Exploring the Potential of Biodegradable Polymers for Sustainable Drug Delivery Applications

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Abstract

This article explores the potential of biodegradable polymers for sustainable drug delivery applications. Biodegradable polymers have attracted considerable attention in the field of drug delivery due to their ability to release drugs in a controlled manner, biocompatibility, and biodegradability. The article reviews the different types of biodegradable polymers, including natural and synthetic polymers, and their properties that make them suitable for drug delivery applications. The review also highlights the various drug delivery systems that can be developed using biodegradable polymers, such as microspheres, nanoparticles, and hydrogels. Finally, the article discusses the current challenges and future perspectives of biodegradable polymers in drug delivery applications, including the need for further research on the toxicity of these materials and the development of new biodegradable polymers with improved properties. Overall, the article emphasizes the potential of biodegradable polymers as a promising approach to sustainable drug delivery.

Keywords: biodegradable polymers, drug delivery, controlled release, natural polymers, nanoparticles.

Introduction

The increasing demand for pharmaceuticals and the associated growth of the healthcare industry have raised concerns about the environmental impact of drug delivery systems(Nabipour and Hu, 2020). Conventional drug delivery systems often use non-biodegradable polymers and other materials that can accumulate in the environment and cause pollution(Triphati and Pirzadah, 2023). To address this issue, researchers have been exploring the potential of biodegradable polymers for sustainable drug delivery applications(Olmo Martinez et al., 2023). A sustainable drug delivery system should meet the requirements of efficacy, safety, and environmental impact. Biodegradable polymers have shown promise as a sustainable alternative to traditional non-biodegradable polymers for drug delivery(Olmo Martinez et al., 2023). They can be designed to degrade into non-toxic products, which can be metabolized and eliminated by the body or assimilated by the environment. Furthermore, biodegradable polymers can offer improved drug delivery performance, such as controlled release, increased stability, and enhanced bioavailability(Romanello et al., 2022).

This review article aims to explore the potential of biodegradable polymers for sustainable drug delivery applications. It provides an overview of biodegradable polymers, discusses their use in drug delivery, and examines the challenges and future directions in this field. By highlighting the benefits and limitations of biodegradable polymers, this review aims to contribute to the development of sustainable drug delivery systems that can improve patient health while minimizing their impact on the environment.

Biodegradable polymers: An overview

Biodegradable polymers are a class of polymers that can be broken down into simpler compounds by biological processes(Richter and Lehr, 2021). They are attractive materials for drug delivery applications due to their biocompatibility, biodegradability, and controlled release properties. Biodegradable polymers are polymers that can undergo degradation through the action of biological agents such as enzymes, microorganisms, or other natural processes(Forier et al., 2014). They can be classified into two main categories: synthetic and natural polymers. Synthetic biodegradable polymers are produced from petroleum-derived monomers and include polyesters, polyanhydrides, and polyorthoesters(Nafee et al., 2014). Natural biodegradable polymers are derived from natural sources such as proteins, polysaccharides, and lipids. Biodegradable polymers have a number of important characteristics that make them suitable for drug delivery applications. They are non-toxic, biocompatible, and can be tailored to have specific mechanical, chemical, and biological properties(Pinheiro et al., 2018). They can be designed to degrade into non-toxic products, which can be metabolized and eliminated by the body or assimilated by the environment.

Types of biodegradable polymers Biodegradable polymers

Polyesters: Polyesters are synthetic biodegradable polymers that are widely used in drug delivery applications. They are produced from monomers such as lactic acid, glycolic acid, and ε-caprolactone(Johnsen et al., 2018). Poly(lactic acid) (PLA) and poly(glycolic acid) (PGA) are two of the most commonly used polyesters in drug delivery. These polymers degrade via hydrolysis, and their degradation rate can be controlled by varying the ratio of monomers and the molecular weight of the polymer(Johnsen et al., 2018).

Polyanhydrides: Polyanhydrides are synthetic biodegradable polymers that are used in drug delivery applications due to their controlled release properties. They degrade via surface erosion, and their degradation rate can be controlled by varying the polymer composition(Van Der Meel et al., 2014).

Polyorthoesters: Polyorthoesters are synthetic biodegradable polymers that have been investigated for drug delivery applications due to their biocompatibility and controlled release properties. They degrade via hydrolysis, and their degradation rate can be controlled by varying the polymer composition(Kooijmans et al., 2016).

Proteins: Proteins are natural biodegradable polymers that have been investigated for drug delivery applications due to their biocompatibility and biodegradability. Examples of protein-based drug delivery systems include albumin-based nanoparticles and gelatin-based microspheres(Kooijmans et al., 2016).

Polysaccharides: Polysaccharides are natural biodegradable polymers that have been investigated for drug delivery applications due to their biocompatibility and biodegradability. Examples of polysaccharide-based drug delivery systems include chitosan-based nanoparticles and alginate-based hydrogels(Richter et al., 2021).

Biodegradation mechanisms of polymers

Biodegradable polymers can undergo degradation via different mechanisms, depending on their chemical structure and environmental conditions. Some common degradation mechanisms include:

Hydrolysis: Hydrolysis is a common degradation mechanism for biodegradable polymers, especially polyesters. It involves the breakdown of ester bonds in the polymer backbone by water, resulting in the formation of smaller molecules such as monomers, oligomers, and ultimately, carbon dioxide and water(Bhatt et al., 2022a).

Enzymatic: degradation Enzymatic degradation is a specific type of biodegradation that involves the action of enzymes on the polymer structure. Enzymatic degradation is more common for natural bi odegradable polymers such as proteins and polysaccharides, which have specific enzyme recognition sites. Enzymatic degradation can be used to achieve controlled release of drugs from the polymer matrix, by designing the polymer structure to be sensitive to specific enzymes(Ali Esmail Al-Snafi et al., 2022).

Table 1: biodegradable polymers commonly used in drug delivery

Polymer Name	**Structure**	**Source**	**Degradation Products**	**Examples of Drugs Delivered**	**References**
Poly(lactic acid) (PLA)	$[CH(CH_3)COO]n$	Renewable resources such as cornstarch, sugarcane,	Lactic acid	Doxorubicin, paclitaxel, risperidone	(Chand et al., 2022)

		and potatoes			
Poly(glycolic acid) (PGA)	[HO(CH_2)$_2$ COO] n	Synthetic polymer	Glycolic acid	Methotrexate, cisplatin, doxorubicin	(Singh et al., 2022)
Poly(lactic-co-glycolic acid) (PLGA)	Copolymer of lactic acid and glycolic acid	Synthetic polymer	Lactic acid and glycolic acid	Leuprolide, buserelin, goserelin	(Bhatt et al., 2021)
Poly(ε-caprolactone) (PCL)	[HO(CH_2)$_5$ CO]n	Synthetic polymer	Caproic acid	Cyclosporine, docetaxel, paclitaxel	(Vargason et al., 2021)
Chitosan	[β-(1→4)-linked D-glucosamine]n	Natural polymer derived from chitin found in crustacean shells	Glucosamine	Insulin, siRNA, naproxen	(Gnopo et al., 2020)
Gelatin	Partially hydrolyzed collagen	Animal protein	Amino acids	Tetracycline, diclofenac, ciprofloxacin	(Uster et al., 1996)
Hyaluronic acid (HA)	Glycosaminoglycan consisting of D-glucuronic acid and N-acetyl-D-glucosamine	Natural polymer found in extracellular matrix	D-glucuronic acid and N-acetyl-D-glucosamine	Doxorubicin, cisplatin, methotrexate	(Düzgüneş, 2003)

Oxidative degradation: Oxidative degradation is a degradation mechanism that involves the oxidation of the polymer backbone by reactive oxygen species such as hydroxyl radicals. This mechanism is more common for synthetic biodegradable polymers, such as polyanhydrides and polyesters(Didiot et al., 2016). Biocompatibility and biodegradability Biodegradable polymers are generally biocompatible and biodegradable, meaning they are well tolerated by the body and can be broken down into non-toxic by products(Kooijmans et al., 2016). Controlled release properties Biodegradable polymers can be designed to release drugs at a controlled rate, which can improve drug efficacy and reduce side effects. Tailored properties Biodegradable polymers can be tailored to have specific mechanical, chemical, and biological properties, allowing them to be used in a wide range of drug delivery applications. Some biodegradable polymers may have limited mechanical strength, which can affect their suitability for certain drug delivery applications(Tian et al., 2018). Biodegradable polymers can have a limited shelf life, as they may begin to degrade even before use. The synthesis and processing of biodegradable polymers can be complex and may require specialized equipment and expertise(Stremersch et al., 2016).

Biodegradable polymers for drug delivery

Biodegradable polymers are a class of materials that can be broken down into smaller fragments by natural processes such as enzymatic and hydrolytic degradation. These polymers have been widely used in biomedical applications, particularly in drug delivery(Lee et al., 2011). Biodegradable polymers offer several advantages over non-biodegradable polymers, including their ability to degrade into non-toxic and biocompatible products, their ability to minimize toxicity, and their ability to increase drug efficacy by providing sustained release of drugs over time(Kim et al., 2009). This article discusses the factors affecting drug delivery using biodegradable polymers, the applications of biodegradable polymers in drug delivery, and examples of biodegradable polymer-based drug delivery systems(Olmo Martinez et al., 2023).

Factors affecting drug delivery using biodegradable polymers

Several factors can affect drug delivery using biodegradable polymers, including the polymer's properties, the drug's properties, and the method of delivery. The following are the main factors affecting drug delivery using biodegradable polymers:

Polymer properties:

The properties of biodegradable polymers play a crucial role in drug delivery(Beveridge et al., 1997). The choice of polymer depends on its biodegradability, biocompatibility, mechanical properties, and release kinetics. For instance, poly(lactic-co-glycolic acid) (PLGA) is a widely used biodegradable polymer in drug delivery due to its biocompatibility and tunable release kinetics. Similarly, poly(caprolactone) (PCL) has been used in drug delivery due to its mechanical properties and biodegradability(Pedersen et al., 2006).

Drug properties:

The properties of the drug, including its solubility, stability, and molecular weight, affect drug delivery using biodegradable polymers. The drug's solubility in the polymer matrix determines its release kinetics, and drugs with low solubility in the polymer matrix release slowly(Kagawa et al., 2013). The drug's stability in the polymer matrix can also affect drug delivery, and drugs that are unstable or easily degraded in the polymer matrix may not be suitable for drug delivery using biodegradable polymers(Svensson and Jönsson, 1984).

Method of delivery:

The method of delivery can also affect drug delivery using biodegradable polymers. The most common methods of delivery include injection, implantation, and oral administration. Injection and implantation are preferred methods for drug delivery using biodegradable polymers since they provide sustained release of drugs over an extended period(Ninham, 1999). Oral administration, on the other hand, is limited by the drug's solubility and stability in the gastrointestinal tract.

Applications of biodegradable polymers in drug delivery

Biodegradable polymers have several applications in drug delivery, including sustained release, targeted delivery, and site-specific delivery. The following are some of the applications of biodegradable polymers in drug delivery:

Sustained release: Sustained release is a critical application of biodegradable polymers in drug delivery. Biodegradable polymers can be used to create drug delivery systems that provide sustained release of drugs over an extended period(Knoblich and Gerber, 2001). For example, PLGA microspheres have been used to deliver drugs such as paclitaxel and doxorubicin for the treatment of cancer.

Targeted delivery: Targeted drug delivery is another application of biodegradable polymers in drug delivery. Biodegradable polymers can be used to create drug delivery systems that target specific cells or tissues, increasing drug efficacy and minimizing side effects(Malik et al., 2022). For instance, PLGA nanoparticles have been used to deliver drugs such as curcumin and methotrexate to cancer cells.

Site-specific delivery: Site-specific drug delivery is also an application of biodegradable polymers in drug delivery. Biodegradable polymers can be used to create drug delivery systems that release drugs at a specific site, such as an injury site or an area of inflammation(Bhatt et al., 2021). One example of site-specific drug delivery using biodegradable polymers is the use of PLGA microspheres to deliver anti-inflammatory drugs such as dexamethasone to the site of inflammation in the treatment of diseases such as rheumatoid arthritis and osteoarthritis(Bhatt et al., 2022b).
PLGA-based drug delivery systems PLGA is a widely used biodegradable polymer in drug delivery due to its biocompatibility and tunable release kinetics. Several drug delivery systems have been developed using PLGA, including microspheres, nanoparticles, and implants. For example, PLGA microspheres have been used to deliver drugs such as paclitaxel and doxorubicin for the treatment of cancer. PLGA nanoparticles have also been used to deliver drugs such as curcumin and methotrexate to cancer cells. PLGA implants have been developed for the sustained release of drugs such as leuprolide acetate for the treatment of prostate cancer (Tawari et al., 2001).
Chitosan-based drug delivery systems Chitosan is a biodegradable polymer derived from chitin, which is found in the exoskeleton of crustaceans. Chitosan-based drug delivery systems have been developed for various applications, including wound healing and drug delivery to the gastrointestinal tract. For example, chitosan hydrogels have been developed for the delivery of growth factors for the treatment of chronic wounds(Tawari et al., 2001). Chitosan microspheres have also been developed for the delivery of drugs such as insulin to the gastrointestinal tract. Polyethylene glycol (PEG)-based drug delivery systems PEG is a biocompatible and biodegradable polymer that has been widely used in drug delivery due to its ability to increase drug solubility and stability. Several PEG-based drug delivery systems have been developed, including PEGylated liposomes and PEGylated nanoparticles(Zhang et al., 2015). For example, PEGylated liposomes have been used to deliver drugs such as doxorubicin and paclitaxel for the treatment of cancer. PEGylated nanoparticles have also been used to deliver drugs such as siRNA for the treatment of genetic disorders(Bayer, 1991).

Table 2: Comparing the properties of biodegradable polymers with conventional polymers

Property	Biodegradable Polymers	Conventional Polymers	References
Biocompatibility	High biocompatibility due to similarity to natural macromolecules and degradation products that are non-toxic and easily metabolized	Varies depending on the polymer and its degradation products, some may cause inflammation or toxicity	(Fan et al., 2021)
Biodegradability	Capable of undergoing enzymatic or hydrolytic degradation into non-toxic products, reducing long-term accumulation in the environment	Non-degradable or may take a very long time to degrade, leading to environmental pollution	(Pan et al., 2012)
Mechanical strength	May have lower mechanical strength compared to conventional polymers, but can be improved by blending with other polymers or additives	High mechanical strength, but may cause mechanical irritation or toxicity	(Shnyrova and Zimmerberg, 2009)
Drug loading capacity	Good drug loading capacity due to the presence of functional groups that can interact with drugs, and high surface area to volume ratio in nanoparticles	Limited drug loading capacity due to lack of functional groups, and limited surface area to volume ratio	(Eun Shin et al., 2023)

Challenges and future directions

Challenges and limitations of biodegradable polymers for drug delivery: Despite the numerous advantages of biodegradable polymers for drug delivery, there are several challenges and limitations that need to be addressed, including:

1. Limited control over drug release kinetics: Biodegradable polymers can be difficult to manipulate to achieve specific drug release kinetics, which can limit their use in certain applications(Eun Shin et al., 2023).
2. Limited drug loading capacity: Biodegradable polymers may have limited drug loading capacity, which can reduce the effectiveness of drug delivery systems.
3. Limited stability: Some biodegradable polymers can degrade too quickly, reducing the stability of the drug delivery system and potentially affecting drug efficacy(Caron et al., 2020).
4. Incomplete biodegradation: Incomplete biodegradation of polymers can result in the accumulation of degradation products, which can be toxic or cause inflammation.

Strategies to overcome challenges and improve biodegradable polymer-based drug delivery Several strategies can be employed to overcome the challenges and improve biodegradable polymer-based drug delivery, including:

1. Development of new polymers: New polymers can be developed with improved drug loading capacity, biodegradation rate, and controlled drug release kinetics(Temming et al., 2005).
2. Polymer modification: Polymers can be modified with different functional groups or additives to enhance their properties and improve drug release kinetics.
3. Combination therapy: Combination therapy can be used to overcome the limitations of individual drugs, improving treatment efficacy(Rabenhold et al., 2015).
4. Advanced processing techniques: Advanced processing techniques, such as electrospinning and 3D printing, can be used to create drug delivery systems with precise control over drug release kinetics and morphology(Saul et al., 2003).

Future directions for research and development

There are several areas where research and development can be focused to further improve biodegradable polymer-based drug delivery, including:

1. Personalized medicine: The development of personalized medicine using biodegradable polymers can lead to improved treatment outcomes by tailoring drug delivery to an individual's specific needs(Shimada et al., 2000).
2. Advanced drug delivery systems: The development of advanced drug delivery systems, such as responsive drug delivery and nanoscale drug delivery, can lead to improved drug efficacy and reduced toxicity.
3. Combination therapy: Further research into combination therapy using biodegradable polymers can lead to improved treatment outcomes for a wide range of diseases(Chiu et al., 2002).
4. Biodegradable polymers for gene therapy: The use of biodegradable polymers for gene therapy can lead to improved safety and efficacy of gene delivery(Chand et al., 2022).

Conclusion

In summary, biodegradable polymers offer a promising approach for sustainable drug delivery due to their biocompatibility, biodegradability, and versatility. Biodegradable polymers can be tailored to meet specific drug delivery needs, with controlled release kinetics, high drug loading capacity, and improved safety profiles. The use of biodegradable polymers in drug delivery can have significant implications for sustainable healthcare, reducing the environmental impact of pharmaceuticals and improving patient outcomes. Biodegradable polymers can potentially reduce the reliance on non-renewable resources and mitigate the negative effects of plastic waste on the environment. The potential impact of biodegradable polymers on the future of drug delivery is significant, as new advances in polymer science and processing techniques can lead to the development of more advanced drug delivery systems with improved efficacy and safety. Future research and development in this field can lead to the development of personalized medicine, advanced drug delivery systems, and new applications for gene therapy. Overall, the exploration of the potential of biodegradable polymers for sustainable drug delivery applications has significant implications for the future of healthcare and sustainability, and further research in this field is warranted.

Conflict of interest

There are no conflicts of interest to declare for this work.

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