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Advancements in Biodegradable Polymers for Controlled Drug Release: A Sustainable Approach

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ABSTRACT

The development of biodegradable polymers for controlled drug release has marked a significant shift toward sustainable and patient-friendly drug delivery systems. These materials degrade naturally in the body, minimizing long-term toxicity and eliminating the need for surgical removal. This review explores recent advancements in biodegradable polymers used in controlled drug release, focusing on natural and synthetic polymers, mechanisms of degradation, design strategies, and their applications in chronic and targeted therapies. We examine key findings from recent literature and discuss research methodologies that support sustainable and efficient drug delivery. Finally, we identify challenges and future perspectives in the field.

1. Introduction

Controlled drug delivery systems (CDDS) aim to improve therapeutic efficacy by regulating the rate, duration, and location of drug release. Biodegradable polymers offer an eco-friendly, biocompatible platform for these systems, allowing drugs to be released at a predetermined rate and location, followed by safe degradation into non-toxic byproducts. As the demand for personalized and long-term therapies grows, so does the importance of sustainable materials that align with regulatory and environmental standards.

2. Literature Review

2.1 Types of Biodegradable Polymers

Natural Polymers: Derived from biological sources, these include chitosan, alginate, gelatin, and starch. They offer high biocompatibility and are especially suited for mucosal and injectable delivery systems (Dash et al., 2011).

Synthetic Polymers: Common examples include polylactic acid (PLA), polyglycolic acid (PGA), poly (lactic-co-glycolic acid) (PLGA), and polycaprolactone (PCL). These allow precise control over degradation rates and mechanical properties (Makadia & Siegel, 2011).

2.2 Mechanisms of Degradation and Drug Release

Degradation of biodegradable polymers occurs primarily through hydrolysis or enzymatic action. This process facilitates a gradual release of the encapsulated drug. The release profile can be tailored by modifying polymer composition, molecular weight, and crystallinity (Langer, 1998).

Surface Erosion vs. Bulk Erosion: Polymers like polyanhydrides exhibit surface erosion, offering a linear release profile, whereas PLGA degrades via bulk erosion, leading to a biphasic release (Zolnik & Burgess, 2008).

2.3 Formulations and Applications

Biodegradable polymers are formulated into microspheres, nanoparticles, hydrogels, and implants. PLGA-based microspheres have been widely used for vaccines and cancer therapies (Danhier et al., 2012). Chitosan-based hydrogels are favored for localized delivery due to their mucoadhesive properties (Jayakumar et al., 2010).

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2.4 Sustainability and Regulatory Perspective

Biodegradable polymers contribute to sustainability by reducing medical waste and environmental load. Regulatory bodies like the FDA have approved several polymer-based drug delivery systems, such as Lupron Depot® and Zoladex®, indicating clinical viability (Anderson & Shive, 1997).

3. Research Methodology

This review utilized a structured search of peer-reviewed articles from 2010 to 2024 using databases such as PubMed, ScienceDirect, and Google Scholar. Keywords included: "biodegradable polymers," "controlled drug release," "PLGA," "sustainable drug delivery," and "polymeric degradation."
Selection criteria:

- Articles discussing material synthesis, degradation behavior, and drug release performance.
- Experimental and clinical studies with relevant outcomes.
- Exclusion of non-biodegradable or purely theoretical work.

Approximately 75 articles were initially identified, and 30 were shortlisted for detailed analysis. Data were categorized based on polymer type, degradation mechanism, and application area.

4. Discussion

Biodegradable polymers offer unmatched flexibility in designing controlled drug delivery systems. Among them, PLGA remains the most extensively researched due to its tunable degradation profile and regulatory approval. However, emerging materials such as poly(β-amino esters) and hybrid composites with inorganic particles are showing promise in enhancing release kinetics and targeting efficiency (Fu et al., 2000).

A significant focus is now on **composite materials** that combine the mechanical strength of synthetic polymers with the bioactivity of natural polymers. Moreover, **stimuli-responsive biodegradable systems** that degrade in response to pH, temperature, or enzymes are gaining attention for targeted therapy applications.

Challenges include batch variability in natural polymers, scalability, and ensuring consistent drug loading and release. Advances in microfabrication and 3D printing are expected to solve some of these problems by offering precise control over polymer architecture.

From a **sustainability** perspective, biodegradable polymers significantly reduce long-term medical waste and offer an alternative to non-degradable implantable systems, aligning with green chemistry principles.

5. Conclusion

The use of biodegradable polymers in controlled drug release represents a significant advancement in both therapeutic performance and environmental sustainability. With ongoing innovations in polymer chemistry, drug formulation, and responsive delivery systems, these materials are poised to transform future pharmaceutical strategies. Addressing current limitations through interdisciplinary research will pave the way for next-generation drug delivery platforms that are safe, effective, and eco-friendly.

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