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ARTICLE

Next-Generation Biodegradable Polymers: From Synthesis to Industrial Applications

Ismat Ullah Khan

Government Post Graduate College Lakki Marwat, Lakki Marwat 28420, Pakistan

ABSTRACT

Biodegradable polymers of the next generation have become a hopeful move towards reducing the increasing environmental issues regarding the problem of plastic pollution. Being made out of renewable bio-based feedstock, these polymers also possess the option of naturally degrading within the environment, minimizing plastic waste and the impact it has on the environment. This review will be discussing the synthesis process, characteristics as well as commercial uses of biodegradable polymers with a given emphasis on their mechanical, thermal, and biodegradability properties. Two to three major advances in the polymerization technologies, materials design and functionality have been discussed in the article and they play a significant role in improving the performance of biodegradable polymers in numerous applications such as in packaging, agriculture, biomedical, and textile industries. Though it has a bright future, there are challenges associated with it, including cost, scalability, performance ceiling, and waste management that still exist, and it is necessary to tackle these problems to complete the mass adoption of biodegradable polymers. The future trends in development of new materials with high performance, low costs and potential with environmental responsibility are addressed where there is a need of continued innovation in this area so as to facilitate more sustainable and circular economy.

Keywords: Biodegradable Polymers; Bio-Based Feedstocks; Environmental Sustainability; Polymer Synthesis; Industrial Applications

*CORRESPONDING AUTHOR:
Ismat Ullah Khan, Government Post Graduate College Lakki Marwat, Lakki Marwat 28420, Pakistan; Email: iukhan@chem.qau.edu.pk

ARTICLE INFO
Received: 15 August 2022 | Revised: 7 October 2022 | Accepted: 14 October 2022 | Published Online: 21 October 2022
DOI: https://doi.org/10.55121/nefm.v1i1.860

CITATION
Khan, I.U., 2022. Next-Generation Biodegradable Polymers: From Synthesis to Industrial Applications. New Environmentally-Friendly Materials. 1(1): 42–64. DOI: https://doi.org/10.55121/nefm.v1i1.860

1. Introduction

The rising worldwide awareness of plastic pollution has been leading to the search of sustainable solutions to regular synthetic plastic. Plastic, as much as it is needed in many industries because of its low cost, durability and versatility has been proved to be a major threat to the environment since it is non-biodegradable. This has seen the development of plastic waste in the landfills, oceans, and the ecosystems with dire ecological damages. The extensive incorporation and persistence of polymers based on petroleum has attracted vast considerations of getting biodegradable polymers-who can decompose adequately without forming any harmful residues. The need of these solutions has made the researchers as well as the industries be concerned about developing biodegradable polymers. One reason is to create these polymers to break down in nature under normal degrading circumstances and cause less pollution and make the future more sustainable [1].

Biodegradable polymers by definition are substances that can be broken down microbially or enzymatically, which yields non-toxic end-products which may be water, carbon dioxide or methane depending on the setting. One of the advantages of these polymers is that they have formed a favourable alternative to conventional plastics because they reduce the impact towards environmental pollution. Formerly, the vast majority of attained bio degradable polymers were exclusive to the products of natural origins, which include starch, cellulose, and proteins. Nevertheless, early materials usually presented drawbacks, such as weak mechanical characteristics, low resistance, and a small choice of processing procedures, which did not allow their large-scale use.

Developing the next generation of bio-degradable polymers has evolved to create more versatile bio-degradable polymers that have enhanced performance and sustainability. The term next-generation means a major advance over past methods with a focus on new achievements in the chemistry as well as engineering of such polymers. These new breeds of biodegradable polymers are designed not only to be degraded effectively in different conditions but to obtain the standards of performance required in the industrial world, of food packaging to medical implants. Advanced materials involving renewable bio-based feedstocks and novel polymerization methods have developed polymers that have high mechanical and durability properties, adjustable degradation rates, and a small overall environmental impact [2–4].

No-one can underestimate the significance of these new-generation polymers which are biodegradable. With the society still struggling with the adverse impact of plastic waste, there is increased eagerness to find a material that would go in line with the ideas of a circular economy, where resources are reused and consumption of material is minimal. With adequate planning and execution, biodegradable polymers can form the center stage of this transition. Moreover, biodegradable polymers are likely to find increased market acceptance, especially in packaging industries, agricultural industry, healthcare, and textiles as industries, governments, and consumers shift focus on sustainability issues [5,6].

A lack of addressing what was short in the previously used biodegradable polymers is one of the driving forces behind the development of the new generation of materials. Although traditionally popular types of biodegradable polymers (polylactic acid (PLA) and polyhydroxyalkanoates (PHA)) are effective in specific uses, they have issues such as mechanical characteristics, degradation rate and cost. An example of such plastics is PLA, which is commonly used in packaging, but can often be brittle and do not withstand much heat. Likewise, PHAs are very expensive to manufacture at large quantities because of high rates of biodegradation whereas at the commercial scale, they have a low viability [7–10].

These challenges have prompted the exploration of new monomers, polymerization methods, and processing techniques to design biodegradable polymers that do not compromise on performance, ease of use, and environmental benefits [11]. To address these challenges and validate the performance of next-generation biodegradable polymers, comprehensive characterization methods are essential. These techniques span physical, chemical, thermal, and biological analyses (**Figure 1**), enabling researchers to evaluate structural integrity, degradation kinetics, and environmental compatibility. Such multi-faceted assessments ensure that new materials meet both industrial requirements and sustainability goals [12].

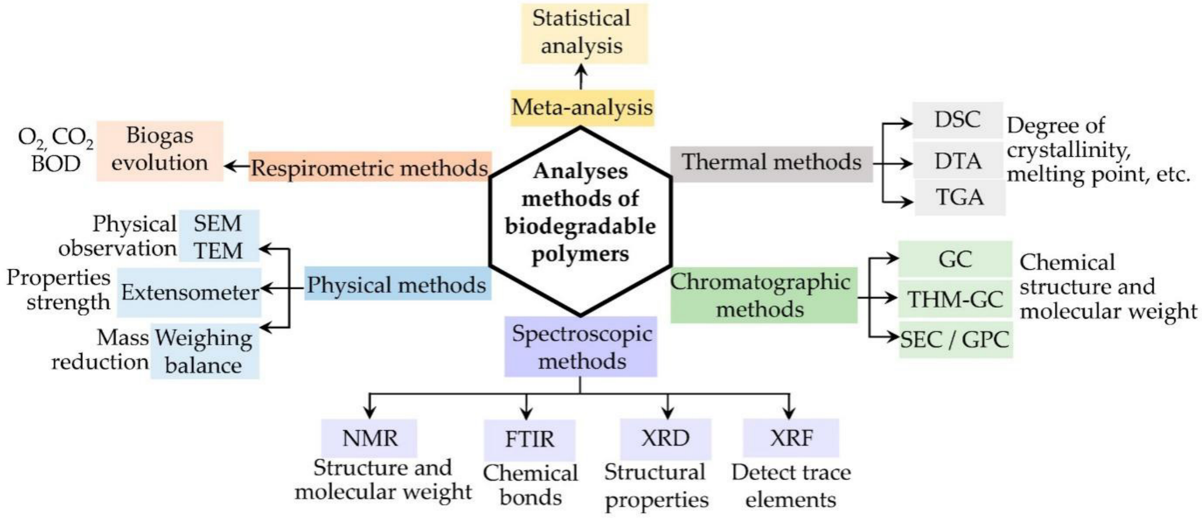

Figure 1. Analytical methods of biodegradable.

Research in the area of biodegradable polymers is also expanding to incorporate bio-based feedstocks, which are sourced from renewable materials such as plant oils, agricultural residues, and even waste biomass. **Figure 2** categorizes the primary renewable sources and synthesis approaches for next-generation biodegradable polymers, including (1) natural biopolymers like polysaccharides and proteins, (2) synthetic biopolymers such as polyacids and polyesters, and (3) hybrid systems combining microbial synthesis with biopolymer blends. This diversity of feedstock options enables tailored solutions for different application requirements while maintaining environmental sustainability. By replacing petroleum-derived feedstocks with renewable ones, these next-generation polymers not only reduce the reliance on fossil fuels but also decrease the carbon footprint associated with their production. Furthermore, advances in polymer synthesis, such as ring-opening polymerization and controlled radical polymerization, are enabling the creation of complex polymer architectures that improve biodegradability while enhancing mechanical strength and thermal stability [13–14].

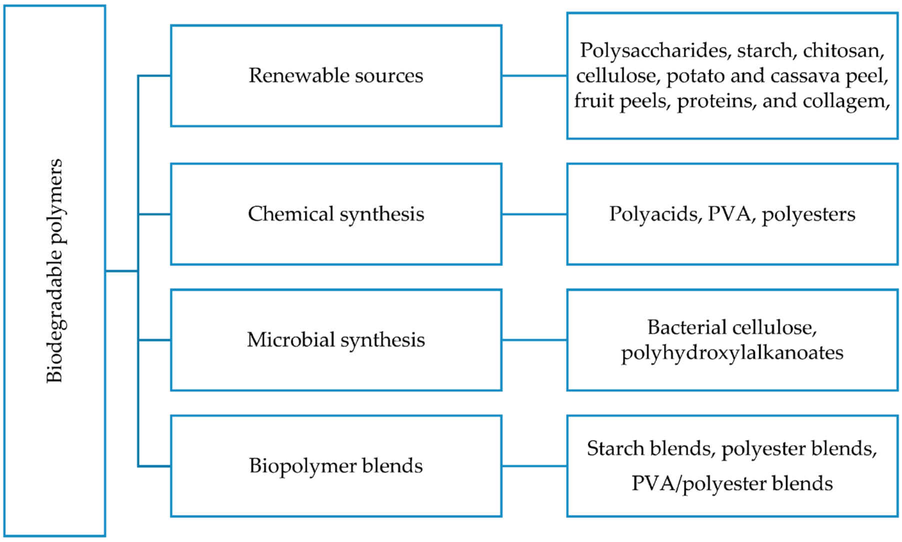

Figure 2. Classification of production processes for biodegradable polymers [15].

The field of biodegradable polymers is rapidly evolving, with innovations in both material design and processing technologies pushing the boundaries of what is possible. **Figure 3** shows a sharp increase in research on biodegradable polymers is indicated and it is an indicator of the increasing scientific and industrial interest in biodegradable polymers. Research has also explored the use of nanomaterials to enhance the strength and biodegradability of polymers, thereby creating more viable materials, as well as the incorporation of functional additives to improve polymer performance in specific applications, such as nanocellulose-based polymers. Such developments are giving rise to polymers that are increasingly hardy as well as versatile, and serve the varieties of needs across industry, such as agricultural plastics to medical equipment [15].

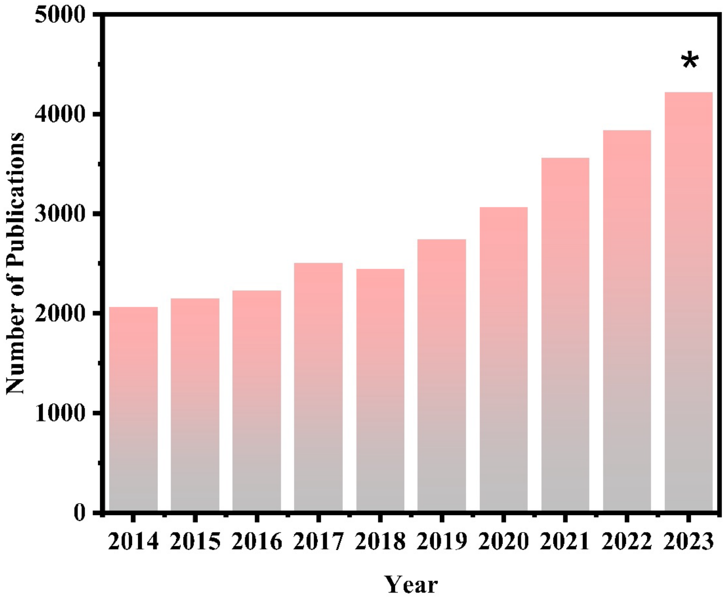

Figure 3. Articles published articles on Biodegradable polymers. The information is retrieved from Scopus with a keyword "Biodegradable polymer" on 13 August 2023.

As we move towards an age of next-generation biodegradable polymers, biodegradability has become the standard as much as making materials that fit the requisites of different industries. This review article strives to discuss the synthesis, properties and applications of these innovative materials giving a detailed insight on the gains towards the field, the remaining challenges in the field, and the way forward in research and development. And whether it is sustainable packaging solutions or recent applications in the medical, biomedical fields, next-generation biodegradable polymers are ready to be in the middle of the spotlight that would create a more sustainable and environment-friendly future [12,16].

2. Key Properties of Biodegradable Polymers

Bio-degradable polymers are one of the most versatile products that require knowledge of their nature in order to be developed and utilized in different sectors. To be used effectively in the place of conventional synthetic plastics and serve the purpose of being environmentally friendly, biodegradable polymers have to come up to certain requirements. This part will explore into the main aspects of biodegradable polymers with emphasis on biodegradation, mechanical, thermal property aspects as well as their general environmental effects. All the above properties are critical in dictating the prospective utilization and future life of these materials in practical uses [17].

2.1. Biodegradability and Biocompatibility

Biodegradability refers to the ability of a polymer to break down into harmless by-products (such as water, carbon dioxide, or methane) through biological processes, typically involving microorganisms, fungi, or enzymes. This is the defining characteristic that sets biodegradable polymers apart from conventional plastics, which persist in the environment for decades or longer. For a polymer to be classified as biodegradable, it must degrade within a specified time frame under natural environmental conditions without leaving toxic residues behind.

The biodegradation process can be broken down into several stages. The first stage is hydrolytic degradation, in which water molecules break the polymer's chemical bonds, leading to the formation of smaller fragments. The second stage is enzymatic degradation, where microorganisms and enzymes further degrade the polymer fragments into non-toxic by-products, such as carbon dioxide, methane, and water. The final stage is composting. Some biodegradable polymers are designed to degrade rapidly under composting conditions, in which the polymer breaks down in the presence of heat, moisture, and microbial activity.

For polymers used in practical applications, the degradation rate needs to be controlled to ensure the material performs its intended function before breaking down. For example, packaging materials need to have sufficient durability to protect products but should degrade quickly once discarded in composting or waste environments [18].

It is a very important feature, especially when a biodegradable polymer will be used in biomedical applications, and biocompatibility is an issue of some concern. Biocompatibility is defined as the behaviour of the polymer relative to living tissue preventing any adverse effect to the same. Medical device applications Polymers must be chosen carefully when used in medical devices, sutures, drug delivery systems or tissue scaffolds because they must degrade, without activating any inflammatory cascades or toxicity, in the body. Often, the biodegradable polymer biocompatibility also depends on the chemicals into which it degrades. The medical application of polymers requires that during degradation processes, by-products are non-toxic so that they do not harm the body in which they exist.

2.2. Mechanical Properties

It is indeed the mechanical properties of biodegradable polymers that determine whether they are qualified to be utilized in a wide range of industrial applications. Such properties include tensile strength, elasticity, impact resistance, and stiffness. Conventional plastics are regarded as having excellent mechanical performance, and in order to substitute conventional plastics, biodegradable polymers must possess comparable or even superior performance, depending on the application.

Tensile strength refers to the ability of a polymer to withstand stretching or breaking under tension. A high level of tensile strength is required in applications where the material needs to hold loads, such as in packaging and agricultural films. Elasticity is the characteristic of a polymer that allows it to deform and then return to its original shape. For instance, biodegradable polymers used in product packaging or textiles must possess sufficient elasticity to ensure that the structure and shape can endure stress without permanent deformation. Impact resistance is another essential property, as biodegradable polymers must resist cracking or breaking upon impact. This property is particularly crucial in packaging and consumer goods, where durability is a key requirement. Stiffness refers to a polymer's resistance to deformation when subjected to force. In applications such as construction materials or automobile parts, biodegradable polymers need to be sufficiently stiff to serve their intended purpose effectively [19,20].

These properties have been improved through innovations in developing next-generation biodegradable polymers. For example, incorporating nanofillers such as nanocellulose or clay nanoparticles into the polymer matrix can enhance mechanical strength and toughness without compromising biodegradability. This area of research is significant, as it allows biodegradable polymers to achieve performance levels that can compete with conventional plastics.

2.3. Thermal and Processing Properties

Agreeing upon appropriate thermal properties for biodegradable polymers is crucial, as thermal behavior under the influence of heat plays a significant role in both processing and end-use applications. The key thermal properties include thermal stability, glass transition temperature, and melting temperature.

Melting temperature (Tm) refers to the temperature at which a polymer changes its state from solid to molten. Higher melting temperatures are preferred for polymers that are exposed to heat, such as those used in packaging or vehicle components. Glass transition temperature (Tg) is the temperature below which a polymer becomes stiff and brittle, and above which it becomes more flexible. For applications like flexible packaging or biodegradable coatings, polymers with a low Tg are desirable to prevent brittleness under natural usage conditions.

Thermal stability describes the ability of a polymer to maintain its structure and performance when exposed to high temperatures. Many bio-based monomers and their corresponding polymers tend to have lower thermal stability compared to petroleum-based ones, which can limit their use in high-temperature environments. Researchers are actively addressing this limitation by adding stabilizers or developing alternative polymerization methods to enhance the thermal stability of biodegradable polymers [21].

The properties involved in processing, such as the melt flow index, viscosity, and ease of processing, are also significant. Biodegradable polymers are processed in traditional ways, such as extrusion, injection molding, and blow molding; however, there are bio-based plastics that require modifications to processing conditions. An example can be cited of biodegradable polymers not exhibiting as high melt viscosity as synthetic plastics necessitating either adjustments to their processing equipment or the addition of some additives to aid particular viscosity and procedure.

2.4. Environmental Impact

The environmental impact of biodegradable polymers is one of the main driving forces behind their development. These materials are designed to reduce the carbon footprint associated with traditional plastics, which are typically derived from fossil fuels. The environmental benefits of biodegradable polymers extend beyond their degradation process and encompass several important factors.

Carbon footprint reduction is a major advantage of biodegradable polymers, especially those produced from renewable resources such as starch, cellulose, or plant oils. During production, these polymers generate a lower carbon footprint compared to petroleum-based plastics. By utilizing renewable feedstocks, biodegradable polymers decrease dependence on non-renewable resources and support the transition toward a circular economy. Non-toxic degradation is another key benefit. Unlike conventional plastics that may release harmful microplastics or toxic additives as they degrade, biodegradable polymers break down into environmentally safe by-products that do not cause pollution. This property is particularly crucial in marine ecosystems, where plastic waste poses a severe threat to aquatic life.

Biodegradability under various environmental conditions also contributes to their environmental value. The overall environmental impact of a polymer depends not only on whether it degrades but also on the conditions required for degradation. Some biodegradable polymers are engineered to decompose rapidly under composting conditions, while others are formulated to degrade more gradually in soil, ensuring minimal disturbance to the surrounding environment [7,14,22].

On one hand, there are evident environmental gains of using biodegradable polymers; on the other hand, it is crucial to mention that such polymers have to be managed in a proper way not to have unexpected effects. An example is that some biodegradable polymers might be too short lived under specific conditions like in landfills where it might emit methane as opposed to carbon dioxide. Thus, it is imperative to note down the circumstances under which these polymers could break down in order to maximize their benefits to the environment.

2.5. Summary of Key Properties

To conclude, biodegradable polymers have to come to a compromise between the preferable environmental performance and material properties. What makes them an alternative to conventional plastics is their high levels of biodegradation, the presence of properties such as mechanical and thermal properties which make them desirable in industrial sectors. Current research efforts to enhance these properties are underway, including the ultimate goal of producing polymers that, in addition to biodegrading in an environmentally acceptable way, should at least perform or better than the specifications needed to satisfy many potential applications. Such important properties will determine the creation of the new generation of biodegradable polymers and contribute to the future industrial application [14,23].

3. Synthesis of Next-Generation Biodegradable Polymers

Syntheses of next-generation biodegradable polymers entail the development of materials that can fulfil the standard of biodegradability, in addition to having an overall higher performance than the conventional biodegradable polymers. The aim is to arrive at good, non-toxic polymers which disintegrate efficiently, having appropriate mechanical properties, thermal stability and functionality to carefully chosen industrial uses. The main processes in the synthesis of these advanced materials include selection of bio-based monomers, polymerization techniques, and the architecture of polymers, and all these issues are discussed in this section [24].

3.1. Bio-based Monomers

The constituents of biodegradable polymers are primarily bio-based monomers. The raw materials used to produce these monomers are renewable and naturally occurring substances—often derived from agricultural waste or plant materials—rather than petroleum-based resources used for conventional plastics. The use of bio-based monomers is a crucial step toward developing more sustainable polymers and promoting a circular economy. These monomers are gaining increasing attention due to their accessibility, affordability, and ability to produce high-performance materials suitable for a variety of applications.

Lactic acid is one of the most widely used bio-based monomers. It is the main building block for polylactic acid (PLA), a popular biodegradable polymer synthesized through the fermentation of sugars found in agricultural crops such as corn. PLA has been utilized in packaging, medical devices, and textiles. However, its brittleness and sensitivity to temperature limit its use in more demanding applications. Subsequent modifications and copolymerization techniques have led to improved versions of PLA with enhanced flexibility and thermal stability.

Hydroxyalkanoates are another important class of bio-based monomers obtained through microbial fermentation of sugars or lipids. Certain bacteria are capable of producing biodegradable plastics such as polyhydroxyalkanoates (PHA), which include polymers like poly(3-hydroxybutyrate) (PHB). PHAs have found applications in packaging, agriculture, and medical fields. Despite their potential, the high production cost and relatively slow degradation rate of PHAs remain challenges that researchers are working to overcome.

Dicarboxylic acids and diols form a group of monomers that can be synthesized from renewable sources such as vegetable oils or biomass. These monomers are used to produce biodegradable polyesters, including polybutylene succinate (PBS) and polyethylene furanoate (PEF). Their superior thermal stability and durability have made them increasingly popular in packaging applications. Cellulose derivatives are another major category of bio-based monomers. Cellulose, one of the most abundant components of plant biomass, is a renewable and versatile raw material. Through chemical modification, cellulose can be transformed into monomers used to produce biodegradable polymers such as cellulose acetate and cellulose ethers. These materials are widely used in films, coatings, and medical applications due to their biodegradability and functional versatility [25,26].

Bio-based monomers are mainly important in the determination of the end properties of the biodegradable polymer. Monomers are selected depending on their availability, prices and whether the monomers can provide the required physical, chemical and mechanical properties required by the desired application.

3.2. Polymerization Methods

After identifying the appropriate bio-based monomers, the next step involves polymerization, a process that forms long molecular chains to create polymers. Polymerization plays a crucial role in determining the final structure, properties, and performance of biodegradable polymers. Depending on the nature of the monomer and the desired properties of the resulting polymer, several polymerization techniques can be employed [27].

Ring-Opening Polymerization (ROP) is a widely used method for polymerizing cyclic monomers. For instance, lactic acid can be converted into lactide, which then undergoes a ring-opening polymerization process to produce polylactic acid (PLA). The main advantage of ROP is the high level of control it offers over molecular weight, polymer structure, and polymerization rate. This precision is particularly important in the enzymatic production of high-function biodegradable polymers used in biomedical applications such as drug delivery systems and tissue scaffolds.

Condensation Polymerization involves reactions between two or more functional groups (such as –OH or –COOH) on different monomers, resulting in polymer formation and the release of small by-products like water or methanol. This process is commonly used to produce polyesters (such as polybutylene succinate, PBS) and polyamides (such as bio-based nylon). Although condensation polymerization tends to proceed more slowly and may require elevated temperatures, it is effective for creating biodegradable materials with desirable mechanical properties and thermal stability.

Addition Polymerization is typically used for unsaturated monomers such as acrylic acid or styrene derivatives, which are polymerized in the presence of catalysts or initiators. This method is particularly useful for producing copolymers, where two or more monomers are combined into a single polymer to modify its properties. For example, copolymerizing PLA with other biodegradable monomers such as PHA or PBS can enhance the polymer's mechanical strength, flexibility, and degradation rate. Transesterification and Polycondensation reactions are also employed to produce biodegradable polyesters.

Transesterification involves the transfer of ester groups between molecules and is often used to synthesize materials such as polybutylene succinate-co-adipate (PBSA). Such polymers can be blended with other biodegradable materials to achieve a balanced combination of biodegradability, flexibility, and mechanical strength.

Controlled/Living Polymerization is a more advanced and versatile technique that allows precise control over polymer molecular weight and architecture. Methods such as atom transfer radical polymerization (ATRP) and nitroxide-mediated polymerization (NMP) enable the synthesis of well-defined copolymers with specific functionalities and tailored properties. This high level of design control makes the resulting polymers suitable for specialized applications, including drug delivery and tissue engineering. Through these polymerization methods, scientists can fine-tune the molecular weight, structural architecture, and degradation rates of biodegradable polymers to meet the needs of diverse applications [28,29]. A comparison of the mechanisms and advantages of these polymerization techniques is presented in **Table 1**.

Table 1. Comparison of polymerization methods for bio-based biodegradable polymers: Mechanisms and advantages.

Polymerization Method	Mechanism	Advantages
Ring-Opening Polymerization (ROP)	Polymerization of cyclic monomers (e.g., lactide) via ring cleavage, often catalyzed to control reaction rate and molecular weight.	- Precise control over molecular weight and polymer architecture- High purity polymers- Suitable for biomedical-grade biodegradable polymers
Condensation Polymerization	Step-growth reaction between monomers with two or more reactive groups (e.g., –OH, –COOH), releasing a small molecule (e.g., water, methanol).	- Good for producing polyesters and polyamides- Can yield polymers with good mechanical and thermal properties- Applicable to various bio-based monomers
Addition Polymerization	Chain-growth reaction of monomers with unsaturated bonds (e.g., vinyl, acrylic), initiated by catalysts/initiators.	- Rapid polymerization- Enables copolymer formation to tailor properties- Versatile range of monomers
Transesterification & Polycondensation	Exchange of ester groups between molecules, often followed by polycondensation to increase molecular weight.	- Enables synthesis of copolyesters with balanced biodegradability and mechanical strength- Good for blending with other biodegradable polymers
Controlled/Living Polymerization	Specialized radical or coordination polymerization (e.g., ATRP, NMP) allowing precise growth without chain termination.	- Fine control over molecular weight and architecture- Ability to introduce specific functionalities- Ideal for advanced applications like drug delivery and tissue engineering

3.3. Polymer Architecture

The architecture of a polymer is the structure of its monomeric units, its molecular weight, branching and crosslinking one to another. Polymer architecture is significantly important in defining the characteristics of the material such as the nature of biodegradability, mechanical properties and thermal characteristics of a material. In the next generation of biodegradable polymers, there is a need to regulate polymer architecture to satisfy the particular end use.

Several strategies can be employed to design advanced polymer architectures. Combining two or more distinct biodegradable polymers or copolymerizing different monomers can produce materials that integrate the desirable properties of each component. For instance, blending PLA with PHA or PBS can improve the flexibility and resilience of PLA, which is typically hard and brittle. Through this approach, the performance characteristics of biodegradable materials—such as impact resistance, elasticity, and heat stability—can be significantly enhanced to meet diverse application needs. Block copolymers are synthesized by polymerizing different monomers in separate segments within the same chain. This method allows for the creation of polymers with unique combinations of properties that are difficult to achieve using a single monomer. For example, block copolymers formed from a biodegradable hydrophobic polymer and a hydrophilic monomer can be engineered to achieve controlled degradation rates and water resistance, making them suitable for specialized applications such as biomedical devices or coatings.

The mechanical and barrier properties of biodegradable polymers can be substantially improved by incorporating nanomaterials such as nanocellulose, nanoclays, or carbon nanotubes into the polymer matrix. These nanocomposites exhibit superior toughness, strength, and durability while maintaining biodegradability. Such materials are particularly effective for use in biodegradable packaging, where improved performance and environmental compatibility are both critical. Crosslinking involves chemically bonding polymer chains together to form a network-like structure. This process enhances a polymer's resistance to deformation, dimensional stability, and mechanical strength. Crosslinking can be achieved through physical means, such as irradiation, or chemical means, using crosslinking agents. Crosslinked biodegradable polymers are particularly valuable in applications such as wound dressings, controlled drug release systems, and materials that require enhanced strength and durability [30–32].

Essential concepts of strategic design of polymeric architecture would allow the researchers to design materials with specific characteristics that meet a specific need in different industries like packaging, medicine, and even the textile industries. These materials have the ability to be optimized with respect to the mechanical properties, biodegradability, and even thermal stability, by choosing the optimal monomers used and the even the type of polymerization technique used. As well, the performance of the materials can be further improved through the formation of complicated polymeric structures including copolymers, block copolymers, and nanocomposites. This has made such polymers applicable to a wide scope of industrial processes.

4. Advanced Materials and Functionalization

Essential concepts of strategic design of polymeric architecture would allow the researchers to design materials with specific characteristics that meet a specific need in different industries like packaging, medicine, and even the textile industries. These materials have the ability to be optimized with respect to the mechanical properties, biodegradability, and even thermal stability, by choosing the optimal monomers used and the even the type of polymerization technique used. As well, the performance of the materials can be further improved through the formation of complicated polymeric structures including copolymers, block copolymers, and nanocomposites. This has made such polymers applicable to a wide scope of industrial processes [33].

4.1. Nanostructured Biodegradable Polymers

The process of including nanoscale materials into a polymer matrix and modifying the properties of the latter material is called nano structuring, usually the nanoscale is described as between 1 and 100 nanometres. Nano structuring biodegradable polymers has the potential to improve bulk mechanical strength, thermal stability, barrier functionality, and even biodegradation rates and as a result, allow nano-structured biodegradable polymers to be used in more challenging industrial applications [34].

4.1.1. Role of Nanomaterials

Nanomaterials such as nanocellulose, nanoclays, carbon nanotubes (CNTs), and metal nanoparticles are commonly incorporated into biodegradable polymers to enhance their overall performance. These nanomaterials play a crucial role in improving the mechanical, thermal, and functional properties of biodegradable polymer composites while maintaining their environmentally friendly nature.

Nanocellulose, derived from plant fibers, is a renewable and biodegradable nanomaterial that can significantly strengthen biodegradable polymers. Its high surface area and crystalline structure contribute to improvements in tensile strength and stiffness without compromising biodegradability. Nanocellulose can also be sourced from various renewable materials, including wood, agricultural waste, and algae, making it a sustainable choice for reinforcing biodegradable composites.

Nanoclays, such as montmorillonite and kaolinite, are layered minerals that, when uniformly dispersed within biodegradable polymers, enhance barrier properties—particularly resistance to oxygen and water vapor—as well as mechanical strength. Nanoclay-reinforced biodegradable polymers are increasingly utilized in packaging applications, as they reduce moisture absorption and extend the shelf life of packaged products.

Carbon nanotubes (CNTs) are cylindrical carbon structures renowned for their exceptional tensile strength, flexibility, and thermal stability. When incorporated into biodegradable polymers, CNTs can significantly enhance mechanical performance, improve thermal stability, and even impart electrical conductivity. However, achieving uniform dispersion of CNTs within the polymer matrix remains a key challenge, as poor dispersion can reduce performance efficiency.

Metal nanoparticles, such as silver and zinc oxide nanoparticles, are also used to impart specific functionalities to biodegradable polymers. For instance, silver nanoparticles provide antibacterial properties, making them particularly useful in biomedical applications such as wound dressings, surgical sutures, and controlled drug release systems. These nanoparticles enable biodegradable polymers to not only replace conventional plastics but also offer advanced functional capabilities for specialized applications.

The integration of nanomaterials into biodegradable polymers not only enhances the physical properties of the material but also promotes self-healing, antimicrobial activity, and lightweight characteristics. These advantages make nanostructured biodegradable polymers highly versatile, enabling them to be used in a wide range of applications, including medical devices, packaging, agriculture, and textiles [35,36].

4.1.2. Mechanical, Barrier, and Thermal Enhancement

The incorporation of nanomaterials into biodegradable polymers results in substantial enhancements in their overall performance, particularly in mechanical, barrier, and thermal properties.

Mechanical properties are significantly improved through the reinforcement provided by nanomaterials, which increase tensile strength, elasticity, and impact resistance. For instance, the addition of nanocellulose can enhance the toughness and flexibility of polylactic acid (PLA), a biodegradable polymer that is otherwise prone to brittleness. Such reinforcement allows biodegradable polymers to achieve mechanical performance comparable to, or better than, that of conventional plastics.

Barrier properties are also enhanced when nanoclay particles are uniformly dispersed within the polymer matrix. These nanoparticles reduce the permeability of the material to gases and liquids, making nanostructured biodegradable polymers particularly suitable for food packaging applications where moisture and oxygen resistance are essential for preserving product quality and extending shelf life.

Thermal properties of biodegradable polymers can be improved by incorporating nanomaterials such as carbon nanotubes (CNTs) and nanocellulose, which increase thermal stability and resistance to heat. This enhancement is particularly beneficial for packaging materials that must endure high temperatures during processing, storage, or transportation [37,38].

Overall, the integration of nanostructured materials into biodegradable polymers enables the development of materials that can match or even exceed the performance of conventional synthetic plastics in several key areas, while maintaining biodegradability and environmental sustainability.

4.2. Functionalization for Specific Applications

Functionalization refers to the alteration of either a polymer's surface or molecular structure to provide the polymer with properties that enable it to meet specific applications. The modification of biodegradable polymers offers improved performance by incorporation of new functions including improved water resistance, antimicrobial effect, UV stability and controlled degradation. Researchers can, for example, change the chemical structure or add functional groups to the polymer and fine-tune it to match the requirements of the particular industries such as medicine, packaging, agriculture as well as textiles [39,40].

4.2.1. Surface Modifications

Surface functionalization refers to the modification of a polymer's surface rather than its bulk physical properties. This technique plays an important role in improving the interaction of biodegradable polymers with other materials or biological systems and in providing additional protection against environmental factors such as UV radiation, moisture, and chemicals that may cause degradation. By altering surface characteristics, the performance, durability, and application potential of biodegradable polymers can be greatly enhanced.

Hydrophobic and hydrophilic modifications are among the most common surface treatments, and the choice between them depends on the intended use. For example, hydrophobic (water-repellent) surface modification can improve the water resistance of biodegradable packaging materials, making them more suitable for moisture-sensitive products. Conversely, hydrophilic (water-attractive) surface modification can be applied to improve interactions with biological fluids, which is particularly useful in biomedical applications such as drug delivery systems where controlled absorption and compatibility with tissues are required.

Surface grafting is another key method that enhances the adhesiveness and functionality of biodegradable polymers. This technique involves attaching specific functional groups—such as amino or carboxyl groups—to the polymer surface to increase its reactivity or binding capability. Such surface modifications are valuable in biomedical fields, especially in applications like tissue engineering or medical device fabrication, where polymers must bond effectively with proteins, cells, or other biological components.

UV stability is also an important consideration, as biodegradable polymers are often susceptible to degradation from ultraviolet radiation, leading to reduced mechanical strength and durability. UV resistance can be improved by incorporating stabilizing additives or surface coatings that absorb or block harmful UV rays. Examples include halogenated aromatic compounds such as benzophenones or substituted amines like hindered amine light stabilizers (HALS). This enhancement is particularly crucial for applications such as agricultural films, where materials are exposed to sunlight for prolonged periods [41,42].

4.2.2. Antimicrobial Properties

Biodegradable polymers can be functionalized with antimicrobial agents to enhance their ability to prevent the growth of harmful microorganisms, making them particularly useful in applications where hygiene and pathogen control are critical. Such modifications are especially valuable in areas like food packaging, wound dressings, and medical devices, where maintaining sterile conditions and preventing bacterial or fungal contamination are of utmost importance.

Antibacterial agents such as silver nanoparticles, copper, or zinc oxide can be incorporated into biodegradable polymers to impart strong antimicrobial properties. In medical applications, these functionalized polymers are often used in wound care products, where preventing infection is essential to promote healing. The metal ions released from nanoparticles can disrupt bacterial cell walls and inhibit microbial growth, providing effective and long-lasting antibacterial protection.

Biocidal properties can also be achieved through environmentally friendly approaches by functionalizing biodegradable polymers with natural antimicrobial substances. Examples include essential oils such as thyme, oregano, and eucalyptus, as well as plant-based extracts known for their antibacterial and antifungal capabilities. These natural biocides are gaining increasing attention in food packaging applications, where they help extend the shelf life of perishable products while reducing or eliminating the need for synthetic preservatives.

4.2.3. Controlled Degradation

In case of drug delivery systems and tissue scaffolds, among others, it is crucial to regulate the degradation rate of a polymer. Introduction of the functional groups to the polymer chain by the process of functionalization can be used to regulate the extent of degradation of biodegradable polymers to impact the hydrophilicity of the polymers, chemical stability, or biotic degradation to reach the desired extent.

pH-sensitive functionalization: Degradation rates can be controlled by introducing pH sensitive groups (carboxylic acid or amine groups) in the polymer, where the degradation rate can be adjusted with respect to the pH at the surrounding environment. Such can be used in drug delivery systems, whereby on exposure to acidic or basic conditions in various body parts, the polymer breaks down in a specific rate.

Enzyme-sensitive linkages: The controlled degradation of the polymer on exposure to the enzyme activity of the biological system is also possible through the introduction of enzyme-sensitive linkages, like peptide-peptide/amino acid sequences. This is particularly useful in the biomedical field, such as tissue engineering and wound healing, needing controlled degradation in order to facilitate tissue growth or drug release [43,44].

4.3. Tailored Biodegradable Polymers for Industrial Applications

Nano structuring of functionalized polymers provides tailored biodegradable polymers optimised to a particular industrial need. Such high-tech materials can offer the correct combination of biodegradability, mechanical qualities and functionality necessary to utilize in areas like:

Packaging: Development of advanced biodegradable polymers having improved barrier properties, like nano clay composites is under development to pack food and beverages. The polymers are highly resistant to oxygen and moisture weather coupled with biodegradability and lessen the effects of the plastic waste on the environment.

Biomedical devices: One of the most popular applications of biodegradable polymers in the medical field is sutures, drug delivery systems and wound healing products, which are usually functionalized using antimicrobial agents, UV stabilizers or very sensitive to enzyme degradation attachments. The controlled degradation that these polymers offer establishes that the medical devices, which rely on polymers, can be used as required and are able to degrade in an effective manner in the human body.

Agriculture: Biodegradable films, and coatings, often UV stabilized and antimicrobial treatments are used in agricultural films, including applications in controlled-release fertilizers, and pesticide delivery. Such functionalized polymers contribute to a rise in crop production and minimise the environmental burden of plastic waste in agriculture.

The focus of the next generation of biodegradable materials is nanostructured biodegradable materials and their functionalization. Biodegradable polymers may also be improved to fit the industrial sector needs through application of nanomaterials and surface functionalization techniques. Such materials provide the additional benefits of increased mechanical strength, barrier effect, antimicrobial activity, UV resistance and specific degradability in an otherwise bio-degradable or sustainable material. With the current development of the biodegradable polymers under the fore, such innovations will be the determinant towards the spontaneous promotion of biodegradable materials in various areas such as packaging and agriculture, medicine and textile areas [45].

5. Industrial Applications of Biodegradable Polymers

The use of biodegradable polymers has increasingly emerged as a plausible way of stabilizing the negative effects of the normal plastics to the environment. The applications of these polymers in many industries are numerous in the packaging industry, agriculture, healthcare, textiles, electronics, etc. The increasing requirements of sustainable materials have stimulated innovations in which biodegradable polymers are becoming appropriate to use in the real world and at high-performance levels. Here, in this section, we shall explore the important areas where there have been increased applications of biodegradable polymers taking into consideration the benefits and perils in each arena.

5.1. Packaging Materials

Packaging represents one of the largest contributors to global plastic consumption and waste accumulation. Conventional petroleum-based plastics such as polyethylene (PE), polypropylene (PP), and polystyrene (PS) are not biodegradable and can persist in the environment for decades, contributing to severe pollution and ecological harm. This growing concern has driven the development and adoption of biodegradable alternatives that can naturally decompose, thereby mitigating the plastic waste crisis.

In recent years, traditional plastics used in packaging have been increasingly replaced by biodegradable polymers such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), polybutylene succinate (PBS), and polyethylene furanoate (PEF). These materials offer several notable advantages. Sustainability is one of their key strengths—biodegradable polymers are typically derived from renewable sources like corn, sugarcane, or plant oils, reducing reliance on fossil fuels and lowering the carbon footprint associated with their production. End-of-life disposal is another benefit, as biodegradable packaging materials can break down into harmless substances such as water, carbon dioxide, or methane under suitable environmental conditions, thereby reducing landfill accumulation and environmental pollution. Additionally, functional properties of many biodegradable polymers—such as transparency, flexibility, and resistance to gases like oxygen and moisture—make them ideal for preserving food quality and extending shelf life.

However, despite these advantages, several challenges continue to limit the widespread adoption of biodegradable polymers in packaging. Cost remains a major obstacle, as many biodegradable polymers are still more expensive to manufacture than petroleum-based plastics, making them less accessible for large-scale industrial use. Degradation conditions also pose a challenge since many of these materials require specific environments—such as industrial composting facilities or high humidity—to properly biodegrade, conditions that are not always present in conventional waste management systems. Finally, performance limitations affect their application range; for instance, certain biodegradable polymers like PLA lack sufficient durability, heat resistance, or flexibility for packaging that must endure high temperatures or mechanical stress, such as hot food containers [14,46].

Overall, while biodegradable polymers mark a crucial advancement toward sustainable packaging solutions, continued research and innovation are essential to improve their performance, reduce production costs, and enhance their degradation efficiency across diverse environmental conditions.

5.2. Agricultural Films and Coatings

Biodegradable polymers have found significant applications in agriculture, particularly in the areas of mulching films, controlled-release fertilizers, and pesticide coatings. Their adoption offers major environmental and practical advantages, especially by reducing plastic waste accumulation in soil and enabling the customization of degradation rates to suit specific agricultural requirements.

Mulch films made from biodegradable polymers such as polybutylene succinate (PBS) and polylactic acid (PLA) are used to conserve soil moisture, suppress weed growth, and regulate soil temperature. Unlike traditional plastic mulch films, which require manual removal and can lead to soil contamination, biodegradable mulch films naturally decompose after use, thereby minimizing labor, disposal costs, and environmental waste. Controlled-release fertilizers utilize biodegradable polymer encapsulation to deliver nutrients and pesticides gradually over time. This controlled release mechanism enhances nutrient efficiency, reduces application frequency, and minimizes nutrient loss to the surrounding environment, contributing to more sustainable and efficient farming practices. Similarly, pesticide coatings made from biodegradable polymers allow the active ingredients to be released steadily and effectively over extended periods, improving pest control while reducing chemical runoff and overuse.

However, there are several challenges in applying biodegradable polymers in agriculture. Degradation rate control is one critical issue—if the polymer decomposes too quickly or too slowly, it may not align with the crop growth cycle or desired release timing, thereby reducing its effectiveness. Soil interaction presents another challenge, as the interaction between the polymer and soil can influence moisture retention, aeration, and nutrient balance. Improperly formulated biodegradable polymers might even cause unwanted soil effects if they fail to degrade completely or alter soil structure.

Despite these challenges, the use of biodegradable polymers in agriculture holds considerable promise. They offer a practical means to reduce plastic pollution, enhance resource efficiency, and improve overall sustainability in farming operations. Continued research and development are necessary to optimize their degradation behavior, enhance performance, and ensure compatibility with various soil and crop conditions

The application of biodegradable polymers in agriculture presents several challenges that must be addressed to ensure their effectiveness and environmental safety. One major issue is degradation rate control. The rate at which biodegradable polymers break down must be carefully synchronized with the growth cycles of crops or the intended release of fertilizers and pesticides. If the degradation occurs too rapidly or too slowly, it can diminish the polymer's effectiveness and disrupt agricultural processes. Another important consideration is soil interaction. The contact between biodegradable polymers and soil can have varying effects—some polymers may not dissolve efficiently, potentially causing issues related to moisture retention, soil aeration, or even localized pollution. Therefore, comprehensive testing and optimization are necessary to ensure that these materials do not negatively affect soil health. Despite these challenges, biodegradable polymers in agriculture hold great promise for reducing plastic pollution and improving farming efficiency. Continued research is essential to optimize their degradation rates, enhance performance, and ensure that they function effectively under diverse agricultural and environmental conditions [47].

5.3. Biomedical Applications

In the biomedical field, there is a diverse scope of use written with regards to the field on biodegradable polymers and its safety in degrading in the body. They find use as in drug delivery systems, dressing wounds, sutures, use in scaffold-based tissue, and implants.

Drug delivery: Controlled release drug delivery systems are frequently formulated using biodegradable polymers, including PLA, and poly (lactic-co-glycolic acid) or PLGA, and PHA, which degrade slowly and may allow controlled release of drugs over an extended period of time. This is most essential in chronic disorders, cancer therapies, and post-surgery procedures where enhanced delivery of the drug has shown to enhance patient outcomes and the frequency of dosing.

Wound dressings and sutures: Polymer wound dressings and surgical stitches are best suited to wound care and wound stitches, as they give temporary support and can then biodegrade naturally, and there is no need to remove it. This has less risk of infection and less patient discomfort.

Biodegradable polymer technology is widely used in tissue engineering, particularly in the development of tissue scaffolds and implants. In tissue scaffolds, biodegradable polymers serve as a structural framework that supports the regrowth of new tissue. These scaffolds provide a temporary matrix where cells can adhere, proliferate, and form new tissues while the polymer gradually degrades over time as regeneration progresses. Similarly, biodegradable implants, such as those used in joint or bone repair, are designed to dissolve naturally within the body after serving their purpose. This eliminates the need for secondary surgical procedures to remove implants, thereby reducing patient discomfort and healthcare costs.

Despite these significant advantages, the application of biodegradable polymers in the medical field faces several challenges. One critical concern is biocompatibility—the polymer must not trigger immune responses or cause inflammation, and any degradation by-products must be non-toxic and safely absorbed or excreted by the body. Another important factor is mechanical strength. Medical devices often require specific material properties such as strength, flexibility, and elasticity, which must be balanced with biodegradability to ensure the material performs effectively during the healing or treatment process. Furthermore, control of degradation rate is essential; the polymer must degrade in harmony with tissue regeneration or drug release schedules. If degradation occurs too rapidly or too slowly, it could compromise the treatment's effectiveness.

In spite of these challenges, biodegradable polymers are revolutionizing the biomedical field, offering safer, more effective, and sustainable alternatives to conventional medical materials. Their ability to integrate with biological systems while minimizing long-term complications highlights their transformative potential in modern medicine [48,49].

5.4. Textiles and Fibers

Biodegradable polymers are also making their way into the textile industry, which has been under intense scrutiny for its environmental impact—particularly the fast-fashion sector. This industry has been harshly criticized for its heavy reliance on synthetic, non-biodegradable fabrics such as polyester, which contribute significantly to pollution and landfill waste. The substitution of these materials with sustainable biodegradable fibers presents a promising solution to counteract the environmental burden caused by discarded textiles, offering an eco-friendly alternative that supports waste reduction and resource efficiency.

Biodegradable fabrics made from polymers such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), and starch-based fibers are now being used to produce clothing, draperies, and home textiles. These materials naturally decompose at the end of their lifecycle, thereby reducing waste accumulation in landfills. Similarly, non-woven textiles—used in disposable products such as diapers, sanitary napkins, and wipes—are increasingly being manufactured using biodegradable polymers, typically cellulose-based fibers or PHA. These compostable and biodegradable materials avoid the long-term persistence associated with conventional non-woven synthetic fabrics, which can take centuries to degrade.

Furthermore, biodegradable fibers derived from PLA-based polymers are being developed for eco-friendly clothing. These fibers are breathable, lightweight, and comfortable, exhibiting performance characteristics comparable to conventional synthetic fibers while maintaining biodegradability. Such advancements highlight the growing potential of biodegradable polymers in creating sustainable textile solutions without sacrificing functionality.

However, the adoption of biodegradable polymers in the textile industry is not without challenges. One major issue is durability and performance, as textile fibers must endure repeated wear, washing, and exposure to environmental factors. Achieving the right balance between biodegradability and long-term performance remains a key technical challenge. Standard durability tests—such as thermo-oxidative aging, creep and fatigue analysis, and environmental exposure assessments—are typically conducted to evaluate fiber reliability, as illustrated in **Figure 4**. Another challenge is cost, since the production of biodegradable fibers and fabrics often remains more expensive than conventional synthetic alternatives. To enable widespread adoption, advancements in manufacturing technology and sustainable raw material sourcing are necessary to lower production costs and enhance market competitiveness.

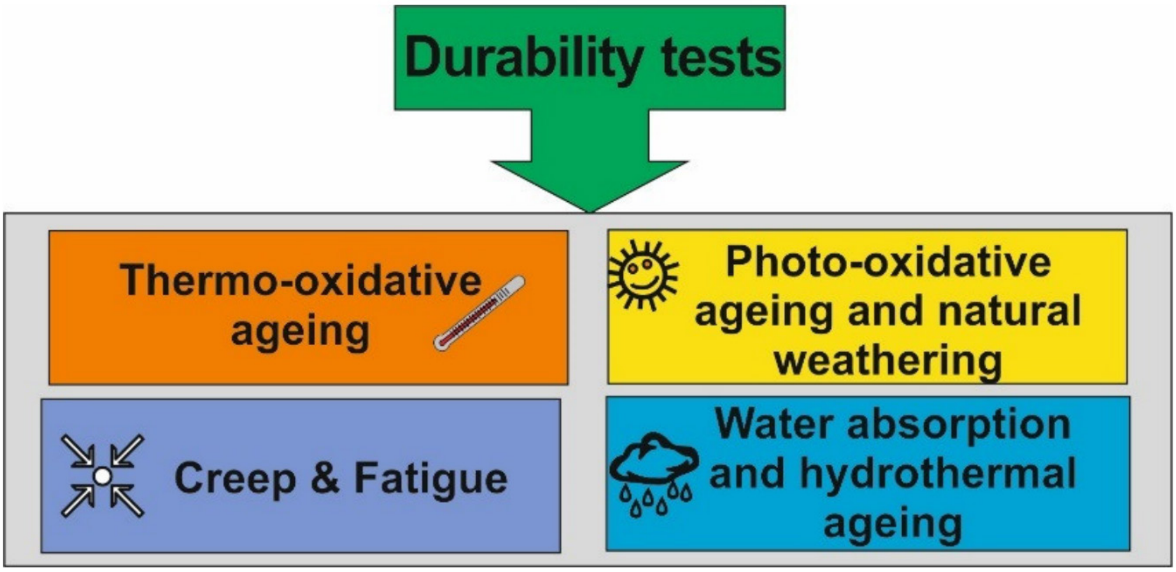

Figure 4. Basic types of durability tests for polymer composite materials [50].

Despite these challenges, the potential for biodegradable polymers to revolutionize the textile industry is vast, offering a solution to the environmental problems associated with textile waste [50].

Biodegradable polymers are also being explored in the production of consumer goods and electronic components, with the aim of reducing the environmental footprint of everyday products and minimizing electronic waste (e-waste). These innovations represent a growing commitment to sustainable material development that aligns with circular economy principles.

In the realm of consumer goods, biodegradable polymers are increasingly used to manufacture eco-friendly items such as toys, cosmetics packaging, cutlery, and dental products. By replacing conventional plastics with biodegradable alternatives, manufacturers can offer consumers products that maintain functionality and quality while significantly reducing long-term waste accumulation. This shift empowers consumers to make more sustainable choices in their daily lives, contributing to broader environmental preservation efforts.

In electronics, researchers are testing biodegradable polymers for use in developing biodegradable electronic devices, such as disposable sensors and wearable technologies. The objective is to create components that can safely decompose after use rather than persisting as e-waste. Such materials could revolutionize the electronics industry by enabling the production of short-lived or single-use devices that naturally break down at the end of their lifecycle, thus mitigating one of the fastest-growing sources of global pollution.

Despite the promising applications of biodegradable polymers in consumer goods and electronics, several challenges hinder their widespread adoption. One of the primary issues is electrical performance. Electronic components require materials that can withstand high electrical conductivity, thermal stability, and mechanical strength — properties that most biodegradable polymers currently lack. Therefore, significant research is being directed toward improving the electrical conductivity, heat resistance, and long-term stability of biodegradable polymers to make them suitable for electronic applications. Beyond electronics, biodegradable polymers have proven valuable across multiple industries, including packaging, healthcare, and textiles, due to their environmentally friendly nature and versatility.

Their ability to minimize pollution, reliance on renewable resources, and multifunctional properties make them a cornerstone of sustainable innovation. However, persistent challenges remain — particularly related to cost, performance limitations, and specific degradation conditions required for effective breakdown. Addressing these issues through continued advancements in material design, processing technology, and large-scale production will be essential. As technology progresses and manufacturing processes are optimized, biodegradable polymers are expected to become an indispensable material in creating a more sustainable and eco-friendly future. [51].

6. Challenges and Future Directions

While the development and application of next-generation biodegradable polymers show immense potential for reducing environmental impact and improving sustainability across various industries, several challenges remain. Overcoming these challenges is crucial to ensuring the widespread adoption and successful implementation of these materials in real-world applications. This section explores the key challenges currently faced in the field of biodegradable polymers, followed by a discussion of the future directions and innovations that could shape the industry.

6.1. Cost-Effectiveness and Scalability

Cost is one of the greatest issues that limit the potential commercialization of biodegradable polymers. Creation of bio monomers and polymers usually entail complicated long procedures and the expensive raw materials as compared to other petroleum affected materials. Renewable feedstocks, e.g. corn or sugarcane can be used to make polylactic acid (PLA), polyhydroxyalkanoates (PHA) which may use costly feedstocks relative to traditional petrochemical-based monomers.

A major contributor to these costs lies in raw material prices. The availability and price of renewable agricultural sources fluctuate based on factors like climate, crop yield, and market demand, leading to potential cost instability. Moreover, the cultivation of these materials may compete with food production, further increasing costs due to intensive agricultural processes. Another critical issue is the production scale of biodegradable polymers. At present, bio-based polymer manufacturing operates on a much smaller scale compared to petroleum-based plastics. Scaling up production to meet global demand requires substantial investments in infrastructure, technology development, and supply chain optimization, all of which add to overall production costs.

In terms of economic competitiveness, conventional petroleum plastics still dominate due to their well-established production systems, mature supply chains, and economies of scale that drive down manufacturing expenses. To make biodegradable polymers more economically viable, the industry must focus on improving production efficiency, reducing raw material costs, and developing environmentally friendly, high-efficiency polymerization and compounding techniques. Ultimately, innovations in production technologies, sustainable sourcing of raw materials, and cost-reduction strategies will be essential for making biodegradable polymers a competitive and sustainable alternative to traditional plastics.

The industry requires production technology, raw source and industrial scale production cost-cutting innovations on the biodegradable polymers market. This will play a critical role in ensuring that these materials are more competitive to traditional plastics and sustainability of the materials [20].

6.2. Performance Limitations

Although biodegradable polymers present a number of benefits, they tend to lack in some of these aspects of performance relative to the conventional synthetic plastics. Biodegradable polymers must meet challenges presented within the mechanical, thermal, and life demands of their petroleum-based counterparts to be potentially useful in high-performance applications.

One of the primary limitations lies in mechanical properties. Many biodegradable polymers, such as polylactic acid (PLA), are inherently brittle and lack the flexibility or impact resistance required for demanding applications in packaging, consumer goods, and construction. For instance, PLA tends to crack or fracture under stress, which restricts its use in products that require long-lasting durability and mechanical resilience.

Another significant issue is thermal stability. Biodegradable polymers generally exhibit lower resistance to heat than petroleum-based plastics. PLA, for example, has a relatively low melting temperature, rendering it unsuitable for high-temperature applications like hot food containers or packaging materials that undergo heat sterilization. This thermal limitation poses a major obstacle to replacing traditional plastics in industries that rely on heat-tolerant materials.

Moisture sensitivity also presents a challenge. Many biodegradable polymers are hygroscopic, meaning they readily absorb moisture from the environment. This can weaken their mechanical properties, diminish barrier performance, and compromise overall integrity—particularly in humid conditions. In packaging applications, exposure to moisture can accelerate polymer degradation and reduce product shelf life, undermining reliability.

Finally, degradation control remains a critical concern. While biodegradability is a desirable feature, managing the rate of degradation is complex. In applications such as medical implants or controlled drug delivery systems, the polymer must maintain structural integrity for a precise period before safely breaking down. If the degradation rate is too fast, it may impair product performance; if too slow, it negates the environmental benefits. Thus, achieving an optimal balance between functionality and biodegradability is essential for advancing the practical use of these materials.

Addressing these performance limitations is a priority for the field. By modifying polymer structures, improving polymerization methods, and developing composite materials (such as incorporating nanomaterials), researchers are working to enhance the mechanical strength, thermal stability, and water resistance of biodegradable polymers to match the performance of traditional plastics [14,52]. A concise summary of the key properties, their associated limitations, and potential solutions is provided in **Table 2**.

Table 2. Key properties of biodegradable polymers, their performance limitations,and potential solutions.

Property	Limitation	Potential Solutions
Mechanical Properties	Many biodegradable polymers (e.g., PLA) are brittle and have low impact resistance; prone to cracking under stress.	- Copolymerization with more flexible monomers- Blending with elastomers or plasticizers- Reinforcement with natural or synthetic fibers/nanomaterials
Thermal Stability	Lower melting temperature and thermal degradation resistance compared to petroleum-based plastics; unsuitable for high-temperature applications.	- Incorporation of heat-resistant fillers (e.g., silica, clay, graphene)- Crosslinking to improve thermal stability- Development of high-Tg biodegradable copolymers
Moisture Sensitivity	High water absorption in humid environments leads to loss of mechanical strength and barrier performance.	- Surface coating with hydrophobic layers- Blending with water-resistant biopolymers- Incorporation of moisture-barrier nanoparticles
Degradation Control	Difficult to precisely control degradation rate; may degrade too quickly or too slowly for intended application.	- Tailoring polymer crystallinity and hydrophobicity- Using controlled-release additives or surface modifications- Designing copolymers with adjustable degradation profiles

6.3. Environmental Impact and Waste Management

While biodegradable polymers offer a promising solution to plastic waste, their environmental impact and waste management still require careful consideration. Several issues remain that need to be addressed to ensure these polymers fulfill their potential for sustainability.

End-of-life degradation conditions are one of the major concerns. Biodegradable polymers require specific environmental parameters—such as controlled temperature, humidity, and microbial activity—to decompose effectively. Many of these materials break down efficiently only under industrial composting conditions, which are not always available in typical waste disposal systems. When disposed of in landfills, oceans, or natural environments lacking these optimal conditions, biodegradable polymers may persist for years, undermining their eco-friendly intent. In some cases, their breakdown in anaerobic landfill conditions can even lead to methane emissions, further contributing to greenhouse gas accumulation.

Another issue is incomplete degradation. Some biodegradable polymers do not fully decompose and instead fragment into microplastics or leave behind partially degraded residues. These remnants pose significant risks to ecosystems, as they can be ingested by marine life or contaminate soil and water systems. Therefore, it is crucial to design and test biodegradable polymers to ensure that they degrade completely into non-toxic, environmentally safe by-products.

Recycling compatibility also poses a major challenge. Biodegradable plastics generally cannot be processed alongside conventional plastics within existing recycling systems. Mixing the two can compromise the quality of recycled materials and hinder overall recycling efficiency. Establishing dedicated recycling streams for biodegradable polymers could mitigate this issue, but it would require substantial investment, infrastructure development, and collaboration among industries, policymakers, and waste management systems.

Lastly, the use of additives in biodegradable polymers can further complicate environmental outcomes. Additives—such as plasticizers, colorants, and fillers—are often incorporated to improve flexibility, appearance, or processability. However, these substances can interfere with the degradation process or produce harmful by-products during decomposition. To ensure the long-term environmental safety of biodegradable polymers, it is essential to carefully regulate and evaluate the impact of these additives, promoting formulations that support complete and non-toxic degradation [53,54].

To enhance biodegradability of the polymers, future research on the effects of biodegradable polymers on the environment, how to dispose them, and how to manage them in the waste stream should be carried out. Maintaining the capacity of biodegradable materials to decompose without causing any harm in humans or in the case of natural environments will prove critical in their sustainability.

6.4. Regulatory and Market Acceptance

To be successfully implemented, the biodegradable polymers have to match up with regulatory guidelines and market acceptance on the basis of performance and environmental benefits. The regulations set by the government and the demand by the consumer are both instrumental in the extensive application of biodegradable polymers.

Presently, there is no consistency in the regulation of biodegradable materials in regions and industries. In other instances, it could become unclear regarding what is deemed as biodegradable or compostable and this creates a dilemma amongst the manufacturers and the consumer. International acceptance of what constitutes biodegradable and compostable is also required as a means of ensuring performance and environmental expectations of biodegradable polymers are met.

To enable consumers to have informed options, there should be a proper certification of biodegradable products and their labelling. These certification programs include the Biodegradable Products Institute (BPI) or the European Union, EN 13432 whereby they prove certain criteria of biodegradability and compostable businesses. But these certification initiatives will need to be expanded and greater market awareness created to push consumer confidence and demand in biodegradable polymers.

Even with improved performance and regulatory clarity, consumer behavior plays a significant role in the acceptance of biodegradable polymers. Price sensitivity, convenience, and lack of awareness about the benefits of biodegradable materials may slow down the transition away from conventional plastics. Public education campaigns and corporate responsibility initiatives could help change consumer perceptions and encourage the adoption of biodegradable alternatives [14,55–57].

6.5. Future Innovations

The future of biodegradable polymers lies in overcoming the challenges mentioned above through continued research, innovation, and the development of new technologies. Innovations in polymerization methods, such as living/controlled polymerization and green chemistry approaches, will allow for more efficient, scalable, and sustainable production of biodegradable polymers. These methods could enable better control over polymer structure, leading to improved performance and reduced costs.

The development of functional biodegradable polymers, such as those with antimicrobial, antioxidant, or self-healing properties, could open up new applications in healthcare, packaging, and electronics. By integrating these functionalities into biodegradable polymers, researchers can design more specialized materials for specific industrial applications. Biodegradable polymers could also become a key component of a circular economy model, where materials are designed to be recycled, reused, and biodegraded in a closed-loop system.

Research into biodegradable recycling technologies and the development of composite biodegradable polymers could enable more efficient recycling and less waste generation. Smart materials, considered biodegradable polymers responding to external stimuli such as temperature, pH, or moisture, may give rise to highly adaptive and efficient materials, potentially to be used in diverse applications in the medical field, including biomedical devices, packaging, and crop management [4,13,58–60].

With these novel solutions in mind, the future of the biodegradable polymers industry is ready to grow out of its shortcomings and play a serious role in the exit of plastic pollution and environmental regression. To summarise, a future generation of biodegradable polymers contains a lot of promise but presents difficulties in terms of cost, performance, environmental and market. These obstacles will only be able to be overcome through further research, innovation and partnership at the industry, government and academic levels. Biodegradable polymers have the potential to become an affordable and safe, yet high-performance alternative to classical plastics, which is why such materials signal the future of a more sustainable future as the field continues to advance.

7. Conclusions

The innovation of the next-generation biodegradable polymers is a major quest towards environmental restoration of plastic wastes. Since the issue of non-biodegradable plastics continues to accumulate in land-fill sections, oceans, and other biological systems, biodegradable plastics would serve as an alternative since it is both environmentally friendly and functional. Being made of renewable bio-based feedstocks, these polymers can be naturally decomposed, without leaving a harmful residue, which allows them to be an important part of sustainable materials in the numerous industrial applications.

Although biodegradable polymer field has achieved exceptional progress in the enhancement of mechanical, thermal and processing properties, limitations in cost, performance and large-scale applicability still persist. The factors that present challenges to widespread biodegradable polymers use include high cost of production, shortcomings when used in aggressive applications and the effective end-of-life management. Nevertheless, advances in material design, polymer synthesis, and methods of functionalization keep the efficiency, performance and cost-effectiveness of such materials continually on the rise.

The uses of biodegradable polymers in the industry are numerous and include package related products, agriculture, healthcare, textile and even electronics. Through its ability to curb plastic waste in packaging and allowing it to create medical devices that can safely break down in the human body, biodegradable polymers can transform a variety of industries. Nonetheless, they can be technically implemented successfully only in the case when their execution addresses not only technical issues of performance but also issues of potential environmental hazard regarding poor performance conditions and waste disposal.

When taking a look towards the future, where the future of biodegradable polymers is going, one can only imagine solving these complications by further research and development. New approaches to polymerization, functionalization of used materials, and implementation of the circular economy can be the key to legitimizing biodegradable polymers as the answer to plastic pollution. Biodegradable polymers have the ability to play significant role in making the world a better place by shifting towards a more ecologically friendly environment by streamlining the degradation, the enhancement of its performance, and the development of more efficient production strategies.

To sum up, new generation biodegradable polymers have excellent potential to replace traditional plastics as a sustainable source. As investment in research, development and infrastructure continues, there is good reason to believe that these materials can play a critical role in arresting plastic waste and achieving sustainability in the various industrial sectors and, eventually in making the world a cleaner and greener place in the future generations.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Conflicts of Interest

The author declares that there is no conflict of interest.

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