

## IMPORTANCE OF BIODEGRADABLE POLYMERS IN MODERN PHARMACEUTICAL DRUG DELIVERY TECHNOLOGIES

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#### Abstract

In modern drug delivery systems, biodegradable polymers have gained significant importance due to their ability to safely decompose into non-toxic byproducts after fulfilling their therapeutic purpose. These polymers facilitate controlled and sustained drug delivery, improve bioavailability, and enable targeted delivery, thereby enhancing therapeutic effects while minimizing side effects. Commonly utilized biodegradable polymers include natural varieties such as chitosan, alginate, and gelatin, as well as synthetic options like polylactic acid (PLA), polyglycolic acid (PGA), and their copolymers. The composition, molecular weight, and crystallinity of these polymers can be adjusted to achieve precise control over drug release kinetics, as they can be engineered to influence degradation behavior. Biodegradable polymer-based carriers are widely employed in various drug delivery systems, including microspheres, nanoparticles, hydrogels, implants, and gastroprotective systems. They are particularly beneficial in managing chronic diseases, especially in cancer treatment, as they reduce dosing frequency and enhance patient compliance. Furthermore, biodegradable polymers eliminate the need for surgical removal of delivery devices, offering significant clinical advantages. Despite their promising applications, challenges related to stability, scalability, and reproducibility remain. Overall, biodegradable polymers represent a versatile and effective approach to designing drug delivery systems and continue to play a crucial role in pharmaceutical research and development.

**Keywords:** Biodegradable polymers, Drug delivery systems, Control led release, targeted delivery, regenerative medicine.

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#### INTRODUCTION

Drug delivery systems (DDS), which aim to maximise therapeutic effectiveness while minimising side effects, are critical for efficient therapeutic administration. Traditional drug administration techniques frequently have limitations such as systemic toxicity, rapid elimination, and low bioavailability. Due to their ability to release drugs in controlled, sustained, and targeted manner, biodegradable polymers is an essential component of advanced drug delivery systems [1].

Biodegradable polymers are materials that can be degraded by various environmental microorganisms, such as bacteria and fungi, into simpler compounds such as water and carbon dioxide [2]. Biodegradable polymers are being developed as an alternative to non-biodegradable polymeric materials for a variety of applications [3]. Biodegradation of biodegradable polymers is defined as the chemical decomposition of substances accomplished through the enzymatic action of microorganisms, resulting in changes in chemical composition, mechanical and structural properties, and the formation of environmentally friendly metabolic

products such as methane, water, biomass, and carbon dioxide [4].

The most effective way to manage non-biodegradable plastic waste is to replace uneconomical and non-biodegradable materials used for recycling or reuse with environmentally friendly biodegradable polymers [5]. Due to the environmental pollution caused by the use of non-biodegradable materials, research and development on biodegradable materials have increased significantly [6]. Biodegradable polymers are materials that can function for a limited period before degrading into easily disposable products through a controlled process [7]. They can be produced from a variety of wastes or bioresources, including food, animal, and agro-waste, as well as other sources such as starch and cellulose [4]. Biodegradable plastics and polymers were first developed in the 1980s [8]. Polyesters were the first successful biodegradable polymers developed for suture materials [9].

Bioplastics derived from renewable resources are often less expensive than those obtained from microbial sources, leading manufacturers to focus on producing bioplastics from renewable materials. The use of

biodegradable polymers offers environmental advantages such as renewable raw material utilisation, biodegradation, and reduced carbon dioxide emissions, thereby helping to minimise global warming [10]. The biodegradation process is influenced by the polymer's molecular weight, shape, structure, and chemical and radiation treatments [11].

## 1. TYPES OF BIODEGRADABLE POLYMERS [12]

Biodegradable polymers can be broadly classified into natural polymers and synthetic polymers.

Natural Biodegradable Polymers

### 1. Polysaccharides

Examples include **chitosan, alginate, and dextran**. These polymers are biocompatible and exhibit excellent biodegradability.

### 2. Proteins

Examples include **collagen, gelatin, and silk fibroin**. Protein-based polymers provide a natural matrix for cell attachment and growth.

#### 1.1 Natural Polymers

##### Protein-Based Polymers

- Collagen
- Albumin
- Gelatin [13]

##### Polysaccharides

- Starch
- Agarose
- Alginate
- Carrageenan
- Hyaluronic acid
- Dextran
- Chitosan
- Cyclodextrins [14]

#### 1.2 Synthetic Polymers

##### Polyesters

- Poly(lactic acid) (PLA)
- Poly(glycolic acid) (PGA)
- Poly(hydroxybutyrate) (PHB)
- Poly( $\epsilon$ -caprolactone) (PCL)
- Poly( $\beta$ -malic acid)
- Polysiloxanes [15]

##### Polyanhydrides

- Poly(sebacic acid)
- Poly(adipic acid)
- Poly(terephthalic acid) and various copolymers [16]

##### Polyamides

- Poly(amino carbonates)
- Polyamino acids

##### Polyphosphoesters

- Polyphosphates
- Polyphosphonates
- Polyphosphazenes

##### Others

- Poly(cyanoacrylates)
- Polyurethanes
- Polyorthoesters
- Polydihydropyrans

- Polyacetals

## Non-Biodegradable Polymers

### Cellulose Derivatives

- Carboxymethyl cellulose
- Ethyl cellulose
- Cellulose acetate
- Cellulose acetate propionate
- Hydroxypropyl methylcellulose (HPMC) [17]

### Silicones

- Polydimethylsiloxane
- Colloidal silica

### Acrylic Polymers

- Polymethacrylates
- Poly(methyl methacrylate) (PMMA)
- Poly(hydroxyethyl methacrylate)

### Others

- Polyvinylpyrrolidone (PVP)
- Ethylene vinyl acetate
- Polyamines [18]

## NATURAL POLYMERS

### Protein-Based Polymers

#### 1. Collagen

Collagen is the most abundant protein in mammals. The collagen family consists of 28 members, each containing at least one triple-helical domain [19]. Three distinguishing characteristics define the family of glycoproteins collectively referred to as collagen. The first is the amino acid repeating sequence (**Gly-X-Y**)<sub>n</sub>, with and without interruptions. The second characteristic is the presence of proline and its hydroxylated counterpart, hydroxyproline, which predominantly occupy the X and Y positions, respectively. The third distinguishing feature is collagen's unique quaternary structure, formed by the assembly of three left-handed polyproline  $\alpha$ -chains of the same length into a right-handed triple helix. The structure of various collagen types, their splice variants, the presence of additional non-helical domains, their assembly, and functions are highly complex and diverse. Although peptides were initially heterogeneous polymers, the development of solid-phase peptide synthesis enabled the synthesis of peptides with defined lengths and sequences to mimic biological activity and elucidate the principles governing triple-helix stability [20].

#### 2. Albumin

Albumin is the most abundant plasma protein, accounting for approximately **35–50 g/L of human serum**. Albumin is considered safe due to its low immunogenicity, biocompatibility, and biodegradability. Most importantly, it acts as a transporter for various endogenous and exogenous substances in the plasma [21].

#### 3. Gelatin

Gelatin, derived from fish skin or bones, is well known for its **biocompatibility, biodegradability, good solubility, non-immunogenicity, low cost, and**

**biological origin.** One of its most important characteristics is the abundance of **arginine-glycine-aspartic acid (RGD) groups**, which promote cell adhesion, migration, and differentiation [22].

## 2. SYNTHETIC POLYMERS

### Polyesters

#### 1. Poly(lactic acid) (PLA)

Poly(lactic acid) (PLA) polymer interference screws are commonly used in **anterior cruciate ligament (ACL) reconstruction**, particularly for proximal tibial fixation [23].

#### 2. Poly(glycolic acid) (PGA)

Poly(glycolic acid) (PGA) is a biodegradable polymer widely used in biomedical applications due to its excellent biodegradability and mechanical strength.

#### 3. Poly(lactic-co-glycolic acid) (PLGA)

Poly(lactic-co-glycolic acid) (PLGA) is one of the most extensively studied biodegradable polymers in various biomedical applications, including **drug delivery systems and tissue engineering** [24].

## 3. BENEFITS OF BIODEGRADABLE POLYMERS IN DRUG DELIVERY [25,26]

Biodegradable polymers provide numerous advantages in drug delivery systems, particularly for **controlled release and targeted therapies**. The major benefits are discussed below.

### 1. Controlled Drug Release

Biodegradable drug delivery systems can be designed to release drugs over time at a regulated rate. This controlled release mechanism helps maintain therapeutic drug concentrations in the body, minimises fluctuations in drug levels, and reduces the need for frequent dosing. Biodegradable polymers can be engineered to degrade at predetermined rates, allowing precise control over the timing and rate of drug release [27].

#### Mechanism

- Biodegradable polymers degrade gradually, enabling sustained drug release over an extended period.
- Controlled degradation helps maintain therapeutic drug concentrations in the bloodstream or at the target site.

#### Benefits

- **Improved Patient Compliance:** Reduced frequency of drug administration, as the drug is released over an extended period.
- **Reduced Side Effects:** Stable drug concentrations minimise fluctuations and adverse effects.

### 2. Targeted Drug Delivery [28]

One of the major advantages of biodegradable drug delivery systems is their ability to target specific tissues or cells. Biodegradable nanoparticles and liposomes can be modified on their surfaces (e.g., coated with ligands

or antibodies) to target specific cells, such as immune or cancer cells. This enhances therapeutic outcomes while reducing off-target effects.

#### Mechanism

- Biodegradable polymers can be designed to respond to specific stimuli (e.g., **pH, temperature, or enzymes**) present at the target tissue or disease site.

#### Benefits

- **Increased Drug Concentration at the Target Site:** Higher local drug concentrations can be achieved, improving therapeutic efficacy.
- **Reduced Systemic Toxicity:** Drug action is focused on the diseased tissue, minimising harmful effects on healthy tissues.

### 3. Biocompatibility and Safety [29]

When biodegradable materials are properly designed, they degrade into simple, non-toxic metabolites such as **carbon dioxide and water**, which can be safely eliminated from the body.

#### Mechanism

- Biodegradable polymers break down into non-toxic by-products that can be eliminated through the body's normal metabolic pathways.

#### Benefits

- **Reduced Toxicity:** Degradation products are generally biocompatible, reducing the risk of adverse reactions.
- **Enhanced Safety:** No need for surgical removal, as the polymer naturally degrades after drug release.

## 4. SYNTHESIS AND PROPERTIES [30]

### Synthesis Methods

The synthesis of biodegradable polymers involves various polymerisation techniques, each providing control over the molecular weight, composition, and properties of the resulting polymers.

#### 1. Ring-Opening Polymerisation (ROP)

Ring-opening polymerisation is a widely used method for synthesising polyesters such as **poly(lactic acid) (PLA)**, **poly(glycolic acid) (PGA)**, and **poly(lactic-co-glycolic acid) (PLGA)**. This method offers precise control over molecular weight and polymer architecture.

#### 2. Condensation Polymerisation

Condensation polymerisation is used for synthesising **polyamides and polyurethanes**. This process involves the reaction of monomers containing functional groups, resulting in the formation of polymer chains.

#### 3. Microbial Synthesis

Microbial synthesis involves the production of **polyhydroxyalkanoates (PHAs)** through microbial fermentation processes. This environmentally friendly method produces polymers with high purity, biodegradability, and biocompatibility.

### Properties of Biodegradable Polymers

Biodegradable polymers possess several desirable properties that make them suitable for drug delivery applications. These include:

- **Biocompatibility:** They are generally non-toxic and compatible with biological systems.
- **Biodegradability:** They degrade into harmless by-products that can be metabolised or eliminated by the body.
- **Controlled Drug Release:** They allow sustained and controlled release of therapeutic agents.
- **Mechanical Strength:** Certain biodegradable polymers provide adequate structural support for biomedical applications.
- **Versatility:** They can be formulated into nanoparticles, microspheres, hydrogels, implants, films, and scaffolds.

### TRANSDERMAL DRUG DELIVERY SYSTEMS [31]

#### Mechanism

Polymers are used in transdermal patches or gels to deliver drugs through the skin for systemic therapeutic effects [31]. Transdermal drug delivery (TDD) is a painless method of administering medications systemically by applying a drug formulation to intact and healthy skin [32].

#### Benefits and Applications

- **Hormone Replacement Therapy:** Transdermal patches provide sustained and controlled hormone release.
- **Pain Management:** Analgesic patches are widely used for chronic pain treatment.
- **Improved Patient Compliance:** Non-invasive administration enhances patient convenience and adherence to therapy.
- **Avoidance of First-Pass Metabolism:** Drugs bypass hepatic metabolism, improving bioavailability.

### FUTURE PROSPECTS [33].

Based on the current market size, growth, demand, and emerging trends, the production and consumption of biopolymers are expected to increase significantly in the coming years.

Future developments in biodegradable polymer-based drug delivery systems include:

1. **Simplification of Regulatory Procedures:** Streamlining regulatory approval processes will facilitate the commercialisation of biodegradable polymer-based drug delivery devices. Collaboration among industry, academia, and regulatory agencies can help establish standardised guidelines and accelerate market access.
2. **Improvement in Drug Encapsulation and Release Kinetics:** Advances in formulation science and drug-polymer interactions are expected to improve drug loading capacity and

enable better control of release kinetics, leading to improved therapeutic outcomes.

3. **Development of Novel Biodegradable Materials:** The discovery and synthesis of new biodegradable polymers with improved biocompatibility, biodegradability, and functional properties will broaden biomedical applications.
4. **Nanotechnology Integration:** Incorporating nanotechnology into biodegradable drug delivery systems may improve targeted drug delivery and therapeutic precision.

### APPLICATIONS OF BIODEGRADABLE POLYMERS IN DRUG DELIVERY SYSTEMS [34]

Biodegradable polymers have revolutionised drug delivery systems by offering innovative and effective therapeutic approaches across multiple medical fields.

#### Applications

- **Cancer Therapy:** Targeted delivery of chemotherapeutic agents to tumour tissues reduces systemic toxicity and improves therapeutic efficacy.
- **Vaccines:** Controlled antigen release enhances immune response and reduces the requirement for multiple doses.

#### 1. Gene Delivery Systems [35]

##### Mechanism

Biodegradable polymers protect and deliver genetic material (**DNA and RNA**) to target cells, thereby facilitating gene therapy.

##### Applications

- **Cancer Gene Therapy:** Delivery of genes that induce apoptosis in cancer cells or stimulate immune responses.
- **Genetic Disorders:** Delivery of functional genes to correct inherited genetic abnormalities.
- **Vaccination:** Delivery of DNA vaccines capable of inducing strong immune responses.

#### 2. Stimuli-Responsive Delivery Systems [36]

##### Mechanism

These polymers respond to specific stimuli, such as **pH, temperature, or enzymes**, to release drugs at targeted sites.

##### Applications

- **Targeted Cancer Therapy:** Polymers degrade in the acidic tumour microenvironment, releasing chemotherapeutic drugs.
- **Diabetes Management:** Glucose-sensitive systems are developed for insulin delivery.
- **Inflammatory Diseases:** pH-responsive polymers release anti-inflammatory drugs in response to local inflammation.

#### 3. Transdermal Drug Delivery Systems

##### Mechanism

Polymers in patches or gels facilitate drug delivery through the skin for systemic therapeutic effects.

### Applications

- **Hormone Replacement Therapy:** Provides sustained hormone release.
- **Pain Management:** Delivers analgesics for chronic pain relief.
- **Nicotine Replacement Therapy:** Helps support smoking cessation.

### FUTURE TRENDS [37]

Future advancements in biodegradable polymers are expected to focus on the development of copolymers with hydrophilic and hydrophobic interactions, enabling better control of drug release and enhanced therapeutic efficacy. Complexation networks responding through hydrogen bonding or ionic interactions are also being explored to improve the stability and responsiveness of drug delivery systems. Furthermore, biodegradable polymers are increasingly being developed as nanoparticles for the immobilisation and delivery of enzymes, drugs, peptides, and other biological agents. The discovery of new biodegradable polymers and the development of novel blends of hydrocolloids and carbohydrate-based polymers are expected to expand the scope of biomedical and pharmaceutical applications.

Advances in nanotechnology, smart polymers, and biomaterials are anticipated to improve target specificity, drug encapsulation efficiency, controlled release mechanisms, and patient compliance, making biodegradable polymers an integral part of future drug delivery technologies.

### CONCLUSION

Biodegradable polymers have transformed the field of drug delivery by offering a promising solution to the limitations associated with traditional drug administration techniques. Their ability to degrade at controlled rates and release therapeutic agents in a sustained and targeted manner has significantly improved drug bioavailability while reducing adverse effects. The unique properties of biodegradable polymers, including biocompatibility, biodegradability, controlled drug release, and safety, make them highly suitable for a wide range of pharmaceutical and biomedical applications. These polymers have demonstrated remarkable potential in targeted drug delivery, transdermal systems, cancer therapy, vaccine delivery, gene therapy, and stimuli-responsive drug delivery systems. As research and technological advancements continue, the development of novel biodegradable polymers, polymer blends, nanoparticles, and smart delivery systems is expected to further improve therapeutic efficacy and patient safety. In addition, collaboration among industry, academia, and regulatory agencies will play a vital role in accelerating the development and commercialisation of biodegradable polymer-based drug delivery systems. Overall, biodegradable polymers are expected to play a significant role in shaping the future of drug delivery

and regenerative medicine, ultimately improving patient outcomes and quality of life.

### AUTHOR CONTRIBUTIONS

All authors are contributed equally.

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The authors have no conflicts of interest to declare.

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