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Review Article

Polymeric Nanoparticles for Drug Delivery: Design, Applications, and Future Perspectives

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ABSTRACT

Polymeric nanoparticles have emerged as a promising platform in the field of drug delivery due to their ability to enhance the solubility, stability, and bioavailability of therapeutic agents. These nano-sized carriers, typically composed of biodegradable and biocompatible polymers such as PLGA, PEG, and chitosan, offer precise control over drug release kinetics and can be engineered for passive and active targeting. The versatility in design allows encapsulation of a wide range of drugs, including hydrophilic, hydrophobic, and biological molecules. Polymeric nanoparticles also exhibit potential in overcoming physiological barriers, reducing systemic toxicity, and improving therapeutic efficacy. Various surface modification strategies, including PEGylation and ligand attachment, further enhance their circulation time and targeting capability. Recent advancements have led to the development of stimuli-responsive and multifunctional polymeric systems, opening new avenues for personalized and precision medicine. Despite their advantages, challenges related to large-scale production, regulatory approval, and long-term safety must be addressed for successful clinical translation. This review highlights the design principles, fabrication techniques, therapeutic applications, and recent progress in polymeric nanoparticles, along with future perspectives in nanomedicine.

Keywords: Polymeric Nanoparticles, Drug Delivery, Biodegradable Polymers, Targeted Therapy, Controlled Release

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1. Introduction

The development of efficient drug delivery systems has become a central focus in pharmaceutical and biomedical research due to the limitations associated with conventional dosage forms, such as poor solubility, low bioavailability, rapid degradation, and lack of targeted action. Among the advanced delivery systems, polymeric nanoparticles (PNPs) have emerged as a highly versatile and effective platform for delivering a wide range of therapeutic agents.

Polymeric nanoparticles are submicron-sized colloidal systems typically ranging from 10 to 1000 nm in diameter. They are composed of natural or synthetic polymers that are biodegradable and biocompatible, such as poly(lactic-co-glycolic acid) (PLGA), polyethylene glycol (PEG), polylactic acid (PLA), and chitosan. These nanocarriers can encapsulate both hydrophilic and hydrophobic drugs, enabling controlled and sustained release, protection of the drug from premature degradation, and enhanced drug stability during circulation [1-2].

One of the major advantages of polymeric nanoparticles is their tunability in size, surface properties, and drug release profiles, which can be tailored for specific therapeutic needs. Additionally, surface functionalization with targeting ligands allows active targeting of diseased tissues or cells, such as cancer cells, while minimizing off-target effects and toxicity [3].

Polymeric nanoparticles are being widely investigated for a range of applications including cancer therapy, anti-inflammatory drug delivery, central nervous system targeting, oral and ocular drug delivery, and gene and vaccine delivery. Despite their demonstrated potential, challenges such as batch-to-batch reproducibility, large-scale manufacturing, long-term safety, and regulatory approval remain barriers to full clinical translation.

This review aims to provide a comprehensive overview of the design strategies, fabrication methods, therapeutic applications, and future prospects of polymeric nanoparticles in drug delivery [4].

2. Classification and Types of Polymeric Nanoparticles

Polymeric nanoparticles can be classified based on their structural organization, polymer origin, and drug incorporation mechanism. Structurally, they are mainly categorized into nanospheres and nanocapsules. Nanospheres are solid colloidal particles in which the drug is uniformly distributed throughout the polymer matrix. These systems offer controlled and sustained drug release and are particularly suitable for hydrophobic drugs. In contrast, nanocapsules have a core–shell structure, where the drug is confined within a cavity surrounded by a polymeric membrane. This configuration allows better control over drug release kinetics and protection of sensitive therapeutic agents such as peptides or proteins [5].

Another method of classification is based on the type of polymer used. Natural polymers such as chitosan, gelatin, alginate, and dextran are commonly employed due to their excellent biocompatibility, biodegradability, and low immunogenicity. These materials often possess mucoadhesive properties that enhance bioavailability, particularly in mucosal drug delivery routes. However, they may suffer from batch-to-batch variability and lower mechanical strength compared to synthetic alternatives. On the other hand, synthetic polymers like poly(lactic-co-glycolic acid) (PLGA), polylactic acid (PLA), polycaprolactone (PCL), and polyethylene glycol

(PEG) offer reproducible synthesis, well-defined degradation profiles, and tunable physicochemical properties. These features make them more suitable for precise and scalable drug delivery systems, although concerns regarding degradation byproducts and polymer-associated toxicity may arise if not carefully designed [6].

The drug incorporation strategy also influences nanoparticle behavior and performance. In matrix-type nanoparticles, the drug is dispersed or dissolved throughout the polymer matrix, leading to a release pattern that is typically controlled by both diffusion and polymer erosion. In contrast, reservoir-type or core–shell systems encapsulate the drug within a central core, which can be liquid or solid, and the polymeric shell governs the release through diffusion or enzymatic degradation. Understanding these classifications is crucial for selecting the appropriate nanoparticle system tailored to specific therapeutic requirements and biological targets [7-10].

3. Methods of Preparation of Polymeric Nanoparticles

The fabrication method plays a crucial role in determining the physicochemical properties, encapsulation efficiency, particle size, drug release profile, and stability of polymeric nanoparticles. Various methods have been developed depending on the solubility of the polymer and the nature of the drug to be encapsulated. Among the most commonly used techniques are nanoprecipitation, emulsion–solvent evaporation, solvent displacement, salting out, and ionic gelation [10-12].

The nanoprecipitation method, also known as solvent displacement, involves the precipitation of a polymer from an organic solvent into an aqueous solution under moderate stirring. This method is widely used for the preparation of nanoparticles loaded with hydrophobic drugs, and it allows for a simple, reproducible, and scalable process. Emulsion–solvent evaporation is another widely employed technique where the drug and polymer are dissolved in an organic solvent and emulsified in an aqueous phase. Upon solvent evaporation, nanoparticles are formed. This method is suitable for both hydrophilic and hydrophobic drugs and offers high encapsulation efficiency.

The salting out method uses water-miscible organic solvents and salting-out agents to induce polymer precipitation, avoiding the use of high temperatures and making it suitable for thermolabile drugs. The ionic gelation method is primarily used for natural polymers like chitosan and relies on the electrostatic interaction between the polymer and crosslinking agents to form nanoparticles under mild conditions [13-14].

Each method offers distinct advantages and limitations in terms of scalability, reproducibility, and drug-loading capacity. The choice of method must be carefully selected based on the physicochemical properties of the drug and polymer, as well as the intended route of administration and therapeutic application.

Table 1: Common Methods for Preparation of Polymeric Nanoparticles

Method	Key Features	Suitable for	Advantages	Limitations
Nanoprecipitation	Polymer precipitated from organic to aqueous phase	Hydrophobic drugs	Simple, fast, reproducible	Not ideal for hydrophilic drugs
Emulsion–Solvent Evaporation	Drug/polymer in organic solvent emulsified in water	Hydrophilic and hydrophobic drugs	High encapsulation efficiency	Requires use of surfactants and solvent
Solvent Displacement	Polymer dissolved in water-miscible solvent	Lipophilic drugs	Mild conditions, good control of particle size	Limited to certain polymer-solvent pairs
Salting Out	Polymer precipitated using salting-out agents	Thermolabile compounds	Avoids heat and high shear	Requires careful purification
Ionic Gelation	Electrostatic interaction forms nanoparticles	Natural polymers (e.g., chitosan)	Mild, aqueous-based, ideal for biologics	Less control over size and uniformity

4. Therapeutic Applications of Polymeric Nanoparticles

Polymeric nanoparticles have shown tremendous potential in the treatment of various diseases due to their ability to provide controlled drug release, improved pharmacokinetics, and targeted delivery. Their tunable physicochemical properties allow for the incorporation of a wide range of therapeutic agents, including small molecules, proteins, peptides, and nucleic acids [15].

4.1 Cancer Therapy

One of the most extensively explored areas for polymeric nanoparticles is cancer treatment. Nanoparticles enhance the accumulation of anticancer drugs in tumor tissues through passive targeting via the enhanced permeability and retention (EPR) effect, and active targeting through surface modification with tumor-specific ligands. Polymeric nanoparticles loaded with chemotherapeutic agents such as paclitaxel, doxorubicin, and cisplatin have shown improved efficacy and reduced systemic toxicity in preclinical and clinical studies [16].

4.2 Central Nervous System (CNS) Delivery

Delivering drugs across the blood-brain barrier (BBB) remains a major challenge in treating neurological disorders. Polymeric nanoparticles, due to their small size and ability to be functionalized with ligands such as transferrin or lactoferrin, have demonstrated the ability to cross the BBB and deliver drugs to the brain. Applications include the treatment of diseases like Alzheimer's, Parkinson's, and brain tumors [17].

4.3 Antimicrobial and Antiviral Therapy

Polymeric nanoparticles have also been used to enhance the delivery of antibiotics and antiviral agents. Their ability to sustain release and improve drug stability allows for enhanced therapeutic effects and reduced dosing frequency. This is particularly beneficial in combating antibiotic resistance by maintaining consistent drug levels at the infection site [18].

4.4 Ocular and Oral Drug Delivery

In ocular drug delivery, polymeric nanoparticles can prolong residence time on the eye surface and enable better drug penetration into intraocular tissues. For oral delivery, nanoparticles protect drugs from enzymatic degradation in the gastrointestinal tract and enhance intestinal absorption. This is especially important for peptides and poorly soluble drugs.

4.5 Gene and Vaccine Delivery

Recent advancements have extended the application of polymeric nanoparticles to gene and vaccine delivery. These systems protect nucleic acids from degradation, improve cellular uptake, and offer targeted gene expression. Biodegradable polymers such as PLGA and chitosan are commonly used to deliver DNA, siRNA, and mRNA in various gene therapy models and vaccination platforms [19-20].

5. Conclusion

Polymeric nanoparticles have emerged as a promising and versatile platform for drug delivery across a wide range of therapeutic areas. Their tunable size, surface properties, and release profiles allow for efficient encapsulation and targeted delivery of diverse therapeutic agents. Advances in polymer chemistry and nanotechnology have enabled the development of smart, stimuli-responsive, and ligand-targeted systems that enhance therapeutic efficacy while minimizing systemic toxicity.

Despite the significant progress, challenges such as large-scale manufacturing, regulatory approval, and long-term safety must be addressed to fully realize the clinical potential of polymeric nanoparticles. Continued interdisciplinary research combining pharmaceutical sciences, material engineering, and molecular biology will be key to overcoming these hurdles. With ongoing innovation, polymeric nanoparticles are poised to play a central role in the future of precision and personalized medicine.

Conflict of Interest

The authors declare no conflict of interest.

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