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Review Article

Biodegradable Polymers: Synthesis and Applications

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Abstract

Biodegradable polymers have gained significant attention as eco-friendly alternatives to traditional plastics. Derived from renewable resources like plants, animals, and microorganisms, these polymers can degrade naturally, reducing environmental pollution. Common biodegradable polymers include Poly Lactic Acid (PLA), Poly Hydroxyalk Anoates (PHA), and starch-based polymers. Applications range from packaging and textiles to medical devices and tissue engineering. The shift towards biodegradable polymers aims to mitigate plastic waste, decrease greenhouse gas emissions, and promote sustainable development. This review explores biodegradable polymers with emphasis on their synthesis and applications. Research has led to significant advancements in biodegradable polymer synthesis and applications. Findings from this study revealed that PLA, for instance, has shown excellent biodegradability and biocompatibility, making it suitable for food packaging, disposable cutlery, and medical implants. PHAs, produced by microorganisms, exhibit similar properties to conventional plastics and are used in medical devices, tissue engineering, and packaging. Starch-based polymers have been developed for biodegradable plastics, offering a cost-effective and renewable alternative. Studies have also explored blending biodegradable polymers with other materials to enhance mechanical properties and degradation rates. For example, PLA-PHA blends have shown improved toughness and crystallinity. Furthermore, biodegradable polymers have been used in controlled release systems, delivering drugs, pesticides, and fertilizers in a targeted and sustainable manner. Biodegradable polymers offer a promising solution to environmental pollution and sustainable development. With advancements in synthesis and applications, these materials can replace traditional plastics in various industries, reducing plastic waste and promoting eco-friendly practices. Continued research and development are essential to improve performance, scalability, and affordability, ensuring a greener future for generations to come.

Introduction

Global plastic production has increased dramatically since the mid-20th century, surpassing 400 million metric tons annually by 2020 [1]. This relentless growth reflects plastics' versatility, low cost, and durability, which have fueled their adoption across packaging, construction, automotive, and consumer goods industries. However, these same attributes have led to persistent environmental pollution: an estimated 10 million metric tons of plastic waste enter the world's oceans each year, fragmenting into microplastics that accumulate in marine food webs and compromise ecosystems [2,3]. Without significant shifts in material use or waste management, cumulative plastic waste is projected to triple by mid-century, intensifying threats to biodiversity, water quality, and human health [1].

Conventional waste-management strategies landfilling, incineration, and mechanical recycling have proven inadequate to close the loop on plastics. Landfills sequester plastics for centuries, requiring vast land areas and generating leachate laden with persistent organic pollutants [4]. Incineration reduces waste volume but emits greenhouse gases, dioxins, and heavy metals, posing air-quality and public-health risks [4]. Mechanical recycling suffers from contamination, sorting inefficiencies, and polymer degradation, resulting in downcycled products with reduced functionality. As a result, fewer than 10 percent of global plastic products are recycled into equivalent-value materials, and the remainder persists in the environment or dissipates as micro- and nanoplastics [5].

Biodegradable Polymers (BPs) have emerged as sustainable alternatives capable of fulfilling plastics' functional roles while mitigating end-of-life impacts. Unlike traditional thermoplastics, BPs are designed to undergo complete depolymerization via microbial enzymatic action or abiotic hydrolysis under industrial composting or environmental conditions [6]. Representative BPs include Poly Hydroxy Alkanoates (PHAs), microbial polyesters synthesized by bacteria such as Cupriavidus necator; polylactic acid (PLA), derived from the ring-opening polymerization of lactide monomers; and Poly Capro Lactone (PCL), a semicrystalline polyester produced from ε-caprolactone [7,8]. These materials exhibit tunable mechanical strength, barrier properties, and degradation rates, enabling their use in disposable packaging, agricultural films, and biomedical devices such as resorbable sutures and drug-delivery implants.

This review aims to critically appraise the synthesis routes and diverse applications of BPs, positioning them as viable alternatives to petroleum-based plastics. We will first examine chemical and biological polymerization strategies that leverage renewable feedstocks including sugar-derived lactide and plant-oil fatty acids and evaluate catalyst systems, reactor designs, and process parameters that influence polymer molecular weight, stereochemistry, and functionality. Mechanistic aspects of biodegradation will be discussed in depth, covering environmental factors such as temperature, moisture, and microbial community composition, alongside standardized methods for assessing composability and ecotoxicity. Further, we will explore industrial and medical applications of BPs, highlighting case studies in compostable packaging, agricultural mulch films, and tissue-engineering scaffolds to illustrate performance benchmarks, regulatory frameworks, and market adoption challenges. Finally, we will outline future directions for BP technology: advanced monomer architectures for enhanced properties, integrated biorefinery models that co-produce fuels and bioplastics, and policy initiatives including extended producer responsibility and biodegradable standards to accelerate the transition toward a circular, bio-based materials economy.

Environmental and Societal Problem of Plastics

The global scale of plastic production has skyrocketed from just 2 million metric tons in 1950 to over 436 million metric tons in 2023, driven by plastics' versatility and low cost [1]. Despite their economic benefits, conventional plastics persist for centuries, accumulating in landfills, soils, and marine sediments. An estimated 75 percent of all plastics ever produced have become waste, with only about 9 percent recycled globally; the remainder is incinerated or enters natural environments, where it fragments into pervasive microplastics [2]. Table 1 breaks down 2023 regional data for production, waste generation, and recycling, illustrating that Asia leads in both output and waste, while Europe achieves the highest recycling rates.

Table 1: Global plastic production, waste generation, and recycling rates by region.

Region	Production (2023, Mt)	Waste (2023, Mt)	Recycling Rate (2023, %)
Asia	200	110	10
Europe	60	35	32
North America	80	45	22
South America	40	20	5
Africa	25	15	3
Oceania	31	10	15 />---

Source: United Nations Conference on Trade and Development. (2025). Global trade update (August 2025): Mobilizing trade to curb plastic pollution.

Environmental consequences of this plastic deluge are profound. Macro- and microplastics infiltrate ecosystems via runoff, wastewater discharge, and atmospheric deposition, disrupting food webs and habitat integrity [9]. Microplastics particles smaller than 5 mm have been detected in every environmental compartment, from mountain soils to deep-sea trenches, where they adsorb persistent organic pollutants and serve as vectors for invasive microbes [3]. Moreover, the plastic lifecycle contributes approximately 1.8 billion metric tons of carbon dioxide equivalents annually, exacerbating climate change through both production and waste treatment emissions [10]. Soil and freshwater contamination alter nutrient cycling and soil structure, impairing agricultural productivity and water quality. Diagram 1 depicts the pathways through which plastics travel from manufacturing and use to environmental compartments, underscoring the complexity of pollution dynamics.

Human health concerns arise as plastics leach toxic additives such as phthalates, bisphenol A, and heavy metals into food, water, and air. These leachates exhibit endocrine-disrupting properties, interfering with hormonal regulation and reproductive health [11,12]. Microplastics themselves can translocate across intestinal barriers, accumulating in tissues and eliciting inflammatory responses; recent studies have even detected microplastic particles in human blood, raising alarms about systemic exposure and long-term effects [13]. Figure 1 illustrates how microplastics enter the food chain beginning with plankton ingestion and culminating in seafood and crop contamination highlighting an urgent need for material alternatives that minimize exposure.

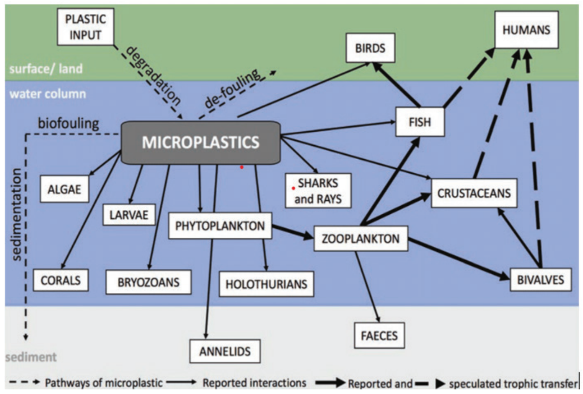

Figure 1: Pathways of plastic pollution in ecosystems.

Source: Wright et al. (2013a)

Economically, global plastic waste management costs exceed USD 46 billion annually, straining municipal budgets and infrastructure, especially in low- and middle-income countries [14]. Regulatory responses vary: the European Union's Single-Use Plastics Directive bans select items and mandates extended producer responsibility; the United States enforces microbead prohibitions and state-level bag bans; China's 2020 government plan phases out non-biodegradable bags; and several African nations impose levies or outright bans on plastic carriers [15]. Table 2 compares these policy frameworks, revealing divergent approaches to mitigating plastic pollution.

Table 2: Comparison of plastic regulation policies in selected countries.

Region	Policy/ Regulation	Key Provisions	Implementation Year
European Union	Single-Use Plastics Directive	Ban on top ten single-use plastic items; extended producer responsibility scheme	2021
United States	Microbead-Free Waters Act; bag bans	Federal ban on microbeads; state/local bans or taxes on plastic bags	2015; 2016+
China	Plastic Pollution Control Action Plan	Ban on non-degradable plastic bags in key cities; phased restrictions on plastic use	2020
Africa	National bag bans and levies	Ban or levy on plastic carrier bags; community-driven recycling initiatives	2015–2023

Source: adapted from [15]

Against this backdrop, Biodegradable Polymers (BPs) emerge as a sustainable solution. Engineered to depolymerize via hydrolysis or microbial attack under defined conditions, BPs such as polylactic acid, Poly Hydroxy Alkanoates, and polycaprolactone degrade into benign end products within months to years, dramatically reducing persistence and ecological footprint [5]. Figure 2 contrasts the environmental lifecycles of conventional plastics marked by persistent waste accumulation and emissions with those of BPs, which follow a circular path from renewable feedstocks to rapid biodegradation. By aligning material design with end-of-life environmental compatibility, BPs offer a viable pathway to close the plastic pollution gap.

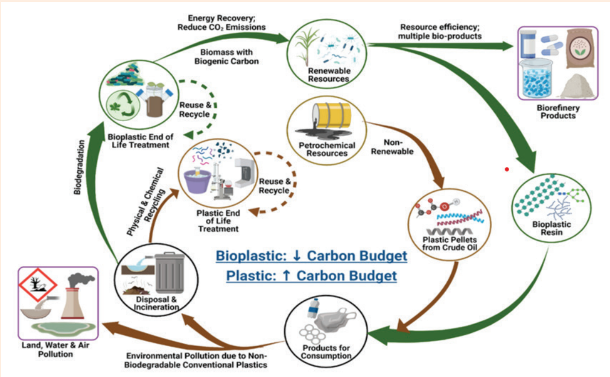

Figure 2: Environmental lifecycle comparison of conventional plastics and biodegradable Polymers.

Overview of Biodegradable Polymers

Biodegradable polymers are defined as macromolecules capable of undergoing degradation into carbon dioxide, water, and biomass via enzymatic or microbial activity under environmental or composting conditions [6]. Unlike conventional plastics, which resist breakdown and persist for centuries, Biodegradable Polymers (BPs) are engineered to depolymerize through hydrolytic cleavages, enzymatic scission, or microbial assimilation, ultimately closing the material loop. BPs can be broadly classified into natural and synthetic categories based on their origin and synthesis pathways [7].

Table 3: Classification of biodegradable polymers (natural vs. synthetic).

Product Type	Material	Application Area	Brand Example
Compostable food packaging	PLA; starch blends	Takeaway containers; cutlery	Vegware; BioPak
Agricultural mulch films	PBS; PHA	Soil cover; weed suppression	BioAgri; Novamont
Controlled-release fertilizers	PCL; PLA	Nutrient delivery in soil	Osmocote Bio
Biodegradable textiles	PLA; cellulose blends	Apparel; medical fabrics	TENCEL™ (Lenzing)
Biodegradable electronics	PLA-PANI composites	Wearable sensors; transient devices	GreenTEG; BioCircuit

Source: [16]

Natural biodegradable polymers derive from renewable biological sources and include polysaccharides such as starch and cellulose, proteins like chitosan, and microbial polyesters known as polyhydroxyalkanoates (PHAs). These materials offer innate biocompatibility and rapid biodegradation but often display lower mechanical strength and thermal stability. In contrast, synthetic biodegradable polymers are chemically synthesized commonly via ring-opening polymerization of cyclic monomers and encompass polylactic acid (PLA), Poly Capro Lactone (PCL), Poly Butylene Succinate (PBS), and copolyesters such as poly (butylene adipate-co-terephthalate) (PBAT). Synthetic BPs provide tunable properties through catalyst design and copolymerization but typically require controlled composting environments to achieve complete degradation [8,5].

Key physicochemical properties govern the rate and extent of BP biodegradation. Polymer crystallinity inversely correlates with hydrolytic susceptibility, as highly crystalline domains restrict water penetration and enzyme access. Molecular weight influences chain mobility and surface erosion: lower molecular weights accelerate depolymerization. Hydrophilicity and the presence of hydrolysable ester or amide bonds facilitate water uptake and bond cleavage, while glass transition temperature (Tg) determines the thermal window for biodegradation. Surface area and morphology further modulate microbial colonization and enzymatic attack [6].

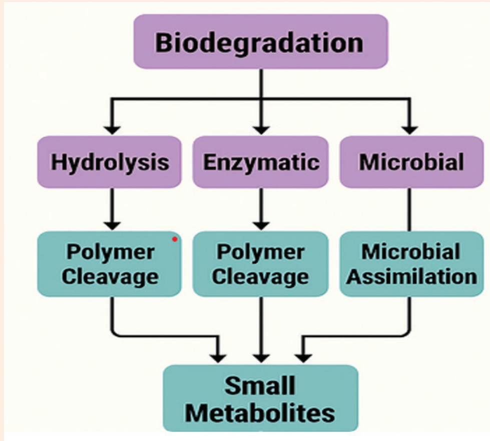

Figure 3: Flowchart of biodegradation mechanisms (hydrolysis, enzymatic, and microbial mechanisms).

Source: [17]

When compared with traditional petroleum-derived plastics such as Poly Ethylene (PE) and Poly Propylene (PP), BPs exhibit distinct physicochemical profiles that underpin their environmental compatibility. Table 4 contrasts key properties: conventional plastics possess densities around 0.90–0.94 g/cm³ and tensile strengths of 20–40 MPa, yet require over a century to degrade. By contrast, PLA and PHA show higher densities (1.20–1.25 g/cm³) and tensile strengths comparable to or exceeding those of PE, while undergoing complete biodegradation within 3–12 months under industrial composting conditions [17,18]. These differential traits underscore BPs' potential to replace conventional materials in applications ranging from packaging to biomedical devices provided that processing and end-of-life infrastructures align with their biodegradation requirements.

Table 4: Physicochemical properties of biodegradable vs. conventional plastics.

Property	Biodegradable Plastics	Conventional Plastics
Density (g/cm³)	1.20–1.25	0.90–0.94
Tensile Strength (MPa)	30–70	20–40
Degradation Time	3–12 months	> 100 years

Source: [17]

Synthesis of Biodegradable Polymers

Biodegradable polymers derived from natural sources represent a foundational class of sustainable materials, offering inherent biocompatibility, renewability, and environmental degradability. These polymers are typically extracted from agricultural biomass, marine organisms, or animal tissues, and their synthesis involves a combination of mechanical, chemical, and enzymatic processes tailored to the molecular structure of each biopolymer. Among the most widely studied natural biodegradable polymers are polysaccharide-based and protein-based macromolecules, which serve as precursors for films, hydrogels, fibers, and biomedical scaffolds.

Polysaccharide-based biodegradable polymers include starch, cellulose, and chitosan each abundant and structurally versatile. Starch, composed of amylose and amylopectin, is primarily extracted from tubers and cereal grains such as potato, cassava, and corn. The extraction process begins with mechanical grinding of the plant material, followed by soaking in water or alkaline solutions to release starch granules. These are then filtered, dried, and processed into a slurry suitable for thermoplastic conversion or blending with other polymers [19]. Cellulose, the most abundant organic polymer on Earth, is sourced from wood pulp, cotton linters, or agricultural residues. Its extraction involves chemical pretreatment typically alkaline digestion or acid hydrolysis to remove lignin and hemicellulose, followed by purification and fiber recovery. The resulting cellulose fibers can be further modified into derivatives such as carboxymethyl cellulose or cellulose acetate for enhanced solubility and processability [20].

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Chitosan, derived from chitin found in crustacean shells, undergoes deacetylation in concentrated sodium hydroxide to yield a cationic polysaccharide with antimicrobial and film-forming properties. The process typically includes deproteinization, demineralization, and deacetylation steps, resulting in high-purity chitosan suitable for biomedical and environmental applications [21]. Its solubility in acidic aqueous media and ability to form hydrogels make it particularly attractive for drug delivery and wound healing systems.

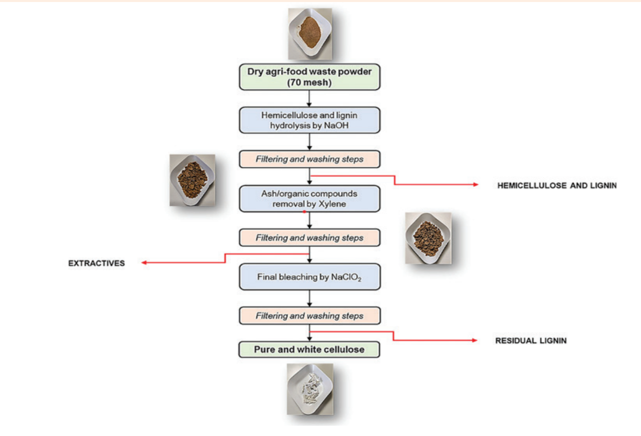

Figure 4: Extraction process schematic for Starch and cellulose polymers.

Source: Adapted from [22]

This flowchart illustrates the sequential stages of natural polymer extraction: starting from raw material collection (e.g., corn, wood pulp), followed by mechanical pretreatment (grinding), soaking or hydrolysis, filtration, and final polymer recovery. The diagram distinguishes between starch slurry and cellulose fibers as products, each destined for different applications in biodegradable material design.

Protein-based biodegradable polymers offer unique mechanical and biological properties due to their amino acid composition and secondary structures. Collagen, the primary structural protein in connective tissues, is extracted from bovine or porcine skin using acid or enzymatic hydrolysis. Partial denaturation of collagen yields gelatin, a thermoreversible gel-forming protein widely used in food packaging, pharmaceuticals, and tissue engineering [23]. Gelatin's ability to form films and encapsulate bioactive compounds makes it a versatile matrix for controlled-release systems.

Silk fibroin, obtained from the cocoons of Bombyx mori silkworms, is isolated through degumming (removal of sericin) followed by solubilization in lithium bromide or ionic liquids. The solution is then dialyzed and freeze-dried to yield purified fibroin, which can be cast into films or spun into fibers. Its β-sheet-rich structure imparts high tensile strength and slow biodegradation, making it ideal for sutures, scaffolds, and implantable devices [24].

Applications of Biodegradable Polymers

Biodegradable Polymers (BPs) have transcended their original niche in packaging to become pivotal materials across biomedical, industrial, and emerging technological domains. Their tunable degradation profiles, biocompatibility, and eco-friendly lifecycle make them ideal candidates for applications where sustainability and functionality must coexist.

Biomedical Applications

In medicine, BPs are revolutionizing drug delivery systems by enabling controlled release and site-specific targeting. Polymers Such as Polylactic Acid (PLA), Polycaprolactone (PCL), and poly (lactic-co-glycolic acid) (PLGA) are used to encapsulate therapeutic agents within nanoparticles, hydrogels, or microneedles, allowing for sustained release and reduced systemic toxicity figure 5 [25]. These systems are particularly effective in cancer therapy, hormone delivery, and vaccine stabilization. Tissue engineering and regenerative medicine also benefit from BPs, which serve as scaffolds that mimic the extracellular matrix. These scaffolds support cell adhesion, proliferation, and differentiation, facilitating the regeneration of skin, cartilage, bone, and even cardiac tissue. For example, electrospun PCL or silk fibroin scaffolds seeded with stem cells have shown promise in repairing myocardial infarctions and osteochondral defects [22].

Additionally, BPs are widely used in surgical sutures, wound dressings, and temporary implants. Sutures made from PGA or PLA degrade naturally after wound closure, eliminating the need for removal. Wound dressings composed of chitosan or gelatin provide antimicrobial protection and promote healing, while orthopedic implants made from bioresorbable polymers gradually transfer load to regenerating bone, reducing long-term complications [26].

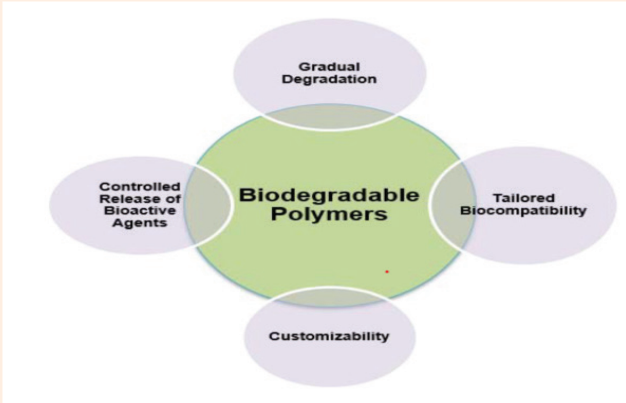

Figure 5: Biomedical applications of biodegradable polymers.

Source: Fischer et al. (2004)

Environmental and Industrial Applications

In the industrial sector, BPs are increasingly used in packaging materials to replace polyethylene and polystyrene. PLA-based films and containers offer compostability and reduced carbon footprint, while starch blends are used in grocery bags and food wraps. These materials degrade under industrial composting conditions, reducing landfill burden and marine pollution [5]. Agriculture has embraced BPs in the form of mulch films and controlled-release fertilizer coatings. These materials protect crops, suppress weeds, and deliver nutrients over time, then degrade into the soil without residue. Poly Butylene Succinate (PBS) and Poly Hydroxy Alkanoates (PHAs) are commonly used for these applications due to their soil compatibility and microbial degradability [17].

Table 5: Commercial biodegradable products and their applications.

Product Type	Material	Application Area
Compostable takeaway packaging	PLA from cornstarch	Foodservice containers, cups, cutlery
Biodegradable shopping bags	Starch-based bioplastic	Retail grocery bags
Cellulose-based food wraps	Cellulose derivatives	Fresh-produce and deli packaging
Bamboo cutlery sets	Bamboo biocomposite	Disposable utensils for catering and events
PLA drinking straws	PLA	Beverage straws for cafes and restaurants

Source: Adapted from Dallaev et al. (2025)

Energy and Nanotechnology Applications

In energy storage, BPs are being integrated into batteries and supercapacitors as separators, binders, and electrode substrates [16]. Figure 6 presents a conceptual categorization of these polymers based on their electron-donating (+) or electron-withdrawing (–) characteristics: natural polymers PEO, HPC, alginate, chitosan,

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pullulan, cellulose, and zein occupy the electron-donating domain, imparting intrinsic ionic conductivity and mechanical flexibility, while synthetic polymers chitin, PVA, PBAT, gelatin, DNA, PLA, PCL, and EC reside in the electron-withdrawing domain, offering enhanced structural integrity and electrochemical stability. This framework informs material selection for flexible, wearable energy devices that align with circular-economy principles. Cellulose nanofibers and chitosan-based hydrogels, as natural electron-donating BPs, exemplify materials that combine ionic transport with stretchability, making them particularly suited for next-generation, low-impact energy systems. Smart biodegradable polymers are gaining traction in environmental monitoring. Shape-memory polymers and conductive composites respond to stimuli such as pH, temperature, or pollutants, enabling real-time sensing and adaptive behavior. For instance, PLA-PEDOT blends have been used in biosensors that detect heavy metals or pathogens in water, then degrade harmlessly after use [27].

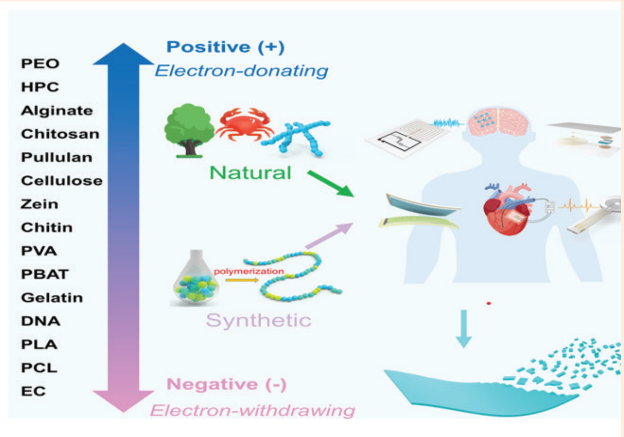

Figure 6: Smart Biodegradable polymers in Energy and Nanotechnology Devices.

Source: Adapted from Dallaev et al. (2025)

Challenges and Limitations

The broad adoption of Biodegradable Polymers (BPs) is hampered by a number of technological, financial, and environmental issues, despite their potential as sustainable substitutes for petroleum-based plastics. The trade-off between biodegradability and mechanical strength is one of the most enduring problems. In comparison to traditional plastics like polyethylene (PE) or polypropylene (PP), several BPs, including Poly Lactic Acid (PLA) and Poly Hydroxy Alkanoates (PHAs), have reduced tensile strength, impact resistance, and thermal stability. Increasing crystallinity and adding fillers are common ways to improve mechanical performance, but these changes may slow down biodegradation or necessitate industrial composting conditions for efficient breakdown [28,29]. Cost is still a major obstacle. Fermentation, enzymatic conversion, or polymerisation of bio-based monomers are commonly used in the manufacturing of BPs; these processes are more costly and energy-intensive than petrochemical synthesis. For example, the difficulty of feedstock purification and polymerisation can make PLA production two to three times more expensive than that of traditional plastics [30]. Price competitiveness is always a challenge even though economies of scale and technical advancement are progressively lowering prices, particularly in low-margin industries like packaging and agricultural.

Other difficulties include scalability and industrial integration. A large number of BPs are made in batch operations with low throughput, and processing them frequently calls for specialised tools or circumstances that are incompatible with current plastic production lines.

Furthermore, feedstock quality fluctuation, particularly when it comes from agricultural waste, can impact polymer performance and consistency, making quality control and regulatory approval more difficult [28]. The shift from laboratory-scale invention to commercial-scale production is hampered by these variables. BP uses are further limited by shelf-life and storage stability issues. Due to their hygroscopic nature and sensitivity to temperature and humidity, certain biodegradable polymers may degrade prematurely or lose their mechanical integrity while being stored. For instance, PLA can experience hydrolytic breakdown at high humidity, lowering its shelf-life and utility in long-term packaging, while starch-based films may absorb moisture and become brittle or sticky [29]. To maintain product reliability, these problems need for precise formulation and packaging techniques.

Incomplete degradation and the possible development of microplastics continue to be environmental issues. In natural settings, when temperature, moisture, and microbial activity are insufficient to cause complete breakdown, BPs may persist even though they are made to decompose under particular circumstances, such as industrial composting. Microplastic pieces produced by partial degradation carry the same ecological hazards as traditional plastics, such as the potential for ingestion by marine life and bioaccumulation in food chains [30]. This emphasises how crucial it is to improve biodegradability testing standards and match material design with realistic end-of-life conditions.

Future Perspectives and Opportunities

The future of biodegradable polymers (BPs) lies in the convergence of biotechnology, materials science, and systems-level sustainability. One of the most promising avenues is the use of genetic engineering to enhance microbial synthesis of biopolymers. By modifying metabolic pathways in bacteria such as Cupriavidus necator or Escherichia coli, researchers have significantly increased yields of Poly Hydroxy Alkanoates (PHAs) and tailored their monomer composition for specific mechanical and degradation profiles [31]. Synthetic biology tools now enable the design of microbial factories that convert agricultural waste or CO_2 into high-performance polymers, reducing reliance on virgin biomass and improving process economics.

Parallel to biological innovation, the development of hybrid and composite materials is expanding the functional range of BPs. Blending biodegradable polymers with natural fibers, nanoclays, or graphene oxide can enhance tensile strength, thermal stability, and barrier properties without compromising biodegradability [18]. These composites are particularly valuable in packaging, automotive, and biomedical applications where durability and environmental compatibility must coexist. Moreover, self-healing and stimuli-responsive biocomposites are emerging for advanced uses such as smart textiles and transient electronics.

Integrating BPs into the circular economy is another critical frontier. While biodegradability offers an end-of-life advantage, recycling and reuse strategies are essential to minimize resource input and environmental footprint. Mechanical recycling of PLA and chemical depolymerization of PHAs are being explored to recover monomers and reprocess materials, though infrastructure and consumer participation remain limiting factors [5]. Designing BPs for recyclability alongside compostability will be key to closing the loop and reducing waste leakage.

Emerging technologies such as Artificial Intelligence (AI), machine learning, and nanotechnology are poised to revolutionize polymer design. AI-driven modeling can predict polymer behavior, optimize synthesis routes, and accelerate material discovery by analyzing vast datasets of structure–property relationships [27]. Nanotechnology enables the fabrication of BPs with controlled porosity, surface functionality, and antimicrobial properties, opening new possibilities in medicine, agriculture, and electronics. These interdisciplinary tools will be instrumental in overcoming current limitations and unlocking next-generation biodegradable materials.

Conclusion

Biodegradable polymers offer a compelling response to the global plastic pollution crisis, aligning material innovation with environmental stewardship. As highlighted throughout this review, BPs derived from natural and synthetic sources can fulfill diverse roles from packaging and agriculture to medicine and energy while minimizing long-term ecological harm. Advances in microbial synthesis, composite engineering, and smart functionality are expanding their capabilities, while circular economy integration and policy support are paving the way for broader adoption.

Yet, realizing the full potential of BPs requires coordinated efforts across disciplines. Material scientists, biotechnologists, engineers, policymakers, and consumers must collaborate to address challenges in cost, performance, scalability, and end-of-life management. With continued innovation and systemic alignment, biodegradable polymers can transition from niche alternatives to mainstream solution driving progress toward a more sustainable and resilient future.

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