The Bioscan
AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES 20(1): 168-174, 2025 www.thebioscan.com

Sustainable Polymers: A Review of Green Synthesis and Applications

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DOI: https://doi.org/10.63001/tbs.2025.v20.i01.pp168-174

KEYWORDS
sustainable polymers, green synthesis, drug delivery systems, biodegradable plastics, biocompatibility.

Received on: 12-11-2024

Accepted on: 10-12-2024

Published on: 24-01-2025

ABSTRACT

Sustainable polymers are revolutionizing materials science by providing eco-friendly alternatives to traditional petroleum-based plastics. These polymers aim to reduce environmental challenges like plastic pollution, carbon emissions, and resource depletion. This review explores the advances in green synthesis methods, such as bio-based monomers, biocatalysis, green solvents, and metal-free catalysis, that reduce dependence on fossil fuels and promote biodegradability. Some of the most prominent materials discussed are PLA and PHA, which come from renewable feedstocks such as agricultural waste and non-food biomass. Although much promise is being held by these materials, scaling up, cost-effectiveness, and mechanical performance are significant challenges to their use. In the pharmaceuticals industry, polymers have revolutionized drug delivery systems, for example, by controlled drug release, improving their biocompatibility, and reducing side effects. Controlled biodegradation has been achieved through synthetic polymers such as PLGA and PEG, and natural polymers, like chitosan and alginate, give biodegradability with biological system compatibility. Examples of advanced drug delivery technologies include stimuli-responsive and mucoadhesive polymers, which show their great flexibility in targeted therapy. The findings emphasize the need for interdisciplinary collaboration to overcome economic and performance challenges in green polymer synthesis. Future directions include optimizing enzyme-based processes, diversifying feedstocks, and integrating sustainable lifecycle assessments. These advancements are pivotal in ensuring sustainable polymers' adoption in a circular economy while addressing pharmaceutical and industrial needs.

INTRODUCTION

Escalating environmental concerns over plastic pollution, carbon emissions, and resource depletion have pushed the search for sustainable polymers as alternatives to traditional plastics.[1] Biodegradable, bio-based, and recyclable versions of these novel materials are designed to meet the urgent ecological challenges by reducing fossil-derived feedstocks and mitigating the negative impacts of plastic waste.[2] Some of the bio-based polymers include polylactic acid (PLA) and polyhydroxyalkanoates (PHAs), one of which comes from renewable feedstocks such as starch produced from corn or sugarcane, and sometimes even waste biomass.[3] According to reported studies, PLA has higher environmental impacts on Marine Eutrophication, Freshwater Eutrophication, and Human Toxicity, but lower greenhouse gas emissions compared to polystyrene and PET, thus paving the way towards alternative reductions for environmental footprints.[4] Bio-plastics show considerable potential for development but are vulnerable to political and economic impacts, with global production capacity forecasted to reach a capacity of 1.2 million tonnes by 2030.[5] However, these promising developments still face significant challenges, including scalability, cost-effectiveness, and mechanical performance, for widespread industrial use. These limitations require further research on green synthesis methodologies and lifecycle assessments to improve the economic and environmental viability of sustainable polymers for various sectors, such as pharmaceuticals.

In the pharmaceutical sector, polymers are revolutionizing the design of controlled drug delivery systems. Such a system ensures precise control over the kinetics of drug release, thus maximizing therapeutic efficacy, patient compliance, and safety.[6] The most used synthetic polymers are PLGA and PEG, approved by the FDA and the EMA, owing to their excellent biocompatibility and modulable degradation profile.[7] For instance, PLGA has been used to a large extent in drug encapsulation for sustained and targeted release due to its ability to degrade into harmless metabolites, lactic and glycolic acids.[8] However, synthetic polymers are not without environmental issues. Being based on petro sources, end-of-life options are very few. Environment-friendly natural polymers derived from renewable resources such as the shells of crustaceans or seaweed-namely, chitosan and alginate-have been drawing attention in the pharmaceutical industry due to several factors, particularly for their inherent biodegradability and compatibility with biological systems.[9] However, their standardization and scalability are practical issues due to variations in their physicochemical properties, which can be attributed to biological variability. Variations prove that the future of advanced research should involve blending or functionalizing these natural polymers for consistency and performance.[10]

This review highlights the recent advancements in green synthesis methods for sustainable polymers integrated into controlled drug delivery systems. It addresses the challenges of sustainability, functionality, and scalability to achieve the trifecta of sustainability, identifies gaps in current technologies and applications, and assesses the potential of innovative approaches such as bio-catalytic polymerization, supercritical fluid processing, and molecular engineering to highlight strategies for overcoming existing barriers. Further, it highlights the need for interdisciplinary collaboration between materials scientists, chemists, and pharmaceutical experts in the creation of next-generation polymer systems. The systems should meet both the stringent functional requirements of controlled drug delivery and be compliant with the imperatives of environmental sustainability, thus forming a platform for a transformation shift in pharmaceutics and materials science.

Green Synthesis of Sustainable Polymers: A Review with Literature Insights

The production of sustainable polymers through green synthesis methods signifies an essential advancement in materials science, emphasizing eco-friendly practices to mitigate environmental concerns associated with conventional polymers.[11] A comprehensive literature review reveals the extent of innovation and ongoing challenges in this domain.

a. Bio-Based Monomers

The use of bio-based monomers sourced from renewable agricultural and biological feedstocks has been a major focus of green polymer research. Polylactic acid (PLA) and polyhydroxyalkanoates (PHAs) have been extensively studied for their biodegradability and applications. According to Farah S et al. (2016), PLA's mechanical and physical properties affect its stability, processability, degradation, and suitability for specific application requirements in medicine and industry, making it suitable for packaging and biomedical uses.[12] PHAs, as highlighted by Muneer F et al. (2020), are Microbial polyhydroxyalkanoates (PHAs) are non-toxic, biodegradable, and can replace synthetic plastics in various applications like packaging, disposable products, and biofuels.[13] However, issues related to high production costs and limited scalability persist, necessitating further exploration of feedstock diversity, including agricultural waste and non-food biomass, as suggested by Bayat H et al. (2021).[14] Advances in metabolic engineering and fermentation processes are actively addressing these barriers to broaden the commercial viability of bio-based polymers.

b. Biocatalysis

Enzyme-catalyzed polymerization has emerged as a sustainable alternative, offering lower energy requirements and fewer toxic byproducts. Studies by Uyama H et al (2000) demonstrated the potential of lipase-catalyzed polymerization for synthesizing aliphatic polyesters under mild conditions.[15] Enzymatic processes have also shown the ability to control polymer microstructures with precision, enabling tailored properties for specific applications. More recent research, such as that by Jiang Y et al. (2016), has explored the enzymatic synthesis of biodegradable polyamides and polycarbonates, emphasizing the compatibility of biocatalysis with green chemistry principles.[16] While promising, challenges related to enzyme stability and cost-effectiveness remain, as highlighted by Kumar P et al. (2024), suggesting a need for advancements in enzyme immobilization and reusability technologies.[17]

c. Green Solvents and Supercritical Fluids

The environmental impact of solvent systems in polymerization has driven the adoption of greener alternatives like supercritical CO_2 and ionic liquids. Nalawade SP et al. (2006) demonstrated the efficacy of supercritical CO_2 in polymerization, showcasing its ability to act as both solvent and reagent in various processes.[18] This approach minimizes waste and eliminates the need for toxic organic solvents. Ionic liquids, as studied by Singh, G (2008), have garnered attention for their non-volatility and tunable physicochemical properties, enabling polymerization under environmentally benign conditions.[19] However, despite their advantages, the economic and environmental implications of producing and recycling ionic liquids require further investigation.

d. Metal-Free Catalysis

The development of metal-free catalysts aligns with the principles of green chemistry by avoiding the toxicity and environmental hazards associated with metal-based systems. Research by Majeed A et al (2024) highlighted the efficiency of organocatalysts in polymerizing cyclic esters, delivering excellent control over molecular weights and polymer structures.[20] These catalysts are particularly beneficial in applications where metal contamination must be avoided, such as in biomedical and food packaging materials.

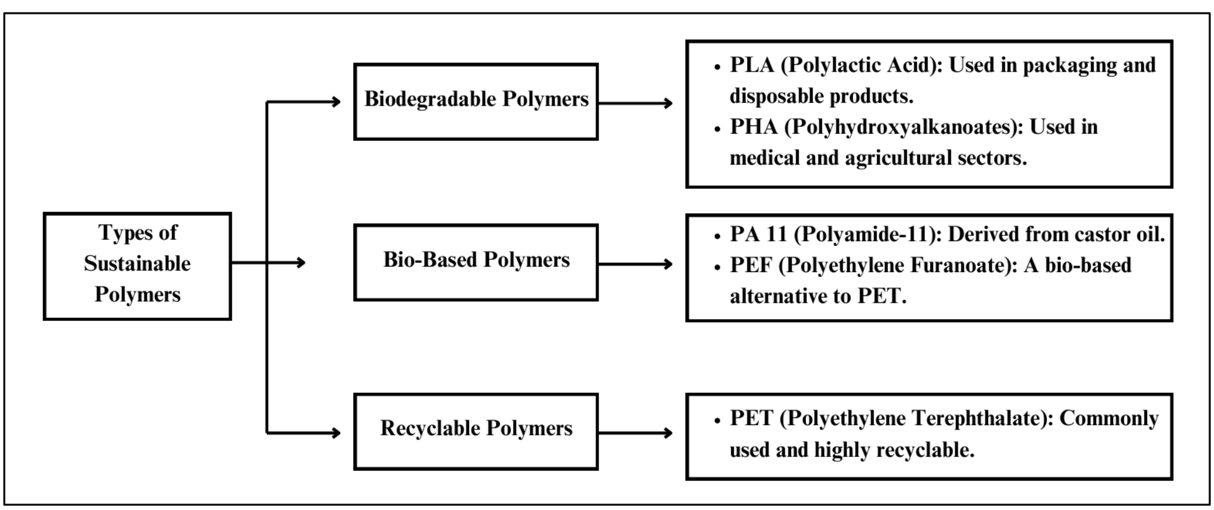

Figure 1: Types of Sustainable Polymers

Applications of Sustainable Polymers

Sustainable polymers have found applications in various industries due to their unique properties, such as biodegradability, renewability, and recyclability:

Biodegradable and Bio-Based Polymers in Packaging

Bio-based and biodegradable polymers such as polylactic acid (PLA) have become increasingly popular in the packaging industry. According to a study by Rajeshkumar G et al. (2021), PLA polymers are utilized extensively for creating environmentally friendly packaging solutions including containers, wraps, and disposable cutlery.[21] These materials help in significantly reducing the volume of plastic waste that ends up in landfills. The study emphasizes that PLA not only offers a reduced carbon footprint but also demonstrates properties that are highly suitable for a variety of packaging applications.

Biodegradable Polymers for Medical Applications

In the medical sector, sustainable polymers like PLA and polyhydroxyalkanoates (PHA) are revolutionizing product designs.

Gregory DA et al. (2022) discussed the use of these polymers in applications such as drug delivery systems, biodegradable sutures, and wound dressings.[22] The materials are especially valued for their ability to decompose within the body, thereby obviating the need for surgical removal and reducing medical waste. This adaptation not only simplifies clinical procedures but also enhances patient comfort and recovery.

Sustainable Polymers in Agricultural Practices

Sustainable polymers are pivotal in the development of biodegradable films and mulches that enhance soil quality while reducing residue pollution. As highlighted by Afrinal Firmanda et al. (2024), biodegradable polymers are employed in controlled-release fertilizers and agricultural packaging, improving sustainability in agricultural operations.[23] These materials degrade naturally, contributing to soil health and reducing environmental impact.

Here's an extended version of the suggested table with additional rows and details:

Table 1: Green Synthesis Approaches and Benefits in Sustainable Polymer Development

Green Synthesis Approach	Description	Key Benefits	Example Polymers	Ref
Bio-Based Monomers	Use of renewable agricultural and biological feedstocks for polymer production.	Reduces dependency on fossil fuels; promotes biodegradability; supports circular economy.	Polylactic acid (PLA), Polyhydroxyalkanoates (PHAs)	[12-14
Biocatalysis	Enzyme-catalyzed polymerization processes under mild conditions.	Energy-efficient, fewer toxic byproducts, and tailored polymer properties.	Aliphatic polyesters, Biodegradable polyamides	[15-17]
Green Solvents	Use of environmentally benign solvents like supercritical CO2 and ionic liquids.	Minimizes toxic emissions, reduces waste, and promotes cleaner production methods.	Polymers synthesized using ionic liquids, Polycarbonates	[18,19]
Metal-Free Catalysis	Employing organocatalysts to avoid toxicity associated with metal-based systems.	Safer for biomedical and food packaging applications; avoids heavy metal residues.	Polyesters, Polylactones	[20]
Renewable Feedstocks	Incorporating agricultural waste, non-food biomass, or CO2 for polymer synthesis.	Diversifies feedstock base, reduces competition with food supply, and promotes carbon recycling.	Polyhydroxyalkanoates (PHA), Bio-polyethylene	[3,14]
Supercritical Fluid Processing	Using supercritical CO2 as a reaction medium or solvent.	Reduces reliance on organic solvents; supports energy-efficient and scalable processes.	PLA composites, Biodegradable polyesters	[18]
Enzyme Immobilization	Enhancing enzyme stability for repeated use in polymerization processes.	Increases efficiency, lowers production costs, and supports sustainable practices.	Biodegradable polyamides, Polycarbonates	[17]
Feedstock Diversification	Exploring non-traditional sources like algae, seaweed, or food waste for polymer precursors.	Reduces waste, enhances sustainability, and lowers ecological footprint.	Alginates, Chitosan-derived polymers	[14,23]
Ionic Liquid Polymerization	Polymer synthesis in ionic liquids due to their tunable properties and negligible volatility.	Enables precise polymer structure control and eco-friendly reaction conditions.	Polyurethanes, Biodegradable elastomers	[19]
Biobased Blends and Composites	Combining biobased polymers with natural fibers or fillers.	Improves mechanical properties, reduces dependency on synthetic reinforcements.	PLA-natural fiber composites, PHA blends	[21,23]

PROPERTIES OF POLYMERS IN DRUG DELIVERY

Essential for Direct Contact with Biological Tissues

Biocompatibility ensures that the polymer does not trigger any adverse immunological or toxic reactions when in contact with the body's tissues. This property is critical for devices intended for long-term contact with body fluids or tissues, such as drug-eluting stents or transdermal patches. Recent literature, such as Sharma SJ (2024), has shown that advanced testing methods are now used to assess the biocompatibility of new polymer materials, ensuring they are safe for medical applications.[24] This includes evaluating the polymer's potential for cytotoxicity, inflammation, and allergenicity.

Key for Reducing Surgical Interventions

The ability of a polymer to biodegrade within the body under natural biological conditions is invaluable, particularly for applications where the polymer is designed to deliver a therapeutic agent over time and then safely degrade. Dintcheva NT (2024) provides insights into how the chemical structure of polymers can be engineered to control the degradation rate, matching the therapeutic needs of the drug release profile.[25] This property is particularly beneficial in reducing the need for secondary surgeries to remove the device after its function has been served.

Ensuring Effective Delivery and Stability

High drug encapsulation efficiency ensures that the maximum amount of a drug is contained within the polymer matrix and is released at the target site in a controlled manner. Dadwal A (2012) describe techniques for enhancing the interaction between the drug and the polymer to prevent premature leakage or degradation of the drug.[26] Aboudzadeh MA (2022) further discusses the impact of polymer morphology on encapsulation efficiency and drug stability, highlighting how micro and nano-structuring of polymer systems can enhance performance.[27]

Reliability Under Physiological Conditions

The mechanical strength of a polymer determines its ability to withstand the physical stresses encountered during the delivery and operational phase within the body. This includes forces exerted during implantation, as well as dynamic forces such as blood flow or body movements. Polymers with adequate mechanical properties ensure the structural integrity of drug delivery systems under these challenging conditions.

Tailoring Release to Therapeutic Needs

The controlled release of drugs from polymers can significantly enhance therapeutic outcomes by providing sustained drug levels at the target site. Fu Y (2010) explains that the release kinetics can be precisely tailored through the copolymerization of different monomers or by incorporating additives that modify the polymer's physical or chemical properties.[28] These modifications allow for the creation of systems that can release drugs at a predetermined rate, improving patient compliance and drug efficacy.

Optimizing Interaction with Biological Environments

Surface modification techniques can be used to alter the interaction between the polymer and its biological environment. Antonov DV (2023) discuss how surface properties such as hydrophobicity/hydrophilicity, charge, and roughness can be engineered to influence drug release rates, enhance biocompatibility, or target specific tissues or cells.[29] This is crucial for ensuring that the drug delivery system is effective in reaching and acting at the site of interest.

Versatility Across Drug Types

Polymers must be chemically and physically compatible with a range of drug types, from small molecules to large biomolecules like proteins or nucleic acids. Jurak M (2021) emphasizes the importance of polymer compatibility in maintaining the stability and bioactivity of the drugs, particularly in systems designed for the delivery of sensitive biologicals.[30]

Extending Drug Residence Time

Mucoadhesive polymers are designed to adhere to mucosal tissues, increasing the residence time of the drug at the site of application. This is particularly advantageous for applications in areas like the nasal cavity, eyes, or vaginal tract, where prolonged drug presence can significantly enhance therapeutic efficacy. Surendranath M (2022) reviews advancements in mucoadhesive technology, noting improvements in polymer formulations that enhance mucosal adhesion without causing irritation or damage to the tissue.[31]

Responsive Delivery for Targeted Therapy

Stimuli-responsive polymers are designed to change their behavior in response to specific environmental stimuli, such as changes in pH, temperature, or the presence of specific enzymes. Alvarez-Lorenzo C (2014) discusses how these materials can be used to create smart drug delivery systems that release their payload in response to specific physiological conditions associated with disease states, thereby maximizing therapeutic efficacy while minimizing side effects.[32]

Adaptability in Drug Delivery System Fabrication

The ease of processing of polymers into various forms is critical for their application in diverse drug delivery technologies. Parawee Rattanakit (2012) explores how polymers amenable to processes like extrusion, injection molding, and 3D printing facilitate the creation of complex drug delivery architectures.[33] This adaptability allows for the customization of drug delivery systems to meet specific medical needs and patient-specific anatomical requirements.

TYPES OF POLYMERS IN DRUG DELIVERY

Natural Polymers in Drug Delivery

Natural polymers are favored in pharmaceutical applications for their biocompatibility, biodegradability, and generally minimal toxicity. Derived from natural sources, these polymers are particularly suitable for use in systems where direct contact with biological tissues is required. As highlighted by Birajdar MS (2021), natural polymers like albumin, gelatin, chitosan, alginate, and hyaluronic acid are extensively utilized due to their ability to integrate seamlessly into biological processes.[34] Albumin and gelatin are particularly valued for their drug binding capabilities and protective gel-forming properties, which are crucial in controlled release systems. Chitosan's mucoadhesive properties make it ideal for mucosal drug delivery, while alginate's unique gelation with calcium ions is exploited in wound dressings.[35] Hyaluronic acid is employed for its viscoelastic properties in ocular drug delivery, underscoring the diverse applications of natural polymers in medicine.

Synthetic Polymers in Drug Delivery

Synthetic polymers offer unparalleled control over physical and chemical properties, making them indispensable in the design of sophisticated drug delivery systems. Their biocompatibility, tunable degradation properties, and mechanical strength are key attributes that enhance their utility in a range of pharmaceutical applications. For instance, biodegradable synthetic polymers such as poly(lactic-co-glycolic acid) (PLGA), poly(caprolactone) (PCL), and poly(hydroxyalkanoates) (PHA) are engineered to degrade at rates that coincide with the drug release needs.[36] PLGA is particularly noteworthy for its adjustable degradation through copolymer ratios, providing versatile solutions for varying therapeutic requirements. Non-biodegradable synthetic polymers like polyethylene glycol (PEG), polyvinylpyrrolidone (PVP), and poly(ethyl methacrylate) (PEMA) serve distinct roles in enhancing drug solubility, stabilizing formulations, and modifying nanoparticulate delivery systems, ensuring broad adaptability across medical therapies.[37]

Semisynthetic Polymers in Drug Delivery

Semisynthetic polymers represent a hybrid approach by modifying natural polymers to enhance their chemical and physical properties while retaining biocompatibility. This category includes materials like carboxymethyl cellulose (CMC), a derivative of cellulose that is tailored to meet specific drug delivery challenges such as increased solution viscosity and improved film formation.[38] These modifications extend the utility of natural polymers, allowing them to be used in more demanding environments and applications that require precise control over drug release kinetics and stability. The adaptability of semisynthetic polymers facilitates their use in a wide range of delivery modalities, including tablets, injectables, and specialized drug release systems.

TYPES OF POLYMERS IN PHARMACEUTICAL INDUSTRY:

Polymers in Floating Drug Delivery Systems

Polymers are integral to floating drug delivery systems, where they are employed to maintain prolonged gastric residence time and targeted drug release within the stomach. Natural polymers such as chitosan, pectin, xanthan gum, guar gum, gellan gum, karaya gum, psyllium husk, starch, and alginates are used for their buoyant properties and compatibility with gastric conditions. These polymers swell in the stomach's acidic environment without dissolving, effectively floating on gastric fluids and gradually releasing the medication at a controlled rate (Patil S, 2021). This technique is particularly beneficial for drugs absorbed primarily in the stomach or those that are more soluble in acidic conditions.[39]

Polymers Used in Mucoadhesive Drug Delivery Systems

In the realm of mucoadhesive drug delivery, polymers such as lectins and lectinomimetics provide significant advantages, including prolonged residence time and enhanced drug penetration at mucosal sites. These polymers ensure localized release and increased drug bioavailability, particularly for buccal drug delivery systems. The site-specific adhesion and enzymatic inhibition facilitated by these polymers optimize the delivery and effectiveness of both small molecular drugs and therapeutic macromolecules (Yetisgin AA, 2020).[40]

Polymeric Micelles

Polymeric micelles, formed from amphiphilic block copolymers, are crafted to meet the critical need for selective drug delivery in treating diseases like cancer. These micelles encapsulate poorly water-soluble anticancer drugs within their hydrophobic cores, shielding them from aqueous environments. Their structural stability and size enable them to exploit the enhanced permeability and retention effect, targeting tumor sites through a passive mechanism, thereby minimizing the cytotoxic effects on healthy cells.[41]

Polymers in Tissue Engineering

In tissue engineering, natural-origin polymers such as proteins and polysaccharides are extensively utilized as scaffolds to support cell growth and new tissue formation. Proteins like collagen, gelatin, silk fibroin, and fibrin provide a matrix that mimics the natural extracellular environment, facilitating cell attachment and proliferation. Polysaccharides like chitosan, starch, alginate, and chondroitin sulfate are valued for their gel-forming capabilities and biocompatibility, which promote effective tissue development and healing (Mohammed ASA, 2021).[42]

Polymers in Micro and Nanoparticles for Targeted Drug Delivery

Research into biodegradable polymers such as polylactide (PLA), polycaprolactone (PCL), and poly(lactide-co-glycolide) (PLGA) for micro- and nanoparticle formulations highlights their role in providing controlled drug release at specific sites. These polymers, capable of degrading within the body, facilitate drug delivery that is both effective and minimizes potential side effects. Moreover, modifications to these polymers enable targeted drug delivery through active mechanisms, involving surface alterations that bind specifically to cellular receptors on target tissues (Jyothika M, 2024).[43]

APPLICATIONS OF POLYMERS IN CONTROLLED DRUG DELIVERY SYSTEMS

Oral Drug Delivery

In the oral drug delivery area, polymers play an important role in controlling the release and stability of drugs in the gastrointestinal tract. Enteric polymers such as cellulose acetate phthalate (CAP) and poly(methacrylic acid-co-methyl methacrylate) (Eudragit) are specifically formulated to resist the acidic environment of the stomach. The dissolution of these materials in the intestines, a more basic environment, ensures the release of the drug in an optimal location for its absorption and also ensures that its degradation by acids in the stomach is minimized. Such targeted release proves to be beneficial to drugs sensitive to gastric acids or those which must be activated in the intestines to manifest their therapeutic effect (Vrettos NN, 2021). This strategy increases the bioavailability of drugs and is compatible with patient-specific dosing regimens, thus improving therapeutic outcomes.[44]

Transdermal Drug Delivery

Transdermal drug delivery systems utilize the controlled release properties of polymers to deliver drugs across the skin. Polymers like polyvinyl chloride (PVC) and polyisobutylene (PIB) are used to create a reservoir or a matrix that allows the gradual diffusion of drugs into the bloodstream.[45] The use of these polymers allows for a controlled and sustained release, which is crucial for treatments that require plasma levels to be consistent over an extended period. For instance, pain relief patches or nicotine replacement therapies benefit highly from this method because it ensures therapeutic drug levels without the need for frequent dosing. Procopio A, in 2022, emphasizes that the drug release is governed by the polymer matrix while providing for mechanical stability and adhesiveness to the skin during the duration of the long-term application patch.[46]

Injectable Drug Delivery

Injectable drug delivery systems use injectable depots mainly comprised of biodegradable polymers such as poly(lactic-co-glycolic acid) (PLGA) and poly(caprolactone) (PCL), thus aiding sustained release formulations. These polymers degrade gradually in the body, releasing the encapsulated drug over weeks or months. The technique is highly valuable for the treatment of chronic diseases where steady levels of medication are needed to treat effectively. Pandya A (2023) presents the application of these polymeric depots for the delivery of chronic pain management, contraceptives, and antipsychotic drugs in reducing the number of injections or administrations, hence enhancing compliance with treatment due to the ease of treatment regimen.[47]

Ophthalmic Drug Delivery

Biodegradable polymers are applied in the preparation of drug-loaded implants or inserts that are directly administered to the eye in the case of ophthalmic drug delivery. This is an advantageous method especially for the treatment of chronic eye diseases such as glaucoma and macular degeneration where frequent dosing of eye drops becomes problematic for patient compliance and effectiveness. These devices are typically fabricated from polymers like poly(ethylene glycol) (PEG) and poly(lactic acid) (PLA). The controlled release properties of these polymers maintain a consistent dosage over time, thereby minimizing the number of eye drops that need to be applied daily. This essentially yields improved therapeutic efficacy (Sanjanwala D, 2024).[48] These ocular systems based on polymers are valuable in reducing systemic effects and improving the quality of life in patients with long-term ocular conditions.

CONCLUSION

The past few years have seen a significant rise in the importance of sustainable polymers as an alternative to traditional petroleum-based plastics. This review will show how new green synthesis approaches, such as bio-based monomers, biocatalysis, green solvents, and metal-free catalysis, have transformed polymer production to be not only environmentally friendly but also scalable. Such approaches decrease dependence on fossil fuels, diminish toxic byproducts, and create a circular economy. Accurate drug delivery, biocompatibility, and patient compliance transform the pharmaceutical industry through polymers. Synthetic polymers, including PLGA and PEG, are increasingly used because they exhibit controlled degradation characteristics, which are widely versatile. Natural and semisynthetic polymers are also very useful because they are environment-friendly and biocompatible. Some of the advanced technologies in polymers are stimuli-responsive polymers and mucoadhesive systems. However, integration of green synthesis methods in pharmaceutical polymers remains an evolving field requiring interdisciplinary collaboration to overcome challenges related to cost, scalability, and performance. Future research should focus on optimizing green synthesis methodologies, exploring diverse feedstocks, and advancing polymer functionalization to enhance both environmental sustainability and therapeutic efficacy. Long-term industry-wide adoption of sustainable polymers will be shaped by advances in rugged lifecycle assessments and recycling technologies. With innovation and collaborative work by materials scientists, chemists, and pharmaceutical experts, sustainable polymers will make great strides toward a more sustainable, circular global economy and meet the rising demands of modern medicine. This study shows the potential of sustainable polymers to play a transformative role in attaining balance between environmental responsibility and technological advancement toward a greener, more sustainable future.

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