JOURNAL OF NANOMATERIALS AND DEVICES
Jan-Jun 2025, VOL. 3, ISSUE 1, pp. 6-9
https://doi.org/10.61577/jnd.2025.100002

RESEAPRO JOURNALS

MINI REVIEW

OPEN ACCESS

Biodegradable nanomaterials: A sustainable future for pharmaceutical formulations

Lipsha Ray and Priyanka Prusty

Department of Biotechnology, Utkal University, Odisha, India

ABSTRACT

The development of biodegradable nanomaterials has emerged as a pivotal advancement in the design of sustainable pharmaceutical formulations. These materials, encompassing a broad spectrum of natural and synthetic polymers as well as lipid-based systems, offer distinct advantages in drug delivery, including controlled release, site-specific targeting, enhanced bioavailability, and reduced systemic toxicity. Crucially, their capacity for enzymatic or hydrolytic degradation into non-toxic byproducts aligns with environmental and biological safety standards, addressing growing concerns over the persistence of conventional drug carriers. This mini-review provides a concise overview of the principal categories of biodegradable nanomaterials, evaluates their functional roles in diverse pharmaceutical applications—ranging from oncology and gene therapy to vaccine delivery—and discusses their potential to replace or complement existing delivery platforms. Furthermore, the review outlines current challenges such as formulation stability, large-scale production, and regulatory considerations that constrain clinical translation. Taken together, biodegradable nanomaterials represent a promising paradigm for the development of next-generation, environmentally responsible therapeutic systems.

KEYWORDS

Biodegradable nanomaterials; Pharmaceutical formulations; Sustainability; Drug delivery; Nanomedicine; Green chemistry

ARTICLE HISTORY

Received 15 January 2025;
Revised 6 February 2025;
Accepted 13 February 2025

Introduction

The increasing global emphasis on environmental sustainability, coupled with the demand for safer and more efficient therapeutic delivery systems, has catalyzed the exploration of biodegradable nanomaterials in pharmaceutical sciences [1]. These materials, characterized by their nanoscale dimensions and capacity to degrade into biocompatible byproducts, have gained considerable attention as alternatives to traditional, non-degradable drug carriers. The integration of nanotechnology into pharmaceutical formulations has already demonstrated significant improvements in drug solubility, stability, pharmacokinetics, and biodistribution. However, many existing nanocarriers are associated with long-term accumulation and potential toxicity, thereby necessitating the development of biodegradable alternatives [2].

Biodegradable nanomaterials comprising natural polymers (e.g., chitosan, alginate), synthetic polymers (e.g., poly(lactic acid), poly(lactic-co-glycolic acid)), and lipid-based systems (e.g., liposomes, solid lipid nanoparticles) are uniquely positioned to address these limitations [3]. Their degradation pathways, which often involve hydrolysis or enzymatic breakdown, enable complete elimination from the body without inducing harmful residues. Moreover, their structural versatility allows for functionalization, controlled drug release, and precise targeting, making them ideal candidates for applications in cancer therapy, vaccine delivery, gene therapy, and chronic disease management [4].

This aims to provide a focused overview of the current landscape of biodegradable nanomaterials in pharmaceutical formulations, emphasizing their classification, mechanisms of degradation, therapeutic advantages, challenges to clinical implementation, and future potential in advancing sustainable and effective drug delivery strategies.

Types of Biodegradable Nanomaterials

Biodegradable nanomaterials are broadly categorized based on their origin and chemical composition. These include natural polymers, synthetic polymers, and lipid-based systems, each offering unique physicochemical properties and degradation profiles that can be exploited for pharmaceutical applications.

Natural polymer-based nanomaterials

Natural polymers such as chitosan, alginate, gelatin, and starch are extensively utilized due to their inherent biocompatibility, biodegradability, and non-immunogenicity. Chitosan, derived from chitin, exhibits mucoadhesive properties and pH-sensitive behavior, making it suitable for mucosal drug delivery [5,6]. Alginate, an anionic polysaccharide, is often used for encapsulating proteins and peptides due to its mild gelation conditions. Despite their advantages, natural polymers may exhibit batch-to-batch variability and limited mechanical stability, which can influence formulation reproducibility [7].

Synthetic polymer-based nanomaterials

Synthetic biodegradable polymers such as poly(lactic acid) (PLA), poly(glycolic acid) (PGA), poly(lactic-co-glycolic acid) (PLGA), and polycaprolactone (PCL) are widely employed in drug delivery due to their tunable degradation rates and

***Correspondence:** Ms. Lipsha Ray, Department of Biotechnology, Utkal University, Odisha, India. email: lipsharay2000@gmail.com

RESEAPRO JOURNALS

well-established safety profiles. These materials degrade primarily through hydrolytic cleavage of ester linkages, producing non-toxic metabolites that are eliminated via natural metabolic pathways. PLGA, approved by the FDA, is one of the most extensively studied and applied materials due to its customizable drug release kinetics and compatibility with a range of therapeutic agents [8].

Lipid-based nanomaterials

Lipid-based carriers such as liposomes, solid lipid nanoparticles (SLNs), and nanostructured lipid carriers (NLCs) represent another class of biodegradable nanomaterials. These systems offer the advantage of mimicking biological membranes, enhancing biocompatibility and cellular uptake. Liposomes, composed of phospholipid bilayers, have been successfully used in various clinical formulations. SLNs and NLCs, consisting of solid or semi-solid lipid matrices, provide improved stability and controlled release profiles while eliminating the need for potentially toxic organic solvents during preparation [9].

Degradation mechanisms

The biodegradability of these nanomaterials is primarily governed by enzymatic, hydrolytic, or oxidative mechanisms, depending on the material type. For instance, ester-based synthetic polymers undergo hydrolysis, whereas polysaccharides are degraded by specific enzymes such as lysozyme or amylase. Understanding these mechanisms is essential for designing delivery systems with predictable degradation kinetics and drug release profiles [10].

Pharmaceutical Applications

Biodegradable nanomaterials have demonstrated significant potential in addressing key challenges in drug delivery, including poor solubility, rapid clearance, non-specific biodistribution, and dose-limiting toxicity. Their tunable degradation profiles and surface properties enable the development of advanced therapeutic systems with enhanced safety, efficacy, and patient compliance. This section outlines the principal pharmaceutical applications of biodegradable nanomaterials.

Controlled and targeted drug delivery

One of the most widely explored applications of biodegradable nanomaterials is in controlled and targeted drug delivery. These systems can modulate the release of encapsulated drugs over time or in response to specific physiological stimuli (e.g., pH, enzymes, temperature). PLGA-based nanoparticles, for example, have been used to achieve sustained release of chemotherapeutics, reducing systemic toxicity and improving therapeutic index. Surface modification with ligands (e.g., antibodies, peptides) further enables receptor-mediated targeting, allowing selective delivery to diseased tissues such as tumors or inflamed sites [11].

Vaccine delivery

Biodegradable nanocarriers serve as efficient vaccine delivery platforms, facilitating antigen stabilization, cellular uptake, and immune system activation. Chitosan and PLGA nanoparticles have been investigated for intranasal and oral vaccine administration, offering needle-free alternatives with enhanced mucosal immunity. These systems also allow co-delivery of antigens and adjuvants, improving immunogenicity and reducing the number of required doses [12].

Cancer therapy

In oncology, biodegradable nanomaterials are employed to enhance the bioavailability and therapeutic index of chemotherapeutic agents while minimizing off-target effects. For instance, liposomes and polymeric nanoparticles have been used to deliver doxorubicin, paclitaxel, and cisplatin with improved tumor accumulation via the enhanced permeability and retention (EPR) effect. Additionally, biodegradable carriers can be engineered for combination therapies, delivering multiple agents with synergistic effects [13].

Gene and nucleic acid delivery

The delivery of nucleic acids such as siRNA, mRNA, and plasmid DNA requires protection from enzymatic degradation and efficient intracellular delivery. Biodegradable nanomaterials, particularly cationic polymers like chitosan and modified PLGA, have shown promise as non-viral gene delivery vectors. These systems offer improved safety over viral methods and can be engineered for endosomal escape and nuclear targeting [14].

Treatment of chronic diseases

For chronic diseases such as diabetes, cardiovascular disorders, and neurodegenerative conditions, long-term and site-specific drug delivery is critical. Biodegradable implants and injectable nanosystems have been developed for sustained release of insulin, antihypertensives, and neuroprotective agents. Their ability to maintain therapeutic drug concentrations over extended periods reduces dosing frequency and enhances patient adherence [15].

Advantages Over Traditional Materials

The integration of biodegradable nanomaterials into pharmaceutical formulations offers several advantages over conventional, non-degradable carriers such as inorganic nanoparticles (e.g., gold, silica) or non-biodegradable polymers (e.g., polyethylene glycol-based systems). These benefits span therapeutic performance, patient safety, and environmental sustainability.

Biocompatibility and reduced toxicity

Biodegradable nanomaterials, particularly those composed of natural polymers or FDA-approved synthetic polymers such as PLGA and PCL, exhibit excellent biocompatibility and are generally well-tolerated by biological systems. Their degradation products such as lactic acid, glycolic acid, or monosaccharides are metabolized and excreted via physiological pathways, significantly reducing the risk of long-term accumulation and chronic toxicity associated with persistent carriers.

Controlled degradation and drug release

A key advantage of biodegradable nanocarriers is their capacity for controlled and predictable degradation, which enables sustained and stimuli-responsive drug release. This feature allows for reduced dosing frequency, minimization of

https://doi.org/10.61577/jnd.2025.100002

peak–trough fluctuations in drug levels, and improved therapeutic outcomes. The degradation rate can be finely tuned by modifying polymer composition, molecular weight, crystallinity, and formulation parameters [16].

Enhanced therapeutic efficacy and targeting

Surface functionalization of biodegradable nanomaterials with targeting ligands (e.g., antibodies, folic acid, aptamers) facilitates active targeting of diseased tissues, improving drug accumulation at the site of action while sparing healthy tissues. In addition, passive targeting via the enhanced permeability and retention (EPR) effect enhances therapeutic efficacy, especially in solid tumors [17].

Improved patient compliance

The sustained and localized release profiles of these systems reduce the need for frequent dosing, enhancing patient adherence, particularly in chronic conditions. Injectable long-acting depots, biodegradable implants, and transdermal delivery platforms exemplify such patient-centered applications.

Environmental sustainability

Unlike traditional materials that persist in the environment and contribute to pharmaceutical pollution, biodegradable nanomaterials decompose into non-toxic, environmentally benign byproducts. This aligns with the principles of green chemistry and sustainable development, making them ideal candidates for reducing the ecological footprint of pharmaceutical manufacturing and waste disposal [18].

Challenges and Limitations

Despite their significant promise, biodegradable nanomaterials face several scientific, technical, and regulatory challenges that hinder their broad clinical and commercial adoption. Understanding these limitations is critical for guiding future research and optimizing formulation strategies.

Scale-up and manufacturing complexity

The transition from laboratory-scale synthesis to industrial-scale manufacturing presents a major barrier. Many biodegradable nanomaterial formulations require precise control over particle size, drug loading, and surface characteristics, which are difficult to replicate consistently at scale. Moreover, batch-to-batch variability in natural polymers and the sensitivity of formulations to processing conditions complicate standardization and quality assurance.

Stability and shelf-life

Biodegradable systems are inherently prone to hydrolysis and enzymatic degradation, which can compromise formulation stability during storage. Ensuring long-term stability without compromising biodegradability remains a technical challenge, particularly for aqueous formulations or those requiring cold-chain storage [19].

Regulatory and toxicological uncertainty

Although many biodegradable polymers are individually recognized as safe, their behaviour in complex nanostructured forms raises new regulatory concerns. Comprehensive toxicological data, especially on long-term biodistribution, immunogenicity, and degradation product interactions, are often lacking. The absence of harmonized global regulatory guidelines for nanomedicines further delays clinical translation and market approval [20].

Cost of production

The use of specialized equipment, stringent processing conditions, and purification steps associated with nanomaterial production contributes to elevated manufacturing costs. This may limit the accessibility of biodegradable nanomedicines, especially in low-resource settings, unless economically viable production strategies are developed.

Future Perspectives

The future of biodegradable nanomaterials in pharmaceutical formulations is promising, with ongoing advancements in materials science, bioengineering, and nanotechnology poised to overcome current limitations and expand their therapeutic applications. Several emerging trends and strategic directions are expected to define the next generation of biodegradable nanomedicines.

Smart and stimuli-responsive systems

The development of stimuli-responsive nanomaterials which degrade or release their payload in response to specific internal (e.g., pH, redox, enzymes) or external (e.g., temperature, magnetic field, ultrasound) triggers offers the potential for highly precise, on-demand drug release. These "smart" systems enable site-specific action and real-time adaptability to pathological environments, improving therapeutic efficacy while minimizing off-target effects.

Advancements in biopolymer engineering

Recent innovations in synthetic biology and polymer chemistry are enabling the creation of novel biopolymers with enhanced functionality, degradation profiles, and targeting capabilities. Engineered polymers such as peptide-based carriers, dendritic polymers, and hybrid nanostructures are under investigation for delivering complex therapeutic agents, including CRISPR components and biologics [21].

Sustainability and green nanotechnology

The alignment of biodegradable nanomaterials with green nanotechnology principles is expected to become a critical factor in pharmaceutical development. Future efforts will likely focus on sourcing raw materials from renewable resources, minimizing energy-intensive synthesis processes, and developing environmentally benign byproducts, thereby reducing the ecological footprint of drug production.

Conclusion

Biodegradable nanomaterials represent a transformative advancement in pharmaceutical formulations, offering sustainable solutions that reconcile therapeutic efficacy with environmental responsibility. Their unique physicochemical properties enable controlled, targeted drug delivery while minimizing systemic toxicity and ecological impact through biocompatible degradation pathways. Despite current challenges related to manufacturing scale-up, formulation stability, regulatory frameworks, and cost, ongoing research and

https://doi.org/10.61577/jnd.2025.100002

technological innovation are rapidly addressing these barriers. Emerging smart materials, personalized delivery approaches, and advances in biopolymer engineering hold great promise for expanding clinical applications. The integration of biodegradable nanomaterials within a regulatory and sustainability-conscious framework will be pivotal in shaping the future of safer, more effective, and environmentally benign therapeutics. Ultimately, these materials are poised to play a crucial role in advancing the global shift towards sustainable pharmaceutical development.

Disclosure Statement

No potential conflict of interest was reported by the author.

References

1. Su S, Kang PM. Systemic review of biodegradable nanomaterials in nanomedicine. Nanomater. 2020;10(4):656. https://doi.org/10.3390/nano10040656
2. Jampilek JO, Kráľová K. Application of nanobioformulations for controlled release and targeted biodistribution of drugs. InNanobiomater. 2018:131-208. https://doi.org/10.1201/9781315204918-5
3. Idrees H, Zaidi SZ, Sabir A, Khan RU, Zhang X, Hassan SU. A review of biodegradable natural polymer-based nanoparticles for drug delivery applications. Nanomater. 2020;10(10):1970. https://doi.org/10.3390/nano10101970
4. Palmerston Mendes L, Pan J, Torchilin VP. Dendrimers as nanocarriers for nucleic acid and drug delivery in cancer therapy. Mol. 2017;22(9):1401. https://doi.org/10.3390/molecules22091401
5. Jiang Z, Song Z, Cao C, Yan M, Liu Z, Cheng X, et al. Multiple natural polymers in drug and gene delivery systems. Curr Med Chem. 2024; 31(13):1691-1715. https://doi.org/10.2174/0929867330666230316094540
6. Kumar A, Vimal A, Kumar A. Why Chitosan? From properties to perspective of mucosal drug delivery. Int. J Biol Macromol. 2016;91:615-622. https://doi.org/10.1016/j.ijbiomac.2016.05.054
7. Ramdhan T, Ching SH, Prakash S, Bhandari B. Physical and mechanical properties of alginate based composite gels. Trends Food Sci Technol. 2020;106:150-159. https://doi.org/10.1016/j.tifs.2020.10.002
8. Xu Y, Kim CS, Saylor DM, Koo D. Polymer degradation and drug delivery in PLGA-based drug–polymer applications: A review of experiments and theories. J Biomed Mater Res B Appl Biomater. 2017;105(6):1692-1716. https://doi.org/10.1002/jbm.b.33648
9. Naseri N, Valizadeh H, Zakeri-Milani P. Solid lipid nanoparticles and nanostructured lipid carriers: structure, preparation and application. Adv Pharm Bull. 2015;5(3):305. https://doi.org/10.15171/apb.2015.043
10. De Anda-Flores Y, Carvajal-Millan E, Campa-Mada A, Lizardi-Mendoza J, Rascon-Chu A, Tanori-Cordova J, et al. Polysaccharide-based nanoparticles for colon-targeted drug delivery systems. Polysaccharides. 2021;2(3):626-647. https://doi.org/10.3390/polysaccharides2030038
11. Gu M, Wang X, Toh TB, Chow EK. Applications of stimuli-responsive nanoscale drug delivery systems in translational research. Drug Discov Today. 2018;23(5):1043-1052. https://doi.org/10.1016/j.drudis.2017.11.009
12. Mangla B, Javed S, Sultan MH, Ahsan W, Aggarwal G, Kohli K. Nanocarriers-assisted needle-free vaccine delivery through oral and intranasal transmucosal routes: A novel therapeutic conduit. Front Pharmacol. 2022;12:757761. https://doi.org/10.3389/fphar.2021.757761
13. Gad A, Kydd J, Piel B, Rai P. Targeting cancer using polymeric nanoparticle mediated combination chemotherapy. Int J Nanomedicine. 2016;2(3):10-6966. https://doi.org/10.16966/2470-3206.116
14. Durymanov M, Reineke J. Non-viral delivery of nucleic acids: Insight into mechanisms of overcoming intracellular barriers. Front Pharmacol. 2018;9:971. https://doi.org/10.3389/fphar.2018.00971
15. Singh AP, Biswas A, Shukla A, Maiti P. Targeted therapy in chronic diseases using nanomaterial-based drug delivery vehicles. Signal Transduct Target Ther. 2019;4(1):33. https://doi.org/10.1038/s41392-019-0068-3
16. Niyom Y, Phakkeeree T, Flood A, Crespy D. Synergy between polymer crystallinity and nanoparticles size for payloads release. J Colloid Interface Sci. 2019;550:139-146. https://doi.org/10.1016/j.jcis.2019.04.085
17. Singh R, Srinivas SP, Kumawat M, Daima HK. Ligand-based surface engineering of nanomaterials: Trends, challenges, and biomedical perspectives. OpenNano. 2024;15:100194. https://doi.org/10.1016/j.onano.2023.100194
18. Rasheed T, Ahmad N, Ali J, Hassan AA, Sher F, Rizwan K, et al. Nano and micro architectured cues as smart materials to mitigate recalcitrant pharmaceutical pollutants from wastewater. Chemosphere. 2021;274:129785. https://doi.org/10.1016/j.chemosphere.2021.129785
19. Roy S, Siddique S, Majumder S, Abdul MI, Rahman SA, Lateef D, et al. A systemic approach on understanding the role of moisture in pharmaceutical product degradation and its prevention: challenges and perspectives. Biomed Res. 2018;29:3336-3343. https://doi.org/10.4066/BIOMEDICALRESEARCH.29-18-978
20. Patel P, Shah J. Safety and toxicological considerations of nanomedicines: the future directions. Curr Clin Pharmacol. 2017; 12(2):73-82. https://doi.org/10.2174/1574884712666170509161252
21. Oksel Karakus C, Bilgi E, Winkler DA. Biomedical nanomaterials: applications, toxicological concerns, and regulatory needs. Nanotoxicol. 2021;15(3):331-351. https://doi.org/10.1080/17435390.2020.1860265

https://doi.org/10.61577/jnd.2025.100002