalyzed polycondensation, ring-opening polymerization, and copolymerization, have enhanced their thermal, mechanical, and degradation properties. Applications extend from packaging to biomedical fields, particularly in drug delivery and tissue engineering, where 3D bioprinting has shown great promise. Despite challenges in cost, scalability, and controlled degradation, biodegradable polymers demonstrate significant potential for reducing plastic pollution. Future research should focus on optimizing performance, standardizing processes, and developing multifunctional composites for broader industrial and medical applications.

Keywords; Biodegradable Polymers, Synthesis Techniques, Plant-Based Biopolymers, Agriculture, Medicine.

INTRODUCTION

Polymers and plastics play an essential role in our daily lives. Plastics are ubiquitous in the contemporary world, and we are unable to envision a world without them. The environmental retention of harmful synthetic compounds, the stifling and starvation of untamed life, and the appropriation of non-local and potentially hazardous life forms are all significant hazards posed by plastic garbage [1]. Plastics undoubtedly help us, but our culture is quite concerned about what will happen to them once they end up in the environment. Environmental contamination caused by non-biodegradable plastics is the primary ecological concern that is currently being addressed in the current era of modernisation. Its affordability, accessibility, light weight, resistance to corrosion, and other additions make it versatile and appropriate for a variety of uses [2]. The issue, however, is that the majority of plastics made from petroleum cannot be recycled. Plastic recycling and deterioration take a long time and produce toxic compounds that are very dangerous to the environment. An estimated one million aquatic species are killed annually when 200 million metric tonnes of trash plastic enter the seas and oceans. In addition, burning plastics has released toxic dioxins and carbon dioxide into the atmosphere over the past few decades, which has been linked to a number of serious illnesses in living things, such as cancer and problems with the human immune system, respiratory system, and reproductive system [3]. The development of ecologically friendly and biodegradable substitutes for these plastics has to be the top priority right now, not just to protect Mother Earth but also for the sake of both human and animal health. Innocent creatures are being choked and sewers are becoming clogged by these polymers [4].

These days, biopolymers derived from plants are popular because they are readily broken down by bacteria in soil. Although it seems unreal to consider plants as a renewable supply for plastics, it actually happens that plants are used in the production of biobased, biodegradable polymers [5]

However, the need for extensive agricultural acreage and the high cost of production impede commercialisation. Even biodegradable plastic production technology has not progressed to the point where businesses can create an environmentally acceptable substitute for plastic at a cost comparable to that of traditional plastic [6]. Therefore, the manufacture of high-quality and high-quantity bioplastics is urgently needed, and microorganisms are a suitable option for producing affordable bioplastics that are naturally degradable and easily accessible in the form of carbon reserves. However, they are unable to match our criteria due to the poor quality and quantity of their output [7].

Biodegradable Polymers

The unique family of polymers known as biodegradable polymers decomposes via a bacterial process after their intended use, producing natural byproducts such water, biomass, inorganic salts, and gases (CO_2, N_2). These polymers are mostly made up of ether, amide, and ester functional groups and may be found in both natural and artificial forms [8]. Their precise structure dictates their characteristics and mode of disintegration. Metal catalysts, ring opening polymerisation, and condensation processes are often used to create these polymers. Biodegradable polymers have a wide range of uses and examples. Edible films are one of the bio-based packaging materials that have attracted increased attention in recent decades as a green alternative because of its cheap cost, non-toxicity, wide diversity, and environmental friendliness [9]. Two categories of biodegradable polymers are distinguished based on their source: synthetic polymers made from oil and natural polymers derived from natural resources.

Biodegradable Polymer Applications

Research into developing more sustainable and eco-friendly materials has recently gained momentum. In this sense, one of the best alternatives to conventional plastics for accomplishing this objective is biodegradable polymers.

Applications In Agriculture

In the agricultural industry, biopolymers may be used in a wide range of goods. We would not have to pick the crops later since they are entangled with them. Examples of these applications are films or instructors. Alginic acid, cellulose, chitin, lignin, and starch are some of the natural polymers used in controlled release systems. Fishing nets and ropes are made from biopolymers in marine agriculture. To increase sustainability and environmentally friendly agricultural methods, low-tunnel cultivation and mulching with biodegradable materials are practical solutions [10]. The ageing and degradation of agricultural films that are embedded in the soil throughout their useful lifetimes necessitate that they possess specific qualities.

Applications In Medicine

Nowadays, simple membranes and surgical implants made of biodegradable polymers are used in vascular and orthopaedic surgery. In tissue engineering, biodegradable polyesters are often used as porous structures because of their high strength and variable rate of disintegration. Other uses for these include implantable matrices or absorbable sutures for the body's regulated release of drugs. Natural gelatin is a polymer that is used in biomedical applications to make coatings and microencapsulations for various drugs, as well as biodegradable hydrogels [10].

Applications In Packing

Packaging is a key area in which biodegradable polymers are used. The use of biodegradable polymers is common to reduce waste production. Among other characteristics, biopolymers have low temperatures and air permeability. PLA It has a modest permeability to water vapour and oxygen. Films, bottles, and cups are among the packaging products that use it. PCL is also used in soft biodegradable packaging [2].

Applications In Other Fields

- **Automotive:** Lighter cars are the goal of the auto industry's use of bioplastics and bio composites.
- **Electronics:** PLA is used as a composite with kenaf in electronics applications. A computer case has previously been made using PLA by the Fujitsu company.
- **Construction:** PLA fibre is used to make the carpet's paving stones and padding. It offers more security than synthetic fibres since it is less combustible.

Benefits Of Biodegradable Polymers

Because biodegradable plastic is better for the environment, it is widely used. Biodegradation, raw material regeneration, and a decrease in CO_2 (carbon dioxide) emissions that contribute to global warming are among the advantages. Numerous biodegradable polymers are consumed by various microorganisms, such as bacteria and fungus, which then transform them into CO_2, H_2O, and methane.

Produces less emissions: Compared to conventional plastic, the production of plant-based polymers results in lower carbon emissions. The carbon emissions from biodegradable polymers are 0.8 tonnes, compared to 4 tonnes from conventional plastic [9].

Less energy is used in their production: The widespread use of biodegradable materials was discovered by numerous scientists. Microorganisms of various types degrade biodegradable materials. They lead to reduced waste and energy consumption, and they may greatly reduce pollution and environmental damage. Aliphatic polyesters are those that have the potential to impact the environment [11].

Decompose Quickly: Not all biodegradable polymers are resistant to natural deterioration. However, they do not generate or accumulate refuse material and can be decomposed by nature. They help tiny chains break spontaneously in a short amount of time. Product degradation is caused by the enzymatic or hydrolytic cleavage of these short chains. This kind is often needed in a number of biological applications where body evacuation is ensured by polymer breakdown [12].Smaller Carbon Footprint: Bioplastics have a lower carbon footprint since they are made from maize, sugarcane, or other plants. One bioplastic that is carbon neutral is polyamide 410. There are no petrol emissions from it. The amount of carbon dioxide produced during the production of polyamide 410 is caused by the mix of castor bean oil with renewable feedstock that is obtained from petrochemical feedstock [13].

Eco-friendly: The fact that biodegradable plastic lessens environmental risks is one of its main advantages. Biodegradable plastics break down very rapidly and reduce the amount of plastic trash that accumulates, unlike traditional plastics that have been a health problem for hundreds of years [14].

LITERATURE REVIEW

(Dallaev et al., 2025) [15] The goal of this study is to provide a thorough overview of the current status of the development of biodegradable polymers, "including their classifications, sources (natural, synthetic, and microbial), degradation processes, material qualities, and commercial uses". It draws attention to important scientific and technical issues, such maximising rates of degradation, guaranteeing mechanical performance, and increasing production from renewable feedstocks. For academics, material scientists, and policymakers, this review is an essential resource since it compiles current research results and regulatory issues. It aims to close knowledge gaps so that biodegradable polymers may be used more quickly as essential parts of a low-impact, circular material economy.

(Yao et al., 2025) [16] "PLA, starch-based polymers, and plant fiber-based polymers" are the focus of this review, which is dedicated to the analysis of the degradation mechanisms of these specific biodegradable polymers. Drug delivery techniques benefit from PLA's improved biocompatibility when combined with HA. Polymers based on starch may be designed to degrade in certain ways. Through certain treatments or the inclusion of nanoparticles, plant fiber-based polymers gain durability and water resistance, expanding their range of potential uses. Techniques for surface modification and synthetic materials may be used to maximise their performance. In addition to exploring the biodegradation reaction processes of these polymers, this work synthesises reaction settings, research methodologies, and their advantages and disadvantages. Applying and advancing these degradation processes in the framework of environmental preservation and sustainable development requires a thorough knowledge of them.

(Himantha Kelaniyagama et al., 2024) [17] concentrate on developing biodegradable polymers that were either chemically modified or derived from renewable resources, "such as polylactic acid, polyhydroxy alkanoates, polycaprolactone, poly(butylene adipate-co-terephthalate), and polybutylene succinate". This paper unequivocally demonstrates that biodegradable plastics generated from renewable resources, including PLA, PHA, PCL, PBS, and PBAT, present a promising alternative to conventional petroleum-based plastics. They assist in addressing the worldwide problem of plastic pollution in addition to lowering the use of fossil fuels. The mechanical and thermal properties of biodegradable polymers have also been enhanced in an attempt to create novel blends and composites that are more similar to non-biodegradable plastics. Nevertheless, there are also disadvantages to selecting biodegradable plastics. Currently, one of the biggest obstacles to biodegradable polymers is their high production costs when compared to traditional plastics.

(Sun, 2024) [18] Biodegradable materials often have a high percentage of polymers, many of which may be synthesised chemically. The manufacturing method is straightforward, and certain basic ingredients are inexpensive to get. This article provides an overview of the degradation mechanisms of several commonly used biodegradable materials, including PLA and PBAT, as well as some highly regarded synthesis technologies. In order to demonstrate the benefits of biodegradable materials over conventional materials and their potential for broad use in a variety of disciplines in the future, it also goes into detail about their uses in a number of industries, such as biomedical, packaging, and agriculture.

(Alaswad et al., 2022) [19] The rapid development of this unique class of polymeric materials in recent decades has been fuelled by the growing importance of the biopolymer area. Biodegradable polymers have garnered significant attention due to their unique qualities of biodegradability and tunable electrical conductivity, which render them intriguing in a variety of applications. Here, we discussed the latest developments in the creation of biodegradable polymers and their uses. We begin by outlining the fundamentals of conducting and biodegradable polymers, followed by discussions of the most successful approaches presently used in the creation of biopolymers. In order to illustrate the latest discoveries, special attention will be paid to the use of biodegradable polymers in wound healing, drug transport, tissue engineering, and several other contemporary biological applications. We have included thorough perspectives on the most recent developments about the difficulties and potential future developments pertaining to the development and commercial use of biodegradable polymers in this study.

(MA Sayed Patwary et al., 2021) [20] Researchers now believe that biodegradable polymers are the most practical substitute for conventional plastic materials, making them one of the most hotly debated topics. Polymers that are biodegradable have already demonstrated their capacity to create innovative, efficient, and advanced drug delivery systems. A variety of bioactive substances may be delivered via them. Natural polymers are crucial for the targeted delivery of medications to specific locations and their controlled release. Because of the potential uses for polymers in the areas of natural insurance and physical wellbeing support, they have received a lot of attention in the last several decades. Numerous methods, such as random and piece copolymerisation or joining, have been developed to improve the characteristics of biodegradable polymers. These kinds of tactics improve the polymers' mechanical qualities as well as their rate of biodegradation. Environmentally friendly polymers are called biopolymers.

(Panchal & Vasava, 2020) [21] The petroleum-derived polymeric polymers are not biodegradable. Because they wind up in landfills, they harm the ecosystem while defying decay. The challenge of obtaining repeatability when utilising natural polymeric materials has led to a growing interest in synthesised biodegradable polymeric materials (BPMs). An extensive array of diverse BPMs can be obtained by modifying natural polymeric materials or materials through "chemical, microbiological, enzyme-mediated, and chemo-enzymatic synthesis" "While synthetic BPMs like PLA, PGA, PCL, PDS, and PLGA" are specifically made to seek desired uses in a variety of fields including whole diagnostics and therapies, modified natural polymeric materials like cellulose, starch, and chitin have improved qualities. It is possible to include customised features into synthesised BPMs to support human neoteric entails.

(Song et al., 2018) [22] Significant progress has been made in the past fifty years in "the creation of biodegradable polymeric materials" for use in biomedical applications. When creating therapeutic devices, such as "temporary implants and three-dimensional scaffolds for tissue engineering", biodegradable polymeric materials are preferred. Biodegradable polymeric materials have been used for pharmacological purposes, including delivery systems for controlled/sustained drug release, with further developments. For these applications to provide successful treatment, certain physicochemical, biological, and degrading features of the materials are needed. Because of this, a large variety of synthetic or natural polymers that can degrade hydrolytically or enzymatically are being researched for use in biomedicine. Current advancements in "biodegradable natural and synthetic polymeric materials" for a range of biomedical uses, such as drug delivery, tissue engineering, temporary implants, and wound healing, are described in this review.

(Díaz et al., 2014) [23] A class of biodegradable polymers known as poly(alkylene dicarboxylate)s is gaining popularity for both specialist and commodity uses. Dicarboxylic acids and biobased diols, including 1,4-butanediol, succinic acid, and carbohydrates, may be used to create the majority of these polymers. The synthesis, biodegradation, and applications of a variety of polymers covering a broad range of properties—that is, materials with elastomeric to rigid characteristics—that are appropriate for applications like hydrogels, soft tissue engineering, drug delivery systems, and liquid crystals are covered in this review. Finally, since intermolecular interactions and molecular chain stiffness may be significantly altered, "the addition of aromatic units and α-amino acids" is taken into consideration. "As biodegradable materials for biomedical purposes", poly(ester amide)s made from naturally occurring amino acids really have a lot of potential and are also the subject of much discussion.

RESEARCH OBJECTIVE

- To study the biodegradable polymers and its type.
- To study the benefits and application of biodegradable polymers.
- To study the various literature’s perspective on biodegradable polymers, synthesis properties and applications.

RESEARCH GAP

Despite significant progress in the development of biodegradable polymers, several research gaps remain. Existing literature largely focuses on synthesis techniques and general applications, but limited attention is given to the scalability of production, cost-effectiveness, and lifecycle assessments under real-world conditions. The long-term degradation behavior in diverse environmental settings and its potential ecological impacts are not well understood. Moreover, studies often emphasize laboratory-based properties rather than performance in industrial or biomedical applications. There is also a need to explore novel polymer blends, advanced processing methods, and standardization of testing protocols to bridge the gap between research and practical deployment.

RESEARCH METHODOLOGY

The research methodology of this review paper is qualitative, based on secondary data analysis to explore the synthesis, properties, and applications of biodegradable polymers. A systematic literature review was conducted, examining journals, scholarly articles, conference proceedings, technical papers, and patents, published between 2014 and 2025. The study critically analyzes advances in polymer synthesis methods, material characterization, and application domains such as packaging, agriculture, and biomedicine. Sources were selected to provide comprehensive insights into current trends, challenges, and future opportunities. The methodology emphasizes comparative evaluation to highlight progress, limitations, and research gaps in biodegradable polymer development.

FINDINGS AND CONCLUSION

The review highlights that biodegradable polymers, such as PLA, PHA, PCL, PBS, and PBAT, present a sustainable alternative to conventional petroleum-based plastics due to their renewable origins, biodegradability, and versatile properties. These polymers significantly reduce environmental burdens, especially in packaging, which remains their primary application. Advances in synthesis methods, including enzymatic polycondensation, ring-opening polymerization, and incorporation of biobased monomers, have enabled the development of polymers with tunable crystallinity, melting points, and improved mechanical and thermal performance. Copolymerization and blending strategies further enhance their durability, making them comparable to non-biodegradable plastics.

Recent developments extend applications beyond packaging to biomedical fields such as drug delivery, artificial scaffolds, and 3D bioprinting, where biodegradable polymers act as bio-inks for tissue regeneration. Additionally, modified starch-based polymers and PLA composites with nanoparticles and hydroxyapatite (HA) show promise for environmental remediation and biomedical use. Despite these advancements, challenges remain regarding large-scale production, cost-effectiveness, and performance consistency under diverse environmental conditions. Understanding degradation mechanisms and ensuring non-toxic by-products are critical for safe and effective deployment.

In conclusion, biodegradable polymers hold vast potential in addressing global plastic pollution and supporting sustainable development. Their adaptability across sectors, from packaging to advanced biomedical engineering, demonstrates their versatility and importance. However, achieving commercial viability requires further research on scalability, cost reduction, and long-term environmental impacts. Future work should focus on novel polymer blends, advanced synthesis methods, and standardized testing protocols. With continued innovation, biodegradable polymers can transition from niche applications to mainstream materials, contributing significantly to environmental protection and human well-being.

REFERENCES

[1] M. A. Ntrivala *et al.*, “Polycaprolactone (PCL): the biodegradable polyester shaping the future of materials – a review on synthesis, properties, biodegradation, applications and future perspectives,” *Eur. Polym. J.*, vol. 234, 2025, doi: 10.1016/j.eurpolymj.2025.114033.

[2] M. Čolnik, M. K. Hrnčič, M. Škerget, and Ž. Knez, “Biodegradable polymers, current trends of research and their applications, a review,” *Chem. Ind. Chem. Eng. Q.*, vol. 26, no. 4, 2020, doi: 10.2298/CICEQ191210018C.

[3] M. Megha, M. Kamaraj, T. G. Nithya, S. GokilaLakshmi, P. Santhosh, and B. Balavaishnavi, “Biodegradable polymers research and applications,” *Phys. Sci. Rev.*, 2023, doi: 10.1515/psr-2022-0217.

[4] A. Das, T. Ringu, S. Ghosh, and N. Pramanik, *A comprehensive review on recent advances in preparation, physicochemical characterization, and bioengineering applications of biopolymers*. Springer Berlin Heidelberg, 2023. doi: 10.1007/s00289-022-04443-4.

[5] H. Nakajima, P. Dijkstra, and K. Loos, "The recent developments in biobased polymers toward general and engineering applications: Polymers that are upgraded from biodegradable polymers, analogous to petroleum-derived polymers, and newly developed," *Polymers (Basel).*, vol. 9, 2017, doi: 10.3390/polym9100523.

[6] M. Karimi, A. Asefnejad, B. Noshadi, F. Iranmanesh, and P. Nasri, "An Overview of Biodegradable Polymers: Revolutionizing Biomedical Applications by Increasing Stability and Biocompatibility for Biomaterial Applications from Lumen-Apposing Metal Stents to Dental Implants," *Nanochemistry Res.*, vol. 10, no. 2, 2025, doi: 10.22036/NCR.2025.02.05.

[7] H. R. Dana and F. Ebrahimi, "Synthesis, properties, and applications of polylactic acid-based polymers," *Polym. Eng. Scienece*, 2022.

[8] S. Jha, B. Akula, H. Enyioma, M. Novak, V. Amin, and H. Liang, "Biodegradable Biobased Polymers: A Review of the State of the Art, Challenges, and Future Directions Swarn," *Polymers (Basel).*, vol. 16, no. 16, p. 2262, 2024, [Online]. Available: https://www.mdpi.com/2073-4360/16/16/2262

[9] Z. Hu and R. Zhou, "Review on Some Important Research Progresses in Biodegradable Plastics/Polymers," *Recent Prog. Mater.*, vol. 06, no. 02, 2024, doi: 10.21926/rpm.2402015.

[10] G. Ravi, P. Iriventi, and R. A. M. Osmani, "Biodegradable Polymers: A Novel Stride in Drug Delivery and Therapeutics," *Res. J. Pharm. Technol.*, vol. 16, no. 6, 2023, doi: 10.52711/0974-360X.2023.00502.

[11] M. Harun-Ur-Rashid and A. Bin Imran, "Emerging Trends in Engineering Polymers: A Paradigm Shift in Material Engineering," *Recent Prog. Mater.*, vol. 06, no. 03, 2024, doi: 10.21926/rpm.2403024.

[12] A. Samir, F. H. Ashour, A. A. A. Hakim, and M. Bassyouni, "Recent advances in biodegradable polymers for sustainable applications," *npj Mater. Degrad.*, 2022, doi: 10.1038/s41529-022-00277-7.

[13] Y. K. Sung and S. W. Kim, "Recent advances in polymeric drug delivery systems," *Biomater. Res.*, vol. 24, no. 12, 2020.

[14] R. Kumar, N. Singh, and R. Singh, "An Introduction of Biodegradable Polymers, Modes of Biodegradation and Designing of Biodegradable Polymers," *Res. J. Pharm. Technol.*, vol. 10, no. 2, p. 625, 2017, doi: 10.5958/0974-360x.2017.00121.4.

[15] R. Dallaev, N. Papež, M. M. Allaham, and V. Holcman, "Biodegradable Polymers: Properties, Applications, and Environmental Impact," *Polymers (Basel).*, vol. 17, 2025, doi: 10.3390/polym17141981.

[16] X. Yao, X. Yang, Y. Lu, Y. Qiu, and Q. Zeng, "Review of the Synthesis and Degradation Mechanisms of Some Biodegradable Polymers in Natural Environments," *Polymers (Basel).*, vol. 17, 2025, doi: 10.3390/polym17010066.

[17] S. Himantha Kelaniyagama, A. Gannoruwa, and A. H. L. Renuka Nilmini, "Synthesize and Applications of Biodegradable Plastics as a Solution for Environmental Pollution Due to Non-Biodegradable Plastics, a Review," *Sustain. Polym. Energy*, vol. 2, 2024, doi: 10.70322/spe.2024.10011.

[18] Y. Sun, "Progress in the Synthesis and Application of Biodegradable Polymers," *Trans. Mater. Biotechnol. Life Sci.*, vol. 32, no. 5, 2024, doi: 10.6023/cjoc1110053.

[19] S. O. Alaswad, A. S. Mahmoud, and P. Arunachalam, "Recent Advances in Biodegradable Polymers and Their Biological Applications: A Brief Review," *Polymers (Basel).*, vol. 14, 2022, doi: 10.3390/polym14224924.

[20] MA Sayed Patwary, Kazi M Maraz, Shahirin Shahida, Arwah Ahmed, and Ruhul A Khan, "A Review on the properties and applications of biodegradable polymers," *GSC Adv. Res. Rev.*, vol. 9, no. 1, 2021, doi: 10.30574/gscarr.2021.9.1.0218.

[21] S. S. Panchal and D. V. Vasava, “Biodegradable Polymeric Materials: Synthetic Approach,” *ACS Omega*, vol. 5, 2020, doi: 10.1021/acsomega.9b04422.

[22] R. Song, M. Murphy, C. Li, K. Ting, C. Soo, and Z. Zheng, “Current development of biodegradable polymeric materials for biomedical applications,” *Drug Des. Devel. Ther.*, 2018, doi: 10.2147/DDDT.S165440.

[23] A. Díaz, R. Katsarava, and J. Puiggalí, “Synthesis, properties and applications of biodegradable polymers derived from diols and dicarboxylic Acids: From Polyesters to poly(ester amide)s,” *Int. J. Mol. Sci.*, vol. 15, 2014, doi: 10.3390/ijms15057064.