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Review

Next-generation biodegradable polymers: toward a circular plastics economy

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Abstract: Research into biodegradable polymers as sustainable alternatives to traditional petrochemical plastics has increased significantly in response to the growing environmental impact of plastic pollution. In this review, we offer a comprehensive, multidisciplinary overview of current advances in the creation, degradation processes, and green energy applications of biodegradable polymers. We examined how chemical structure, environmental factors, and microbiological activity influence polymer breakdown, alongside controlled degradation and lifecycle optimization. Consideration was given to incorporating biodegradable materials into next-generation energy devices such as transient batteries, triboelectric nanogenerators, and supercapacitors. A comparative analysis highlighted the material properties, performance trade-offs, and environmental impacts of key polymers like PLA, PCL, cellulose, and chitosan. Emerging trends were explored within regulatory support and circular economy frameworks, including smart polymers, nanocomposites, and AI-driven material design. In the review, we also emphasized key challenges and future research directions necessary for practical implementation, demonstrating the potential of biodegradable polymers to enable scalable, environmentally friendly solutions across energy and material sectors.

Keywords: Biodegradable polymers; green energy devices; life cycle assessment; Carbon footprint; smart biopolymers; circular economy

1. Introduction

1.1. The plastic pollution crisis

An increasing environmental disaster has been brought on by the exponential increase in plastic production, which now exceeds 400 million metric tons annually. Much of this plastic finds its way into natural ecosystems where it lingers for years. Major ecological and health concerns have been raised by the discovery of microplastics, which are produced as larger plastic garbage breaks down, in drinking water, marine species, and human bloodstreams [1]. Interestingly, the ubiquitous occurrence of microplastics in many environmental matrices is brought to light by this work. The presence of microplastics in drinking water sources, for example, is examined critically in a review published in Environmental Research, which highlights the necessity for standardized analytical techniques as well as the possible health hazards [2]. Furthermore, a mini review published in Waste Management & Research highlights the pressing need to address this worldwide issue by analyzing the effects of microplastic contamination on the ecosystem and human health [3–4].

Several recent reviews have extensively surveyed the chemistry, synthesis, and broad applications of biodegradable polymers, including the highly cited *Chemical Reviews (2023)* and *Polymers (2024)*. While these works provide comprehensive overviews of material classes and conventional applications such as packaging and biomedical uses, they leave important gaps that we address.

First, we focus on the emerging role of biodegradable polymers in green energy devices (e.g., transient batteries, triboelectric nanogenerators, and supercapacitors), an area that has been only superficially treated in prior reviews. We provide a critical comparison between biodegradable and conventional device materials, highlighting trade-offs between performance (conductivity, stability, flexibility) and environmental benefits.

Second, we integrate environmental toxicology considerations into the discussion of biodegradable polymers, emphasizing leachates, additive migration, and degradation products that affect both ecosystems and human health.

Finally, we synthesize performance, safety, and circularity perspectives into a single framework, aligning biodegradable polymer research with life cycle assessments, policy mechanisms, and circular economy strategies. By narrowing the scope toward energy applications and environmental impacts, this work contributes a sharper and more analytically focused discussion than prior reviews.

1.2. Biodegradable polymers' emergence

One promising way to lessen the environmental impact of conventional plastics is to use biodegradable polymers. These materials are designed to break down through microbial activity or environmental exposure into innocuous byproducts like carbon dioxide, water, and biomass. They can be made synthetically with intended degradability or from renewable biological resources (such as starch, cellulose, and polylactic acid) [1]. However, the word "biodegradable" is frequently misinterpreted. Unless certain circumstances are fulfilled, such as high temperatures and wetness, usually only present in commercial composting facilities, many biodegradable plastics do not decompose efficiently in landfills or marine settings [5–6]. If these materials naturally decompose, it can result in improper waste stream management and ongoing pollution.

1.3. Challenges and considerations

Although they offer a sustainable substitute, biodegradable polymers' environmental effectiveness varies depending on the situation. Certain materials may break into microplastics before completely disintegrating, and degradation in natural environments may be partial [7]. Furthermore, upon breakdown, some polymers can release methane, a strong greenhouse gas, in anaerobic environments like landfills [8]. Manufacturing many biodegradable materials necessitates significant land, water, and energy resources, which further complicates the sustainability story. Thus, their actual environmental benefits, through life cycle evaluations (LCAs), are necessary. We can expect to only considerably reduce plastic pollution by coupling biodegradable polymer innovation with strong waste management systems, as stated in a key review [5].

The economic and policy implications of biodegradable plastics pose serious obstacles in addition to environmental ones. Widespread adoption is hampered by greater production costs than traditional polymers and little customer awareness. Furthermore, the creation and application of biodegradable materials are complicated by regionally disparate laws and norms. To ease the shift to biodegradable alternatives, a study by Jha et al. [9] highlights the necessity of comprehensive regulations and public education. The assessment of these materials' actual environmental impact is further complicated by the absence of standardized testing procedures for determining biodegradability under diverse circumstances. A study by Ghosh & Jones [10] emphasizes the need for consistent testing procedures to ascertain how biodegradable plastics degrade in various environments [9,10].

1.4. Review scope

An extensive and up-to-date picture of the state of biodegradable polymers is given in this review, which covers:

- Classification and sources: distinguishing between manufactured and natural biodegradable polymers.
- Mechanisms of synthesis and breakdown, focusing on microbial and hydrolytic reactions.
- Applications in consumer items, packaging, agriculture, and medicine.
- Environmental evaluation, encompassing case studies of degradation and life cycle assessments.
- Future directions such as focus on AI-guided polymer design and intelligent biodegradable materials.

Our objective is to present a critical synthesis of prior research and new trends, while pointing out significant research and policy gaps required to accelerate the transition to a circular plastics economy.

2. Different biodegradable polymer types

Naturally occurring and artificially created categories can be used to classify biodegradable polymers broadly. Every class has distinct characteristics, degradation patterns, and application niches that become more significant when designing materials for a circular, sustainable economy.

Figure 1 presents a visual taxonomy of biodegradable polymers, categorizing them into two primary groups: Synthetic and naturally derived. The naturally occurring polymers are formed from renewable biological entities, including bacteria, plants, and animals, and comprise polysaccharide-based, protein-based, and polyhydroxyalkanoates (PHAs). These materials are preferred because of their eco-friendly degradation profiles and intrinsic biocompatibility. Conversely, although chemically produced, synthetic biodegradable polymers are engineered with functional groups that facilitate degradation under specific environmental circumstances. Polylactic acid (PLA), polycaprolactone (PCL), aliphatic polyesters like polybutylene succinate (PBS) and polybutylene adipate terephthalate (PBAT) are all members of this group. A systematic understanding that is necessary for material selection in sustainable development contexts is supported by the diagram, which emphasizes the hierarchical relationships and application potential across distinct material kinds.

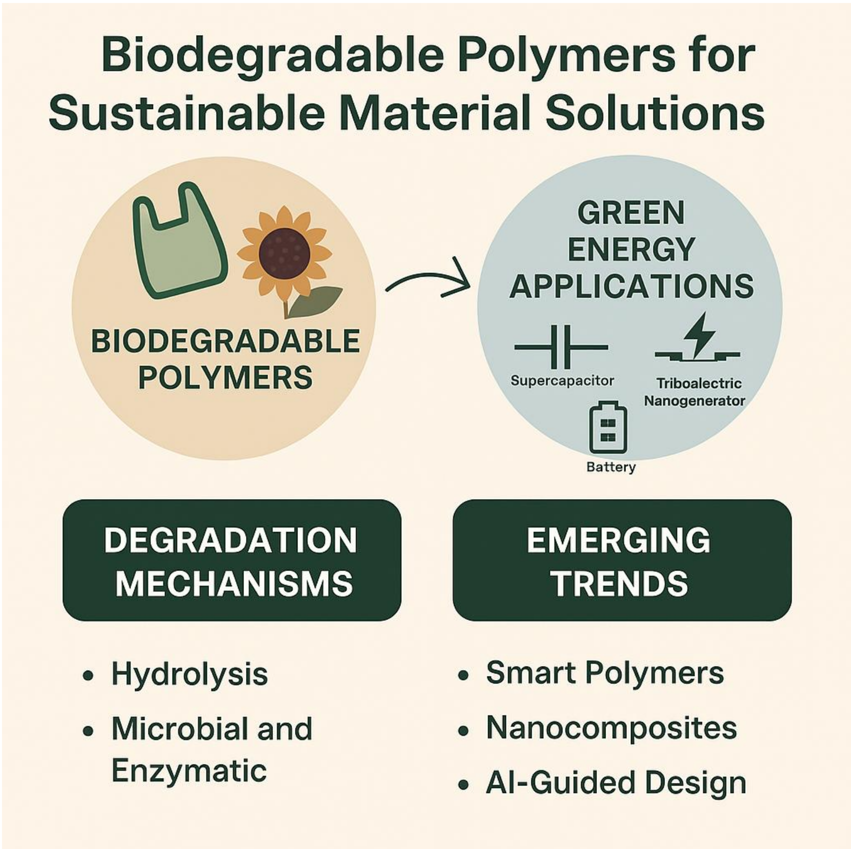

Figure 1. Biodegradable polymers for sustainable solutions.

Figure 2 provides an integrative framework that visualizes the interconnected hierarchy of natural and synthetic biodegradable polymers within sustainable materials science. It highlights how these two major classes differ in origin—biogenic versus petrochemical—yet converge in purpose through engineered degradability and environmental compatibility. The diagram maps the relationships between molecular structure, degradation mechanisms, and end-use applications, illustrating how renewable biopolymers (such as polysaccharides, proteins, and PHAs) and synthetic analogues (such as PLA, PCL, PBS, and PBAT) complement one another in advancing sustainable design. By linking source, structure, and function, the system view underscores the importance of holistic material selection and lifecycle assessment in achieving circularity and reducing ecological impact across diverse application domains.

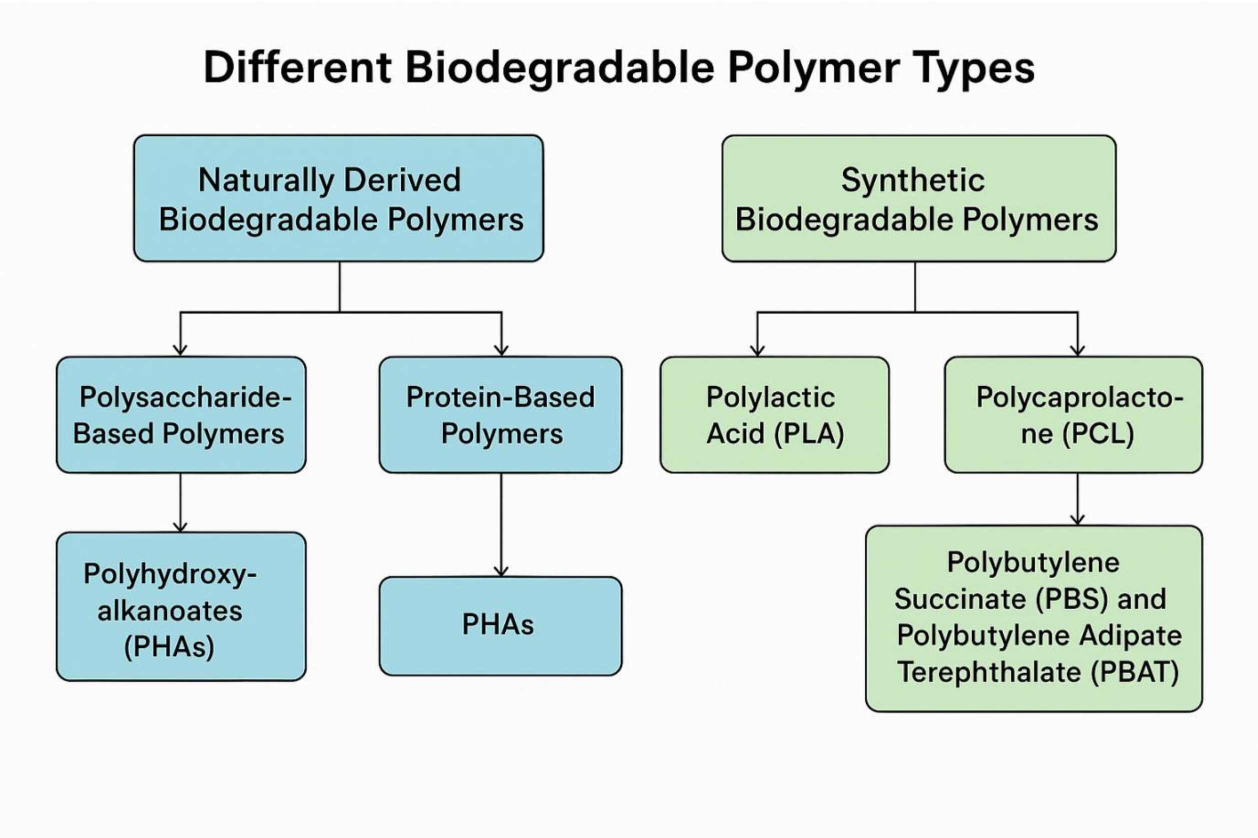

Figure 2. A system view of natural and synthetic biodegradable polymers in the context of sustainability.

2.1. Biodegradable polymers in nature

These polymers come from renewable biological sources like microbes, plants, and animals and are harvested or biosynthesized from them. Their natural ecological origin and biocompatibility are their major advantages. Materials that are extracted or biosynthesized from renewable biological sources, such as plants, animals, and microbes, are known as naturally generated biodegradable polymers. These polymers have special qualities that are useful in a variety of applications since they are made up of natural macromolecules such as proteins, lipids, and polysaccharides. These polymers' major benefits are their intrinsic biocompatibility, or their capacity to interact with biological systems without triggering a negative immunological response. Because of this feature, they can be used in medical applications, including scaffolds for tissue engineering and drug delivery systems [11]. Furthermore, these biomaterials' renewable nature fits perfectly with the growing need for environmentally friendly substitutes for traditional petrochemical plastics, which greatly increase pollution in the environment [12].

The capacity of naturally occurring biodegradable polymers to break down in the environment and prevent trash buildup is a major ecological advantage. Depending on their makeup and the environment, biodegradable polymers can be made to decompose in a matter of months to a few years, as opposed to hundreds of years for conventional plastics [13]. This quick deterioration contributes to a more sustainable ecosystem by reducing the pollution caused by plastic waste. In addition to reducing landfill waste, the biodegradation process replenishes the soil with essential minerals, improving soil quality and promoting plant development [9]. These eco-friendly benefits demonstrate how these materials can help promote a circular economy.

Furthermore, a wider range of applications across several industries, including packaging, agriculture, and medicinal fields, has been made possible by developments in the synthesis and modification of biodegradable polymers. These materials' adaptability enables the creation of customized qualities, including mechanical strength, flexibility, and barrier performance, which makes them appropriate substitutes for conventional plastics in particular applications [13,14]. To improve these materials' performance while preserving their biodegradability, researchers have investigated the use of fillers and additives [15]. The use of organically produced biodegradable polymers in commonplace products holds potential as research advances in lowering our environmental impact and advancing sustainable material science techniques.

2.1.1. Polymers based on polysaccharides

Because of their availability, biodegradability, and functional versatility, polysaccharides like starch, cellulose, chitosan, and alginate are employed extensively. For example, starch-based films have become popular in food packaging, but they frequently need to be blended with other polymers to improve their mechanical strength and moisture resistance [16,17]. Pharmaceuticals and coatings use cellulose derivatives such as carboxymethyl cellulose (CMC) and hydroxypropyl methylcellulose (HPMC). Numerous cellulolytic microbes found in nature aid in their breakdown.

2.1.2. Polymers based on proteins

Particularly in biomedical and packaging applications, proteins, including gelatin, casein, zein, and soy protein, are utilized to create biodegradable films and hydrogels. Although problems like water sensitivity and poor mechanical qualities restrict their application as stand-alone materials, their functional groups enable simple chemical modifications [18,19].

2.1.3. PHAs, or polyhydroxyalkanoates

PHAs are microbial polyesters made in fermentation conditions with low nutrients. They have thermoplastic qualities like traditional plastics and are biodegradable in compost, soil, and marine environments. The widespread commercialization is hampered by high production costs [20].

2.2. Biodegradable Synthetic Polymers

Despite being chemically produced, these are made using cleavable bonds (such as amide and ester) that permit breakdown in particular conditions.

2.2.1. PLA

Lactic acid, usually fermented from corn or sugarcane, is the source of PLA. Because of its industrial compostability, mechanical strength, and processability, it is one of the most commercially successful biodegradable polymers. However, for wider applications, blending or copolymerization is required due to PLA's brittleness and slow breakdown in ambient conditions [15].

2.2.2. PCL

PCL is a synthetic aliphatic polyester that is widely utilized in tissue engineering, controlled medication delivery, and agricultural applications. It breaks down slowly in biological conditions. It is a widely used additive because of its low melting point and good blend compatibility [21].

2.2.3. PBAT and PBS

Flexible aliphatic polyesters, PBS and PBAT, have mechanical qualities comparable to low-density polyethylene and good biodegradability. These are frequently used in packaging and agricultural mulch films. PBAT, for instance, is blended with PLA to increase flexibility and is utilized in compostable shopping bags [22].

3. Environmental factors and degradation mechanisms

The chemical makeup of biodegradable polymers, as well as their exposure to the environment and microbial activity, all significantly influence how they degrade. Designing materials that fit certain end-of-life scenarios, like soil burial, household composting, industrial composting, or marine environments, requires an understanding of the underlying mechanisms in addition to forecasting performance in practical applications.

The substantial impact of environmental conditions on the rates at which biodegradable plastics degrade has been brought to light by recent studies. For example, PLA breakdown is strongly influenced by temperature. PLA can break down in 60 to 100 days under industrial composting settings, which involve temperatures higher than 58 °C. However, PLA exhibits little deterioration even after prolonged exposure to marine conditions, where temperatures are lower and microbial activity is lower. This emphasizes how crucial it is to match applications for biodegradable polymers with suitable disposal settings to guarantee efficient decomposition [23].

Moreover, microbial communities play a crucial part in the biodegradation process. Biodegradable plastics like PCL and polyhydroxybutyrate (PHB) degrade enzymatically in soil settings with a high microbial diversity, thanks to the action of microorganisms. Enzymes released by these microorganisms disassemble polymer chains into monomers, which are subsequently absorbed and mineralized into biomass, water, and carbon dioxide. Several variables that impact microbial activity and enzyme production, including moisture content, pH, and nutrient availability, can impact how effective this process is [24].

3.1. Hydrolytic degradation

One of the most prevalent processes for synthetic biodegradable polymers, such as PLA, PCL, and PBS, is hydrolytic breakdown. Water molecules enter the polymer matrix during this process and break hydrolyzable bonds, usually esters, which lower the molecular weight and cause mass loss. Temperature, pH, and crystallinity are some of the variables that have a big impact on the rate of hydrolysis. For instance, because amorphous regions have easier access to water, they deteriorate more quickly than crystalline ones. Moreover, a key factor in hydrolytic breakdown is crystallinity; for example, PLA's amorphous sections enable water to penetrate more quickly, which speeds up hydrolysis. On the other hand, the tight packing of crystalline areas makes them more resistant to water diffusion. Recent research, however, has demonstrated that even highly crystalline PLA can hydrolyze quickly at temperatures higher than the glass transition temperature (Tg). This is explained by the mobilization of stiff amorphous fractions, which at higher temperatures are more prone to water-induced breakdown [25].

Hydrolytic degradation rates are also strongly influenced by the pH of the environment. The crystal size of PLA fibers exposed to alkaline conditions (such as pH 10) increases over time, indicating that higher pH values may accelerate the breakdown process by encouraging structural alterations in the polymer matrix [26].

On the other hand, PCL exhibits a distinct deterioration profile. Although it does so more slowly than PLA, it has a lower Tg for hydrolysis to take place at room temperature. Environmental elements, including microbial activity and the presence of enzymes, have a greater impact on PCL breakdown than crystallinity. In contrast, PBS shows hydrolytic degradation tendencies that fall somewhere between PLA and PCL, and the rate of this degradation is affected by both crystallinity and environmental factors [28]. It is essential to comprehend these subtle variations to customize biodegradable polymers for uses and disposal settings. Thus, it is feasible to maximize degradation rates and reduce environmental impact by matching polymer qualities with expected end-of-life conditions.

3.2. Microbial and enzymatic degradation

Enzymatic degradation is the main process that occurs in naturally occurring polymers, including gelatin, chitosan, and starch. Enzymes such as cellulases, amylases, or proteases are secreted by some bacteria and accelerate the breakdown of these biopolymers into monomers and oligomers. Following that, these tiny pieces are integrated into the metabolic processes of microorganisms. The efficiency of deterioration is greatly impacted by environmental factors such as temperature, humidity, and microbial variety. In composting settings, this process is essential to the breakdown of bioplastics [27].

3.3. Oxidative and photodegradation processes

Degradation can also be triggered by oxidative chemicals and UV light, particularly for polymers used in outdoor applications like agricultural films. By producing free radicals in the backbone of the polymer, UV light can trigger chain scission.

Photodegradation can speed up disintegration and increase surface area for microbial colonization, but it is not always enough for full biodegradation. A subset of photodegradation known as photo-oxidation occurs when oxygen and UV light work together to create free radicals inside the polymer matrix. This procedure starts a chain reaction that causes polymer chains to split apart, lowering molecular weight and changing mechanical characteristics. According to studies, UV light, for example, breaks polymer chains and produces free radicals, causing photooxidative degradation. Over time, this deteriorates mechanical qualities and results in material failure [29]. A subset of photodegradation known as photo-oxidation occurs when oxygen and UV light work together to create free radicals inside the polymer matrix. This procedure starts a chain reaction that causes polymer chains to split apart, lowering molecular weight and changing mechanical characteristics. According to studies, UV light, for example, breaks polymer chains and produces free radicals, causing photooxidative degradation. Over time, this deteriorates the mechanical qualities and results in material failure.

The chemical structure of polymers determines how susceptible they are to photo-oxidation. The hydrocarbon backbones of polyolefins, such as polyethylene (PE) and polypropylene (PP), lack UV-absorbing groups, making them more vulnerable to this degradation. On the other hand, polymers with aromatic structures, such as polyethylene terephthalate (PET), show more resistance, albeit they are susceptible to deterioration when exposed to UV light for extended periods.

Additives are frequently added to polymer compositions to slow or speed up deterioration. By stimulating the disintegration of polymer chains under UV light, oxidative degradation can be accelerated by oxy-biodegradable additions, usually transition metal salts. The environmental impact of these additives is up for debate, even though they can increase plastic fragmentation and the creation of microplastics. For example, the European Union has expressed worry about the potential for microplastic pollution caused by the inadequate biodegradation of oxo-degradable plastics [30].

It is essential to comprehend how microbial and photodegradation interact. Polymers can be made more receptive to microbial colonization and subsequent biodegradation by increasing their surface area and adding functional groups through photodegradation. Comprehensive research on the environmental destiny of these minerals is necessary because the first fragmentation brought on by UV exposure does not ensure full mineralization [31].

3.4. Dependence on environmental conditions

Depending on the environmental conditions that biodegradable polymers are exposed to, their degradation is significantly impacted [32]. Duration Conditions are set up in industrial composting facilities to hasten the breakdown. These facilities sustain high humidity levels of around 60%, high temperatures of 55 to 60 °C, and enough oxygen availability, promoting microbial activity and making it easier for polymers like PLA to hydrolyze [33].

On the other hand, lower and variable temperatures, typically below 30 °C, as well as less regulated humidity and microbial populations make home composting situations difficult. Many biodegradable polymers degrade at much slower rates because of these considerations.

Variables like temperature, microbial diversity, and moisture content all affect how quickly things degrade in soil environments. According to studies, keeping soil moisture at ideal levels can promote the biodegradation of some polymers; however, changing these parameters can result in uneven degradation outcomes [34].

The breakdown of polymers is particularly difficult in marine conditions. Seawater's lower temperatures decreased nutrient availability, and low microbial activity all greatly hinder the decomposition of biodegradable plastics. Degradation processes can also be impacted by the "plastisphere", or biofilms that grow on plastic surfaces. Designing biodegradable polymers for certain end-of-life situations requires an understanding of these environmental dependencies to ensure efficient degradation and reduce environmental impact [35].

3.5. Controlled degradation design considerations

Designing biodegradable polymers that break down in response to environmental stressors has been made possible by developments in material science. To increase the reactivity of polymers to hydrolysis or enzymatic assault, methods like surface functionalization, copolymerization, and the addition of clever additives are used. For example, the presence of labile ester, anhydride, and amide links in polymer backbones makes them vulnerable to enzymatic cleavage or hydrolysis-based degradation processes, which causes the polymer chains to gradually break apart. Furthermore, it has been demonstrated that post-polymerization changes like thiol-ene reactions speed up the rate at which some copolymers degrade, making them better suited for uses needing regulated biodegradation [36].

Designing polymers with life cycle thinking in mind is essential to minimizing environmental effects and ensuring that materials comply with post-use treatment protocols. The creation of materials that lower greenhouse gas emissions and stop unintended accumulation in ecosystems is guided by Life Cycle Assessment (LCA) studies, which offer insights into the environmental characteristics of biodegradable products. For instance, it has been demonstrated that the manufacture of bio-based polyethylene efficiently reduces the potential for global warming, underscoring the need to take the full life cycle into account when designing polymers. Researchers can create biodegradable polymers that not only satisfy functional needs but also support a sustainable and circular economy by combining environmental considerations with material properties [37].

4. Biodegradable polymer applications

Because of their many uses and environmental friendliness, biodegradable polymers have attracted interest from industries. They provide sustainable substitutes for traditional plastics in a variety of industries, including consumer products, medical, packaging, and agricultural.

4.1. Packaging

The packaging sector remains the largest consumer of biodegradable polymers, driven by regulatory pressures and consumer demand for sustainable alternatives. According to Global Market Insights (2024), the global market for biodegradable packaging was valued at approximately USD 105 billion in 2024 and is projected to grow steadily at ~6% CAGR through 2032. This growth is not only linked to consumer awareness but also to regulatory frameworks mandating the reduction of single-use plastics. For example, the European Union's Single-Use Plastics Directive requires compostable alternatives in certain applications, accelerating the adoption of PLA, PHA, and starch-based films.

Innovation in packaging is also supported by standardization and certification systems that guide market entry. Compostability certifications such as EN 13432 (EU), ASTM D6400 (USA), and ISO 17088 set performance benchmarks for biodegradation under industrial conditions. These policies and standards provide confidence for manufacturers and end-users, thereby enabling the circular transition of packaging materials from fossil-based to renewable and biodegradable alternatives [38,39].

4.2. Agriculture

Biodegradable polymers are being used more and more in agriculture for products like slow-release fertilizers, mulch films, and seed coverings. In addition to improving soil health and crop productivity, these materials significantly reduce labor and environmental impact by doing away with the need to remove and dispose of conventional plastic films. More than 30% of the market for biodegradable polymers came from the agriculture sector in 2023, and this share is expected to increase through 2032 due to environmental restrictions and sustainability programs [38].

4.3. Health and medical

Biodegradable polymers are essential in the medical and healthcare sectors, especially for surgical implants, medication delivery systems, and tissue engineering. Because they may safely break down inside the human body, there is no need for surgical removal, which lowers patient risk and medical expenses. Recent developments have expanded the use of biodegradable materials in tailored therapeutics and regenerative medicine by producing materials with improved biocompatibility and regulated disintegration rates [39,40].

4.4. Biodegradable polymers in green energy devices

An important step toward environmentally friendly and sustainable energy solutions is the incorporation of biodegradable polymers into green energy systems. These polymers, which come from renewable resources, have benefits including flexibility, biodegradability, and biocompatibility that make them appropriate for a range of energy applications. The present status of research on biodegradable polymers in energy devices is examined in this section, with an emphasis on the advantages, disadvantages, and uses of these materials.

4.4.1. Overview of biodegradable polymers in energy applications

Biodegradable polymers, including natural polymers like starch, cellulose, chitosan, and silk fibroin, as well as synthetic polymers such as PLA and PCL, have been extensively studied for their potential in energy devices. Their inherent properties, such as environmental friendliness and processability, make them ideal candidates for fabricating components of energy devices like supercapacitors, batteries, and nanogenerators [41].

4.4.2. Supercapacitors

Energy storage devices called supercapacitors are renowned for their extended cycle life and high-power density. Researchers have concentrated on integrating biodegradable polymers into supercapacitor parts such as electrodes, electrolytes, and separators. Polysaccharide-based materials, such as cellulose and chitosan, have been used to create solid and gel electrolytes with ionic conductivities that range from 80.9 × 10^$^{-3}$ S cm^–1 to 0.0173 × 10^$^{-3}$. Furthermore, biodegradable polymers have shown promise in high-performance supercapacitors by being used to create electrodes with specific capacitances up to 753 F g^$^{-1}$ [42].

4.4.3. Triboelectric nanogenerators (TENGs)

TENGs are machines that employ the triboelectric effect to transform mechanical energy into electrical energy. Because of their mechanical qualities and environmental friendliness, biodegradable polymers have attracted interest for application in TENGs. For instance, biodegradable TENGs based on plant proteins have been created for sustainable agriculture as mulch films that create electric fields to encourage plant development. Additionally, TENGs for wearable electronics have been created using biodegradable polymers like PLA and PCL, which provide flexibility and biocompatibility [43–45]

4.4.4. Energy storage devices and batteries

The environmental issues surrounding electronic waste are addressed through the development of biodegradable batteries and energy storage systems. Biodegradable polymers, which provide power sources that safely decompose after use, have been studied as components of supercapacitors and transient primary cells. For example, biodegradable micro-supercapacitors that utilize agarose gel electrolytes and molybdenum have demonstrated consistent performance before degradation, making them suitable for use in implantable medical devices [45,46].

4.4.5. Comparisons with conventional device materials

The incorporation of biodegradable polymers into energy devices must be critically evaluated against conventional materials that dominate the field. For instance, in supercapacitors and batteries, poly (vinylidene fluoride) (PVDF) remains the industry-standard separator due to its chemical stability and high dielectric constant. By contrast, biodegradable alternatives such as PLA and cellulose-based films offer environmental benefits but suffer from lower thermal stability and reduced ionic conductivity, which limit their operational voltage windows.

Similarly, while carbon-based electrodes (graphite, graphene, activated carbon) provide high conductivity and stability, biodegradable electrodes derived from chitosan or starch composites typically demonstrate lower electrical conductivity but superior biocompatibility and flexibility, making them suitable for transient and implantable electronics.

Electrolyte systems also illustrate important trade-offs. Conventional organic electrolytes (e.g., lithium salts in carbonate solvents) ensure high ionic mobility but pose safety and disposal hazards. Biodegradable gel electrolytes derived from cellulose, agarose, or chitosan are safer and environmentally benign; yet they face limitations in electrochemical stability and moisture sensitivity, often degrading more rapidly under operating conditions.

These contrasts emphasize that the advantage of biodegradable polymers is not simply substitution, but rather application-specific integration where biodegradability and environmental compatibility outweigh absolute performance. For example, biodegradable supercapacitors for transient electronics or implantable sensors may prioritize safe disposal and flexibility, whereas large-scale energy storage relies on conventional materials.

4.4.6. Obstacles and prospects for the Future

The broad use of biodegradable polymers in energy devices is hampered by several issues despite the promising applications. These consist of restrictions on long-term stability, electrical conductivity, and mechanical strength. The goal of researchers is to improve the characteristics of biodegradable polymers by creating composites and altering their chemical makeup. The development of entirely biodegradable energy devices with enhanced performance is the aim of future developments, which will support environmental preservation and sustainability objectives [46]. A sustainable route for the creation of green energy devices is provided by biodegradable polymers [47]. Opportunities to lessen environmental effects and advance the circular economy are presented by their incorporation into supercapacitors, TENGs, and batteries. To overcome current obstacles and fully utilize biodegradable polymers in energy applications, further research and innovation are needed.

Figure 3 highlights the various uses of biodegradable polymers in green energy devices, including biodegradable batteries, triboelectric nanogenerators (TENGs), and supercapacitors. The diagram shows how biodegradable polymers, both synthetic and natural, are used into these energy systems as structural elements, electrolytes, electrodes, and separators. This illustration highlights the increasing importance of environmentally friendly, biodegradable materials in developing sustainable energy systems and demonstrates how materials science and environmental stewardship can work together.

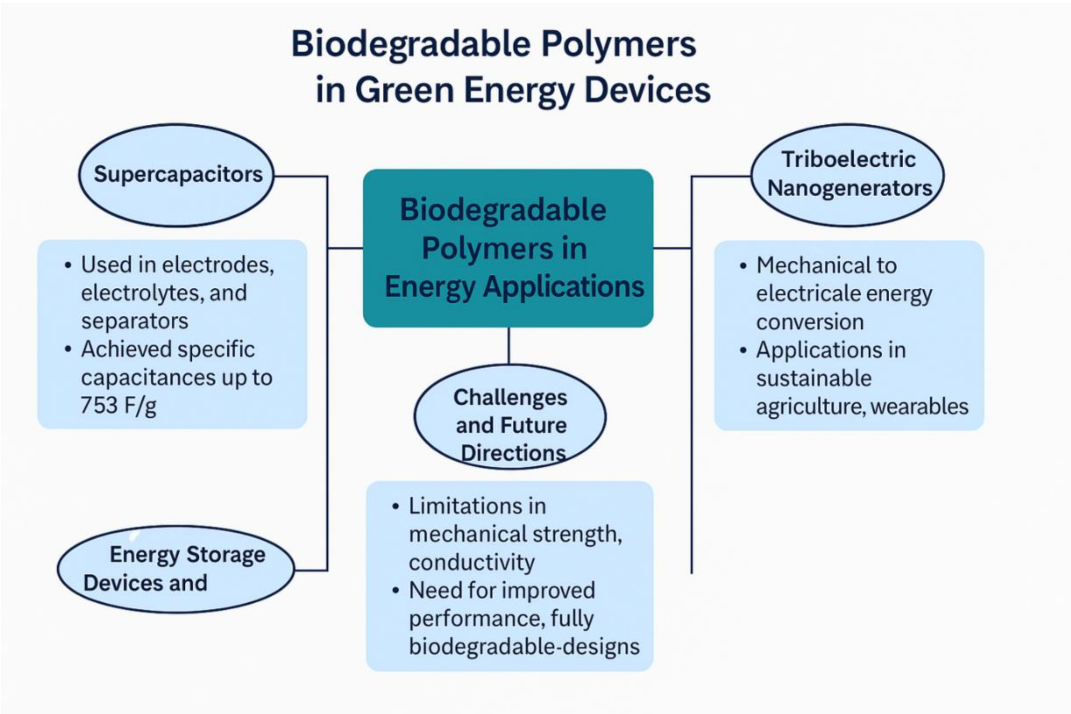

Figure 3. Integration of biodegradable polymers in sustainable energy devices: Applications and functional roles.

4.5. Consumer goods

Biodegradable polymers are being widely used in the consumer goods industry for items like shopping bags, food containers, and disposable flatware. These products, which are frequently used only once before being thrown away, greatly increase the pollution caused by plastic. Manufacturers can satisfy consumer demand for environmentally friendly items and adhere to environmental standards by substituting them with biodegradable substitutes. This change is especially noticeable in areas where plastic usage regulations are strict and consumer awareness of the environment is high [48].

In summary, the various ways that biodegradable polymers are used in various industries demonstrate how they might be used to solve environmental issues related to plastic waste. To completely reap the benefits of these sustainable materials, more research and development are needed, as well as supportive legislation and consumer education. Biodegradable polymers' adaptable properties have made it possible for them to be used in a variety of industries. These uses not only show how versatile these materials are but also how important they are to lowering environmental impact and promoting sustainable growth. The primary application domains of biodegradable polymers are compiled in Table 1, which is backed by recent peer-reviewed research and shows their uses, related materials, and performance results that encourage further study and commercialization.

Table 1. Applications of biodegradable polymers across diverse industries: A literature-based summary.

Application area	Description	Representative polymers	Journal reference
Packaging	Utilized in food packaging, films, and containers to reduce plastic waste and enhance sustainability.	Polylactic acid (PLA), Polyhydroxyalkanoates (PHA), Chitosan	[48,49]
Agriculture	Applied in mulch films, seed coatings, and controlled-release fertilizers to improve crop yield and soil health.	Starch-based polymers, Cellulose, Polyhydroxybutyrate (PHB)	[50]
Medical and Healthcare	Used in tissue engineering, drug delivery systems, and surgical implants due to their biocompatibility and controlled degradation.	Polycaprolactone (PCL), Polylactic acid (PLA), Polyglycolic acid (PGA)	[51]
Textile Industry	Employed in the production of eco-friendly fibers and fabrics, contributing to sustainable fashion and reduced environmental impact.	Polylactic acid (PLA), Polyhydroxyalkanoates (PHA), Bamboo fibers	[52–54]
Green Energy Devices	Integrated into the development of biodegradable components for energy devices like supercapacitors and nanogenerators.	Starch, Cellulose, Silk fibroin, Polylactic acid (PLA)	[41]
Environmental Remediation	Utilized in creating materials that aid in reducing microplastic pollution and enhancing biodegradability in various environments.	Polyhydroxyalkanoates (PHA), Polylactic acid (PLA)	[7]

4.6. Biodegradable polymer integration issues and optimization techniques for energy devices

Integration Challenges of Biodegradable Polymers in Energy Devices: Despite their environmental advantages, biodegradable polymers face significant challenges when integrated into functional energy devices. These limitations are primarily linked to their electrochemical stability, hygroscopic nature, and structural degradation under stress, which contrast sharply with the well-established performance of conventional materials.

4.6.1. Poor electrochemical stability

Biodegradable polymers such as chitosan, cellulose, and PLA-derived electrolytes often suffer from a limited electrochemical stability window. For example, cellulose-based gel electrolytes typically exhibit breakdown voltages below 2 V compared to conventional carbonate electrolytes that can operate at 3–4.5 V in lithium-ion batteries [44,46]. This directly reduces achievable energy density and restricts their use in high-power applications. In supercapacitors, while biodegradable gel electrolytes based on agarose or starch have shown ionic conductivities of 10^{-3}–10^{-2} S cm^{-1}, their stability over repeated cycling remains lower than that of synthetic ionic liquids.

4.6.2. Hygroscopicity of polysaccharides

Polysaccharide-based materials (e.g., cellulose, starch, and chitosan) are highly hydrophilic. While this property promotes ionic conduction, it also makes them prone to moisture absorption, leading to swelling, dimensional instability, and rapid hydrolysis. For instance, chitosan-based films used as electrolytes in supercapacitors displayed a 30–40% drop in capacitance after 1000 cycles under humid conditions [42]. Similarly, cellulose membranes intended as separators often weaken mechanically when exposed to aqueous electrolytes, compromising device safety.

4.6.3. Mechanical and chemical degradation under stress

Energy devices are subjected to repeated charge–discharge cycles, temperature fluctuations, and in some cases, mechanical deformation (e.g., in wearables). Biodegradable polymers generally lack the long-term durability required to withstand such stresses. For instance, PLA-based separators in lithium-ion cells exhibited mechanical failure after only 200 hours of cycling at 60 °C, compared with >1000 hours for PVDF-based membranes [41]. Similarly, in triboelectric nanogenerators (TENGs), protein-based biodegradable films demonstrated excellent initial flexibility but degraded within weeks of continuous operation, whereas synthetic fluoropolymer-based films maintained stable outputs over months [42].

4.6.4. Trade-off between additives and biodegradability

To improve electrochemical and mechanical performance, biodegradable polymers are often combined with conductive fillers such as carbon nanotubes, graphene, or metallic nanoparticles. While this approach enhances conductivity and stability, it compromises biodegradability and introduces new environmental risks through nanoparticle leaching [46]. Thus, a fundamental trade-off exists between enhancing device functionality and maintaining a truly eco-friendly profile.

4.6.5. Case studies highlighting integration challenges

- Supercapacitors: Wu et al. [41] reported chitosan-based supercapacitors achieving a capacitance of 753 F g^{-1}, but stability dropped sharply after 2000 cycles, unlike activated-carbon-based devices that retained >95% capacitance after 10,000 cycles.
- Batteries: Zhai et al. [45] demonstrated PLA-PCL-based biodegradable batteries that fully degraded in soil within 90 days, but capacity retention was only 45% after 50 cycles, compared with >90% for conventional Li-ion coin cells.
- TENGs: Mi et al. [41] showed PLA-based TENGs delivering an initial output of 120 V, but output fell below 60 V after 30 days due to surface hydrolysis and loss of charge-trapping ability.

These examples demonstrate that while biodegradable polymers hold strong potential for transient, short-lifetime, or implantable devices, they are not competitive with conventional polymers for long-term, high-power energy applications. Addressing these challenges requires advanced strategies such as chemical modification, nano-structuring, and AI-driven design optimization (see Section 6)

Biodegradable polymers in energy devices face a series of integration challenges when compared directly to their conventional counterparts [55,56]:

Electrical Conductivity vs. Biodegradability

Most biodegradable polymers (e.g., PLA, PCL, and cellulose) are electrically insulating, whereas conventional carbon-based materials provide high conductivity. While conductive fillers (graphene, CNTs, metallic nanoparticles) can enhance polymer conductivity, they often reduce biodegradability, creating a performance–sustainability trade-off.

Flexibility vs. Stability

Biodegradable polymers generally offer superior mechanical flexibility compared to brittle ceramics and metals. However, this comes at the expense of long-term stability, as many biopolymers absorb moisture and undergo rapid hydrolysis under device operating conditions.

Environmental Safety vs. Electrochemical Window

Natural polymer-based electrolytes (cellulose, chitosan gels) are non-toxic and biodegradable, but their electrochemical windows (~1.5–2.0 V) are significantly narrower than synthetic electrolytes (~3–5 V for carbonate solvents), limiting their energy density.

Processing & Cost vs. Performance

Biodegradable polymers are often easier to process via solution casting, electrospinning, or melt blending compared to ceramic separators or PVDF-based membranes. However, their device-level performance (energy density, cycling stability) remains lower, restricting their use in high-power applications.

To address these issues, hybrid approaches are increasingly explored, such as nanocellulose/PVDF blends, PLA-carbon composites, or chitosan-graphene electrolytes, that attempt to balance biodegradability with device performance. While these hybrids partially compromise on full degradability, they point toward a middle-ground pathway: Incremental replacement of non-degradable components with eco-friendly counterparts while maintaining acceptable performance.

Table 2 presents a systematic comparison of representative biodegradable polymers currently investigated for green energy and environmental technologies, such as bio-batteries, fuel cells, supercapacitors, and energy-harvesting systems. The materials are evaluated based on their physicochemical properties (e.g., mechanical strength, thermal stability, and degradation rate), functional performance parameters, and processing adaptability. The analysis highlights the unique advantages of polymers such as PLA, PHA, chitosan, starch-based blends, and cellulose derivatives in achieving material circularity while maintaining electrochemical efficiency. At the same time, it outlines critical limitations, including moisture sensitivity, restricted electrical conductivity, and scale-up challenges that still constrain their broader industrial application. Overall, the table underscores how targeted material modification and hybridization strategies can bridge the gap between biodegradability and functional performance, enabling more sustainable solutions in next-generation green energy systems.

Table 2. Comparative analysis of biodegradable polymers for green energy applications: Properties, advantages, and limitations.

Polymer	Green energy application	Key properties	Advantages	Limitations	References
PLA (Polylactic Acid)	TENGs, Batteries	Biocompatible, thermoplastic, moderate conductivity	Lightweight, flexible, industrially compostable	Brittle, low conductivity, slow degradation under ambient conditions	[43,45]
PCL (Polycaprolactone)	TENGs, Supercapacitors	Biodegradable polyester, low melting point	Good blend compatibility, flexible, and mechanically stable	Slow degradation rate, moderate conductivity	[41,44]
Cellulose	Supercapacitors, Batteries	High crystallinity, hydrophilic, and renewable	Excellent ionic conductivity, abundant, biodegradable	Hygroscopic, mechanical fragility under wet conditions	[42,46]
Chitosan	Supercapacitors, Electrolytes	Antimicrobial, biopolymer derived from chitin	Film-forming, good ionic conductivity in gel form	Poor mechanical strength, pH-sensitive	[41,55]

5. Environmental and health impacts of biodegradable polymers

Evaluating the effects of biodegradable polymers on the environment and human health is becoming increasingly important as their use grows. Although these materials are promoted as environmentally friendly substitutes for traditional plastics, it is important to carefully assess how they affect biological systems and ecosystems to make sure they live up to their stated environmental goals without posing additional hazards. Figure 4 depicts the effects of biodegradable polymers on the environment and human health throughout their life cycle to give a thorough grasp of the wider ramifications. Important routes are depicted in the diagram, including degradation in different habitats, possible degradation by product release, interactions with aquatic and microbial life, and human exposure issues in consumer and biomedical applications. This illustration highlights the need for a comprehensive evaluation when endorsing biodegradable polymers as sustainable substitutes.

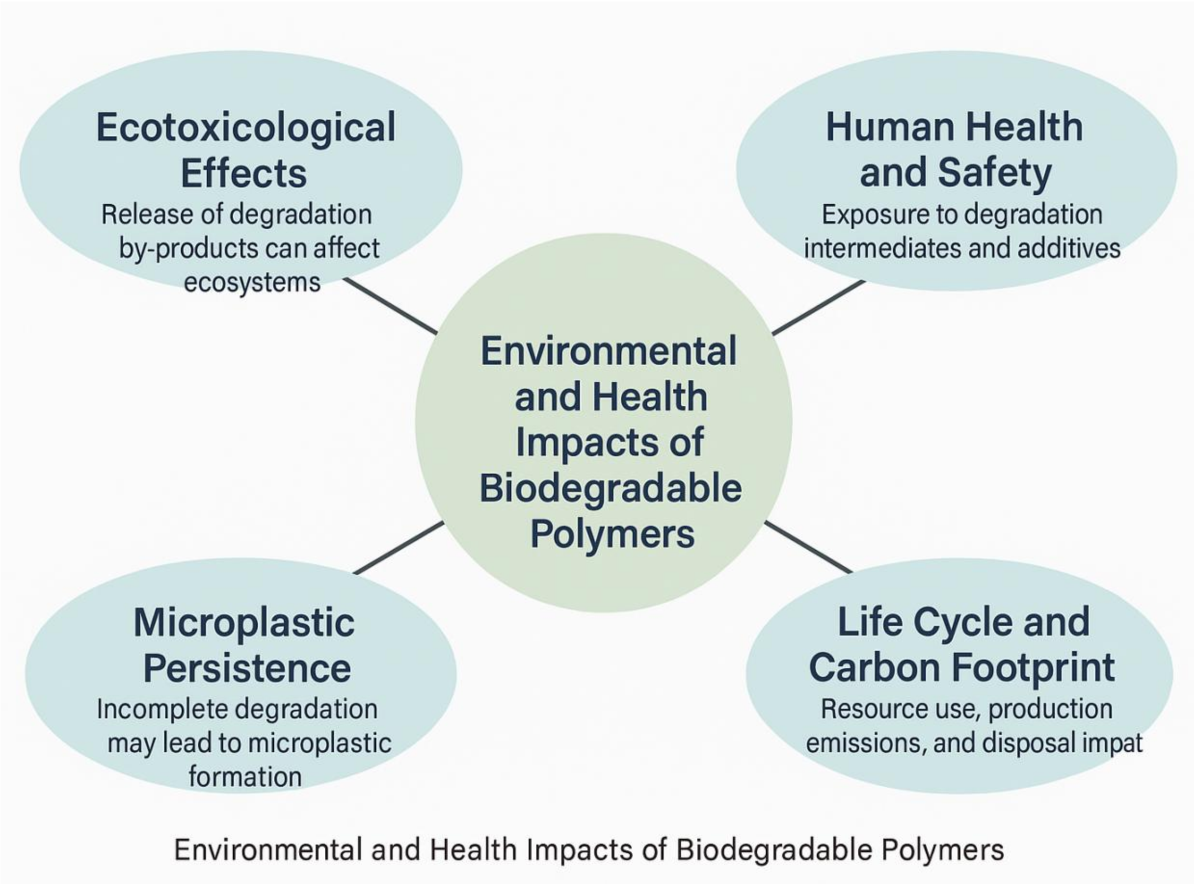

Figure 4. Environmental and human health implications of biodegradable polymers across their life cycle.

Recent evidence indicates that the environmental safety of biodegradable polymers cannot be assumed solely from their degradability. Studies have shown that commercial biodegradable products often contain additives such as plasticizers, stabilizers, and nanofillers, which can leach into surrounding environments during use or degradation. For instance, phthalate esters and citrate-based plasticizers have been detected in leachates from PLA and PBAT-based products, with measurable ecotoxic effects on aquatic organisms and mammalian cell cultures. Similarly, photo-aged biodegradable mulching films have released degradation byproducts that caused developmental toxicity in zebrafish embryos, highlighting that weathering processes can enhance the bioactivity of leachates.

In addition to additive migration, the degradation of bioplastics generates intermediates and micro-/nanoplastic fragments that persist in ecosystems before complete mineralization. Case studies demonstrate that PLA/PBAT-derived microplastics induced cytotoxicity in human THP-1 cells (EC_{50} ≈ 243 mg L^{-1}), while leachates from aged biodegradable microplastics inhibited algal growth more strongly than some conventional plastics [56–58]. These findings suggest that incomplete degradation and the release of reactive byproducts can alter microbial activity, affect soil and aquatic biota, and raise human health concerns when bioplastics are used in packaging, biomedical, or energy-device contexts.

5.1. Ecotoxicological considerations

When biodegradable polymers break down, they release a variety of byproducts into the environment, such as additives, oligomers, and monomers. Not all these byproducts are harmless. Research has demonstrated that PLA and PBAT degradation intermediates might temporarily impact aquatic life and soil microbial populations, potentially changing ecosystem functioning [56,57]. Additionally, in some circumstances, such as in cold soil or coastal habitats, inefficient biodegradation may result in persistent microplastics that are just as dangerous to wildlife as traditional polymers.

5.2. Human health and safety

Biocompatibility and possible toxicity are concerns when biodegradable polymers are exposed to humans, particularly through contact surfaces, food packaging, and medical equipment. Synthetic alternatives like PLA may trigger inflammatory reactions in biomedical applications if breakdown rates are not adequately regulated, even though natural polymers like chitosan and gelatin are typically thought to be harmless [58]. Plasticizers, crosslinkers, and nanofillers are examples of performance-enhancing additives that can leak out and cause cytotoxicity or hormone disturbance, especially in situations involving prolonged exposure [59].

5.3. Life cycle and carbon footprint implications

The overall environmental impact of biodegradable polymers is largely dependent on the sourcing of raw materials, the energy required for manufacturing, and the infrastructure for disposal, even though these polymers frequently have a reduced end-of-life footprint. According to a life cycle assessment (LCA), PLA uses more land and water since it depends on agricultural biomass, but it emits fewer greenhouse gases than PET [58] As a result, the sustainability of biodegradable polymers depends on the setting and necessitates integration with circular economy activities, including effective industrial composting systems, collection, and sorting [60].

Islam et al. (2025) conducted a thorough life cycle assessment (LCA) study that compared the production of PLA from microalgal biomass and cane sugar, evaluating contributions at each stage of production and performing sensitivity analysis to pinpoint important environmental factors. According to the study, the synthesis of PLA from cane sugar used more land and water because it relied on agricultural biomass, but it produced fewer greenhouse gas emissions than PET. According to the data, switching to renewable energy can lessen significant environmental effects [58]. These insights underscore the importance of considering the life cycle of biodegradable polymers, from raw material sourcing to end-of-life disposal, to ensure their environmental benefits are fully realized.

6. Emerging trends and future outlook

Biodegradable polymers are evolving from traditional uses to highly intelligent and functional materials that support global sustainability and digitalization objectives. The development of more intelligent, effective, and ecologically friendly solutions is being propelled by advancements in material science, artificial intelligence, and hybrid systems.

6.1. Smart biodegradable polymers

Intelligent biodegradable polymers are made to react to biological enzymes, light, temperature, and pH. These responsive materials have potential uses in packaging, biomedicine, and agriculture, where performance tweaking or controlled deterioration are crucial. For example, by releasing therapeutic drugs in acidic tumor microenvironments, pH-responsive chitosan derivatives have demonstrated great utility in drug-delivery systems [61]. Likewise, thermoresponsive biodegradable hydrogels have been investigated for use in wound healing and tissue engineering. Additionally, scientists have created shape-memory biodegradable polymers that can regain their shape when exposed to light or body warmth, increasing their application in smart textiles and transient electronics.

6.2. Hybrid bio-based materials and nanocomposites

Hybrid bio-based composites are created by combining biodegradable polymers with nanomaterials like graphene oxide, nanocellulose, or starch-based nanocrystals. These substances enhance the biodegradable matrices' mechanical strength, barrier qualities, and functional performance. In packaging films, for example, it has been demonstrated that nanocellulose-PLA composites increase tensile strength and decrease oxygen permeability [61]. These composites are also becoming more popular in fields like water purification and energy storage where mechanical integrity, biodegradability, and multifunctionality are essential. These patterns show how nanotechnology and green materials science are becoming more and more integrated.

6.3. AI-driven design and optimization

Machine learning and artificial intelligence (AI) are revolutionizing the design and assessment of biodegradable polymers. These days, polymer behavior is simulated, mechanical and thermal properties are optimized, and biodegradability under environmental conditions is predicted using predictive models and materials informatics platforms. For instance, researchers have employed AI to forecast PLA mix degradation kinetics and optimize copolymer ratios for the required mechanical performance [62]. Rapid prototyping of biodegradable solutions tailored to certain industries is made possible by this data-driven method, which also speeds up innovation and drastically eliminates trial-and-error testing.

6.4. Regulatory and policy drivers for market integration

Rather than relying on generalized claims about the "criticality" of biodegradable polymers, recent progress demonstrates that policy frameworks and regulatory standards are the real enablers of circularity. The European Green Deal and Plastics Strategy have established strict recycling and composting targets, directly incentivizing the uptake of biodegradable polymers in packaging and consumer products. Similarly, ISO 17088 and ASTM D6400 define compostability and biodegradability criteria, ensuring consistency across international markets. These standards not only reduce "greenwashing" but also create a level playing field for producers, guiding innovations that meet measurable end-of-life performance [63].

In parallel, extended producer responsibility (EPR) schemes and subsidies for bio-based materials are being implemented in several regions, further strengthening circular-economy pathways. Together, these policies and standards shift the discussion of biodegradable polymers from abstract sustainability goals to concrete mechanisms of market adoption, providing a clear roadmap for scaling biodegradable packaging and energy-device applications within a circular plastics economy.

Moreover, the United Nations Intergovernmental Negotiating Committee (INC-5.2) concluded in Geneva on 15 August 2025 [64], advancing negotiations toward a legally binding Global Plastics Treaty. The draft framework emphasizes regulating the full life cycle of plastics, including production, design, and disposal, with a strong focus on curbing single-use plastics and accelerating the adoption of biobased and biodegradable alternatives where appropriate. Importantly, the discussions highlighted the dual need for (i) standardized biodegradability criteria that align with real-world disposal pathways (home composting, industrial composting, municipal waste streams), and (ii) toxicity assessments of degradation byproducts to prevent unintended environmental harm. These outcomes reinforce the relevance of research on biodegradable polymers, situating them as a technological innovation and a policy-driven solution within the emerging global plastics governance framework.

Table 3 highlights the major recent developments in biodegradable polymer research, providing a summary of advancements. The table emphasizes the unique characteristics, technological drivers, and potential impacts of recent innovations, including bio-based hybrid composites, stimuli-responsive materials, AI-enhanced polymer design, and supportive regulatory frameworks. These trends illustrate how sustainable material science has evolved dynamically and point to groundbreaking applications in industries such as packaging, energy, and biomedicine.

Table 3. Summary table: Emerging trends in biodegradable polymer innovation.

Trend	Description	Applications	Key References
Smart Biodegradable Polymers	Stimuli-responsive materials for triggered degradation or delivery	Drug delivery, sensors, electronics	[45]
Hybrid Bio-Based Composites	Nanomaterial-reinforced biopolymers for improved performance	Packaging, energy devices, and filtration	[65]
AI-Driven Design	Machine learning for polymer prediction and optimization	Rapid prototyping, materials screening	[62]
Regulatory Frameworks	Policy incentives, biodegradability standards, plastic bans	Market acceleration, compliance	[63]

The diagram in Figure 5 (A–D) illustrates the four pivotal trends shaping the future of biodegradable polymers:

1. Smart Biodegradable Polymers: Smart packaging and tailored medicine administration are made possible by materials designed to react to environmental cues like pH, temperature, or light.

2. Hybrid Bio-Based Materials: Combining biodegradable polymers with nanomaterials, such as graphene oxide or nanocellulose, to improve functionality, mechanical strength, and barrier qualities.

3. AI-Driven Design: Application of machine learning and artificial intelligence to forecast polymer behaviors, enhance characteristics, and hasten the creation of personalized biodegradable materials.

4. Regulatory and Policy Support: Impact of international laws and policies encouraging the use of biodegradable polymers using standards, incentives, and prohibitions on non-biodegradable plastics.

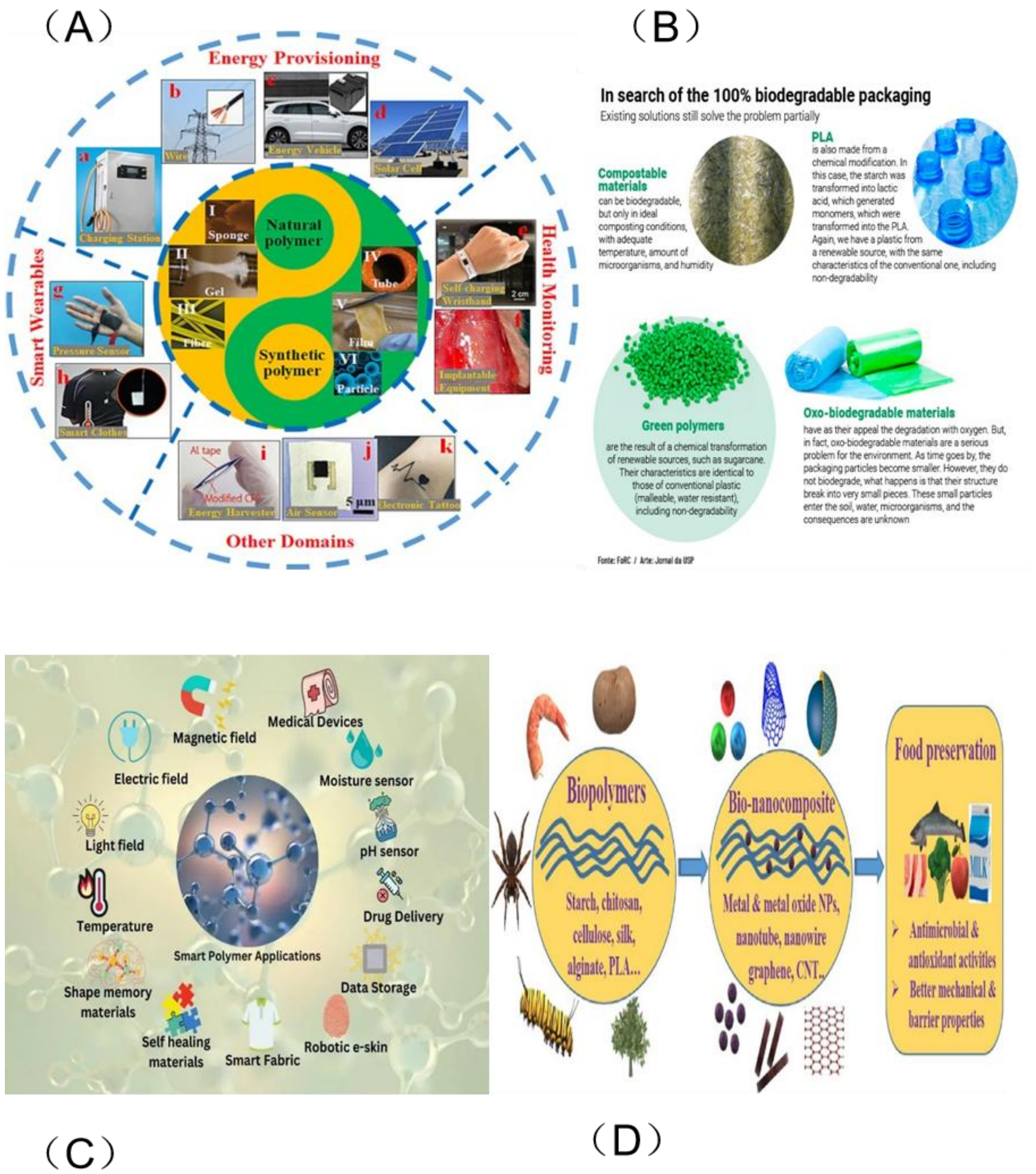

Figure 5. Emerging Innovations in Biodegradable Polymers - Smart Biodegradable Polymers (A), Hybrid Bio-Based Materials (B), AI-Driven Design (C), and Regulatory Policy Support (D) [65–68]. Reuse with permission.

7. Biodegradable polymers in sensors and delivery systems

7.1. Biodegradable polymers in sensors

Recent advances highlight biodegradable polymers as versatile platforms for chemical and biosensing applications. Their biocompatibility, flexibility, and eco-friendly degradation make them attractive alternatives to non-degradable polymers in transient or implantable sensors. For example, polymer matrices based on chitosan, cellulose, and PLA have been functionalized with dyes, nanoparticles, or conductive fillers to create fluorescence- and electrochemical-based sensors for detecting heavy metals, toxins, and biomolecules. Moreover, researchers reported a biodegradable polymer-based optical sensor capable of detecting trace levels of environmental pollutants with high sensitivity [69,70]. Earlier work also demonstrated the potential of biopolymer-metal complexes in sensing applications, particularly in biomedical diagnostics [71]. These developments suggest that biodegradable polymers could play a key role in sustainable sensing platforms, especially where short device lifetime, minimal environmental impact, and safe disposal are critical.

7.2. Biodegradable polymers as delivery systems

In parallel, biodegradable polymers have gained prominence as drug and gene delivery systems, where controlled degradation offers precise therapeutic release and eliminates the need for surgical removal. Polymers such as PLA, PLGA, chitosan, and PEG-based copolymers are widely used as carriers for small molecules, proteins, and nucleic acids. The researchers in [72] demonstrated biodegradable polymer nanoparticles enabling targeted delivery with tunable degradation kinetics, enhancing both bioavailability and safety. Biodegradable systems also enable incorporation of imaging agents or targeting ligands, broadening their utility in theranostics. Given the rising importance of personalized medicine and regenerative therapies, biodegradable delivery platforms stand out as one of the most impactful applications of biopolymers in healthcare.

8. Conclusion

In the search for sustainable materials for various applications, from packaging and agriculture to biomedical devices and green energy technologies, biodegradable polymers represent a revolutionary breakthrough. This review highlights the intricacy of their degradation processes, the environmental factors affecting their functionality, and their evolving role in next-generation technologies. Incorporating biodegradable polymers into energy systems, such as transient batteries, triboelectric nanogenerators, and supercapacitors, demonstrates not only their functional versatility but also their alignment with low-carbon and circular economy objectives.

Significant obstacles need to be addressed to unlock their full potential, such as improving long-term stability, achieving competitive mechanical and electrical performance, and expanding industrial composting and recycling infrastructure. Nevertheless, emerging advances like AI-driven design optimization, hybrid bio-composites, and smart and stimuli-responsive materials suggest a promising future. These innovations emphasize a shift toward materials that are not only high-performing but also environmentally friendly, supported by regulatory momentum and insights from life cycle analysis. Ultimately, interdisciplinary collaboration, legislative support, and ongoing investment in green innovation will be essential to fully realize the potential of biodegradable polymers. These materials will play a key role in reshaping the understanding within material science of the relationship between performance, biodegradability, and ecological impact as global sustainability challenges intensify.

An organized summary of recent and upcoming developments in the field of biodegradable polymer research is provided by this conceptual image. Smart biodegradable polymers that respond to environmental cues, hybrid bio-based composites (such as those based on nanocellulose), AI-assisted design frameworks for enhanced property optimization, and shifting regulatory and policy environments that foster market adoption are among the key innovation pathways. The future of biodegradable materials for industrial and environmental applications is shaped by the synergy between sustainability and technological advancements, as illustrated in the graphic. The recent progress toward a legally binding Global Plastics Treaty (INC-5.2, Geneva, August 2025) further underscores the urgency of aligning biodegradable polymer innovation with standardized testing, toxicity evaluation, and real-world waste management systems, ensuring that scientific advances translate effectively into global sustainability policies.

Figure 6 illustrates the integrated innovation ecosystem that is reshaping the field of biodegradable polymers. It highlights how the convergence of renewable resource utilization, bio-inspired design strategies, and AI-assisted material optimization with regulatory frameworks and sustainability-driven policies speeds up the shift toward a circular plastic economy. The diagram shows interconnected pathways linking laboratory research, process engineering, and industrial implementation, emphasizing ongoing feedback among technological innovation, environmental performance, and policy development. Together, these pathways demonstrate that advancing next-generation biodegradable polymers requires not only material breakthroughs but also systemic coordination across scientific, industrial, and governance sectors, ensuring that innovation effectively aligns with global sustainability goals and the emerging Global Plastics Treaty.

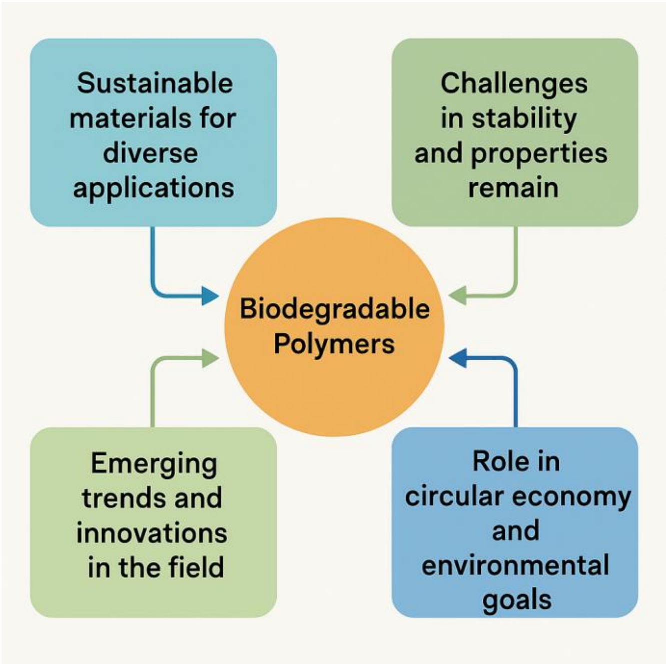

Figure 6. Biodegradable polymer innovation landscape: Pathways toward sustainable material solutions.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflict of interest.

Author contributions

Dr. Agbogo: Writing – writing – original draft, conceptualization. Prof. Sadiku: review,

Supervision. Dr. Mavhungu: Project administration and investigation. Dr. Teffo: Validation, Editing, visualization.

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