Review

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Zhong Lin * and Feng Shi

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Review

Polymeric Nanocarriers for Targeted Therapy: Current Advances and Future Perspectives

Zhong Lin [1,2,*] and Feng Shi [1]

[1] Institute of Biomedical Sciences, Academia Sinica, Taipei City, Taiwan, R.O.C. 115

[2] School of Stomatology, Shandong University, Jinan, China

* Correspondence: tailoredtees2016@gmail.com

Abstract

Polymeric nanomedicine has emerged as a versatile and transformative platform for the delivery of therapeutic agents, offering controlled release, enhanced stability, and targeted delivery across a broad spectrum of medical applications. This review comprehensively discusses the design, functionalization, and therapeutic potential of polymeric nanoparticles, with an emphasis on both natural and synthetic polymers and diverse nanocarrier systems, including nanospheres, nanocapsules, micelles, dendrimers, polymersomes, and nanogels. Advances in surface modification, stimuli-responsive carriers, and multifunctional platforms have enabled precise targeting, improved pharmacokinetics, and reduced off-target toxicity. Key therapeutic applications are explored, spanning cancer therapy, gene therapy, infectious diseases, neurological disorders, and regenerative medicine. The review also addresses challenges in clinical translation, including regulatory hurdles, scalable manufacturing, safety and toxicity considerations, and the design of personalized treatment strategies. Future perspectives highlight the integration of personalized and precision medicine, smart stimuli-responsive polymers, AI/machine learning-driven design optimization, nano-immunotherapy, and hybrid polymeric systems, underscoring their potential to revolutionize global healthcare. By synthesizing current knowledge and outlining translational strategies, this review provides a roadmap for advancing polymeric nanomedicine from bench to bedside, ultimately paving the way for safer, more effective, and patient-specific therapeutic interventions.

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Introduction

Nanomedicine, the application of nanoscale materials and technologies in healthcare, has revolutionized the field of drug delivery [1–3], diagnostics [4–6], and therapeutics [7–9]. Among various nanocarriers, polymeric nanoparticles (PNPs) have emerged as a versatile and highly tunable platform due to their unique physicochemical properties, biocompatibility, and ability to encapsulate diverse therapeutic agents [10]. Polymers, both natural (e.g., chitosan, alginate) and synthetic (e.g., PLGA, PEG, PCL), provide structural stability and can be engineered to achieve controlled release, targeted delivery, and improved pharmacokinetics [11]. These attributes have enabled polymeric nanomedicines to address critical challenges in conventional therapies, such as poor solubility, rapid clearance, off-target toxicity, and multidrug resistance.

Over the past two decades, polymeric nanocarriers have been widely investigated for various applications, including cancer therapy [12], gene delivery [13], infectious disease treatment [14], neurological disorders, and regenerative medicine [15]. Advanced strategies such as surface functionalization, active targeting through ligand-receptor interactions, and stimuli-responsive release have expanded the therapeutic potential of polymeric nanoparticles. Furthermore, the integration of imaging agents within polymeric carriers has facilitated the development of theranostic systems, allowing simultaneous diagnosis and treatment [16].

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Despite significant progress, the translation of polymeric nanomedicines from bench to bedside remains challenging due to biological barriers, potential nanotoxicity, regulatory constraints, and manufacturing limitations [17]. Nonetheless, several polymer-based nanomedicines have achieved clinical approval [8], demonstrating their safety and therapeutic benefits, and numerous candidates are currently undergoing clinical evaluation.

This review provides a comprehensive overview of polymeric nanomedicine, focusing on the design, functionalization strategies, therapeutic and diagnostic applications, clinical translation, challenges, and future perspectives. By critically analyzing current advances and limitations, this paper aims to highlight the potential of polymeric nanocarriers to transform modern healthcare and guide future research toward more efficient and clinically translatable polymeric nanomedicines.

Fundamentals of Polymeric Nanoparticles

Polymeric nanoparticles (PNPs) are broadly classified based on the nature of the polymer into natural and synthetic categories, each offering distinct advantages for biomedical applications. Natural polymers, such as chitosan, alginate, hyaluronic acid, gelatin, and dextran, are derived from biological sources and are inherently biocompatible, biodegradable, and often possess low immunogenicity. For example, chitosan, a cationic polysaccharide, exhibits mucoadhesive properties and can enhance the cellular uptake of drugs and nucleic acids [18]. Hyaluronic acid, a naturally occurring glycosaminoglycan, facilitates active targeting of CD44-overexpressing tumor cells, making it suitable for cancer therapy [19]. The inherent bioactivity of natural polymers can also contribute to tissue regeneration and wound healing applications. However, batch-to-batch variability and limited mechanical stability can restrict their use in certain formulations.

Synthetic polymers, including poly(lactic-co-glycolic acid) (PLGA), polyethylene glycol (PEG), polycaprolactone (PCL), polylactic acid (PLA), and polyanhydrides, offer high structural reproducibility and tunable physicochemical properties. Synthetic polymers can be engineered to achieve precise control over size, surface charge, degradation rate, and drug release kinetics. PLGA, approved by regulatory agencies for clinical use, is widely utilized for sustained and controlled drug delivery [20]. PEG is frequently employed to enhance nanoparticle stability, prolong circulation time, and reduce opsonization [21]. The versatility of synthetic polymers allows for the fabrication of various nanoparticle architectures, including nanospheres, nanocapsules, micelles, dendrimers, and polymersomes, enabling tailored drug delivery and theranostic applications.

The choice between natural and synthetic polymers depends on the intended therapeutic application, desired release profile, and biocompatibility requirements. Increasingly, hybrid systems combining natural and synthetic polymers are being developed to leverage the advantages of both types, improving targeting efficiency, stability, and therapeutic outcomes. Understanding these types of polymeric nanoparticles forms the foundation for designing advanced polymer-based nanomedicines for clinical translation.

Polymeric nanocarriers are versatile vehicles designed to encapsulate, protect, and deliver therapeutic agents with enhanced efficiency, stability, and specificity. These carriers can be broadly classified into nanospheres, nanocapsules, polymeric micelles, dendrimers, polymersomes, and nanogels, each offering unique structural and functional properties that can be tailored for specific biomedical applications.

Nanospheres are solid, spherical polymeric particles in which drugs are uniformly dispersed within the polymer matrix or adsorbed onto the surface [22]. The encapsulation within the dense polymer network allows for controlled and sustained drug release, protection of labile molecules, and improved pharmacokinetics. Nanospheres can be fabricated using natural polymers, such as chitosan and alginate, or synthetic polymers like PLGA and PCL. Their surface can be modified with hydrophilic polymers (e.g., PEG) or targeting ligands to enhance circulation time, reduce immunogenicity, and facilitate site-specific delivery. Nanospheres are particularly useful for delivering poorly water-soluble drugs, peptides, and proteins [23].

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Nanocapsules are core–shell structures in which the drug is confined to a liquid or hollow core surrounded by a polymeric shell [24]. This architecture allows for precise control of drug release and protection of sensitive bioactive molecules. The polymeric shell can be functionalized to respond to stimuli such as pH, temperature, or enzymes, enabling targeted or on-demand release. Nanocapsules are widely employed for anticancer drugs and genetic materials where controlled release and site-specific delivery are critical [25].

Polymeric micelles are self-assembled nanosized structures formed from amphiphilic block copolymers [12]. They consist of a hydrophobic core that solubilizes poorly water-soluble drugs and a hydrophilic shell that stabilizes the micelle in aqueous environments. Micelles are advantageous due to their small size (typically 10 to 100 nm), which facilitates enhanced permeability and retention (EPR) in tumor tissues. PEGylated micelles have shown prolonged circulation times, reduced opsonization, and improved bioavailability. Additionally, stimuli-responsive micelles can release drugs selectively in pathological environments, such as acidic tumor microenvironments [26].

Dendrimers are highly branched, tree-like macromolecules with a central core, interior layers (generations), and multiple surface functional groups [27]. Their unique architecture allows precise control over size, shape, and surface chemistry. Dendrimers can encapsulate drugs in their interior cavities or conjugate them to the surface, enabling high drug-loading efficiency and multifunctionality. Functionalization with targeting ligands or imaging agents allows dendrimers to serve as theranostic platforms for simultaneous therapy and diagnosis. They have been investigated for gene delivery, anticancer therapy, and antiviral applications [27].

Polymersomes are vesicular structures formed from amphiphilic block copolymers, analogous to liposomes but with thicker, more stable polymeric bilayers [28]. They consist of an aqueous core surrounded by a polymeric membrane, allowing encapsulation of both hydrophilic and hydrophobic drugs. The polymeric shell provides mechanical stability, extended circulation, and tunable permeability. Polymersomes can be functionalized with ligands, antibodies, or imaging probes, making them suitable for targeted drug delivery and theranostic applications. Their structural robustness and ability to co-deliver multiple therapeutics offer advantages over conventional liposomal systems [29].

Nanogels are cross-linked, three-dimensional polymeric networks capable of absorbing large amounts of water or biological fluids without dissolving [30]. Their high-water content and soft, deformable structure enhance biocompatibility and allow efficient loading of hydrophilic drugs, proteins, and nucleic acids. Nanogels can be engineered to respond to environmental stimuli, such as pH, temperature, or redox potential, triggering controlled drug release at specific sites. These features make nanogels particularly suitable for localized therapy, gene delivery, and immunomodulation [30].

The diversity of polymeric nanocarriers allows researchers to select or engineer systems based on the physicochemical properties of the therapeutic cargo, target site, and desired release profile. Furthermore, hybrid systems combining multiple polymeric nanocarriers or integrating inorganic components are increasingly being developed to enhance targeting, drug loading, and therapeutic efficacy. Understanding the distinct characteristics and advantages of each nanocarrier type is critical for rational design and optimization of polymeric nanomedicines for clinical translation.

Design and Functionalization Strategies

The therapeutic success of polymeric nanomedicines critically depends on their design and functionalization, which influence circulation time, biodistribution, cellular uptake, and drug release profiles. Rational design involves selecting appropriate polymers, particle architectures, and functionalization strategies to achieve stability, biocompatibility, targeted delivery, and controlled release. Advances in polymer chemistry and nanotechnology have enabled the creation of highly versatile nanocarriers capable of addressing the limitations of conventional therapeutics.

The choice of polymers is fundamental to nanocarrier performance. Natural polymers, such as chitosan, alginate, and hyaluronic acid, offer inherent biocompatibility, biodegradability, and

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bioactivity, making them suitable for drug delivery and tissue engineering. Synthetic polymers, including poly(lactic-co-glycolic acid) (PLGA), polyethylene glycol (PEG), polycaprolactone (PCL), and polylactic acid (PLA), provide tunable physicochemical properties, structural reproducibility, and extended circulation times. Amphiphilic block copolymers enable the formation of self-assembled structures like micelles and polymersomes, which can encapsulate hydrophobic and hydrophilic drugs simultaneously [31].

Nanocarrier architecture also influences drug loading and release. Nanospheres provide uniform drug dispersion within a polymer matrix, ensuring sustained release, whereas nanocapsules with a core–shell structure allow precise control over encapsulated drugs and protection of labile biomolecules. Dendrimers, with their highly branched architecture, offer multiple functional groups for conjugation, enhancing drug-loading capacity and multifunctionality. Polymersomes and nanogels provide additional versatility, supporting co-delivery of multiple therapeutics or genes, and enabling stimuli-responsive release.

Surface modification is a critical strategy for enhancing nanocarrier stability and circulation time by minimizing opsonization and clearance by the mononuclear phagocyte system. Polyethylene glycol (PEG) is commonly grafted onto the nanoparticle surface to create a hydrophilic "stealth" layer, reducing protein adsorption and prolonging systemic circulation [32]. Other hydrophilic polymers, such as poly(vinyl alcohol) or poly(2-oxazoline), can similarly improve colloidal stability and reduce immunogenicity. In addition to stealth properties, surface functionalization can modulate particle charge, size, and hydrophilicity, further influencing biodistribution and cellular interactions.

Targeted delivery enhances therapeutic efficacy while minimizing off-target effects. Passive targeting leverages the enhanced permeability and retention (EPR) effect, in which nanoparticles accumulate preferentially in tumor tissues due to leaky vasculature and impaired lymphatic drainage [33]. Controlling particle size (typically 10-200 nm) and surface charge is essential for optimizing passive accumulation and minimizing renal clearance or hepatic uptake. In contrast, active targeting involves conjugating ligands to the nanoparticle surface that specifically bind to receptors overexpressed on target cells. Common ligands include antibodies, peptides, aptamers, folic acid, and transferrin. For instance, hyaluronic acid-modified nanoparticles target CD44 receptors frequently overexpressed in tumors, improving cellular uptake and therapeutic efficacy. Dual-targeting strategies, where multiple ligands are attached to a single nanoparticle, have also been explored to enhance specificity and overcome tumor heterogeneity.

Stimuli-responsive polymeric nanocarriers enable on-demand or site-specific drug release by responding to environmental cues [34]. pH-responsive systems exploit the acidic tumor microenvironment or endosomal compartments to trigger drug release through cleavage of acid-labile bonds or polymer swelling. Redox-responsive systems utilize intracellular glutathione gradients to break disulfide linkages, releasing therapeutic cargo selectively inside cells [35]. Enzyme-responsive polymers degrade in the presence of specific enzymes, while temperature-, light-, or magnetic-responsive systems provide external control over drug release. By incorporating these stimuli-sensitive features, polymeric nanomedicines can achieve higher therapeutic index and reduced systemic toxicity.

Modern polymeric nanomedicines often integrate multiple functionalities into a single platform. Co-delivery systems simultaneously transport drugs and genetic materials or combinations of chemotherapeutics to achieve synergistic effects [36]. Theranostic polymeric nanoparticles combine therapeutic and diagnostic functionalities by incorporating imaging agents (fluorescent dyes, MRI contrast agents, radionuclides) alongside drugs, enabling real-time monitoring of biodistribution and therapeutic response [37]. Dendrimers, micelles, and polymersomes are particularly suitable for such multifunctional applications due to their modular architecture and high surface functionalization capacity.

Covalent and non-covalent conjugation strategies are central to the functionalization of polymeric nanomedicines. Covalent drug conjugation can improve stability and control release kinetics via cleavable linkers [15]. Non-covalent approaches, such as hydrophobic interactions,

 doi:10.20944/preprints202508.1610.v1

electrostatic adsorption, or host–guest chemistry, facilitate loading of drugs, nucleic acids, or imaging agents without compromising bioactivity. Surface conjugation of targeting ligands, PEG chains, or stimuli-sensitive moieties further enhances nanoparticle performance.

Optimizing polymeric nanomedicine requires careful consideration of particle size, shape, surface chemistry, drug loading efficiency, release profile, and biocompatibility. Advanced computational tools and high-throughput screening methods are increasingly employed to predict nanoparticle behavior and streamline design. The integration of artificial intelligence and nanoinformatics can further enhance the rational design of polymeric nanomedicines, enabling personalized and precision therapeutic approaches.

In summary, the design and functionalization of polymeric nanomedicine are multifaceted processes that combine polymer chemistry, nanotechnology, and biological engineering. By selecting appropriate polymers, optimizing particle architecture, and incorporating surface functionalization, targeting, and stimuli-responsive features, polymeric nanocarriers can achieve precise delivery, enhanced therapeutic efficacy, and reduced systemic toxicity. These strategies continue to evolve, paving the way for the next generation of clinically translatable and multifunctional polymer-based therapeutics.

Therapeutic Applications

Polymeric nanomedicines have emerged as transformative tools in modern therapeutics, offering targeted delivery, controlled release, and enhanced stability of bioactive agents. Their versatility spans various medical domains, including cancer therapy, gene therapy, infectious diseases, neurological disorders, and regenerative medicine.

Polymeric nanoparticles (PNPs) have revolutionized cancer treatment by improving the pharmacokinetics and biodistribution of chemotherapeutic agents. For instance, PLGA-based nanoparticles have been utilized to encapsulate hydrophobic drugs like ifosfamide, enhancing their solubility and prolonging circulation time [38]. Additionally, the incorporation of targeting ligands, such as folic acid or antibodies, facilitates selective delivery to tumor cells, reducing off-target effects. Theranostic PNPs, which combine therapeutic and diagnostic functions, enable real-time monitoring of treatment efficacy, paving the way for personalized cancer therapies [16].

Gene delivery remains a challenging aspect of molecular medicine. Polymeric carriers, particularly cationic polymers like polyethylenimine (PEI) and poly(lactic-co-glycolic acid) (PLGA), have been extensively studied for their ability to condense nucleic acids and facilitate cellular uptake [36]. Surface modifications with targeting moieties, such as aptamers or antibodies, enhance specificity to diseased tissues, improving transfection efficiency and therapeutic outcomes. Moreover, stimuli-responsive polymers that degrade in response to environmental cues offer controlled release of gene payloads, minimizing potential side effects.

The rise of antimicrobial resistance necessitates innovative approaches in treating infections. Polymeric nanocarriers can encapsulate antimicrobial agents, protecting them from degradation and enhancing their stability. Additionally, PNPs can be engineered to release their payloads in response to specific stimuli, ensuring targeted action at infection sites. For example, pH-sensitive PNPs can release antibiotics in the acidic environment of infected tissues, improving therapeutic efficacy.

The blood-brain barrier (BBB) poses a significant challenge in delivering therapeutics to the central nervous system. Polymeric nanoparticles, due to their nanoscale size and surface modifiability, can traverse the BBB via receptor-mediated transcytosis or endocytosis [39]. Surface functionalization with ligands such as transferrin or apolipoprotein E enhances targeting to brain cells. For instance, PLGA nanoparticles conjugated with transferrin have shown improved delivery of neuroprotective agents in models of Alzheimer's disease.

Polymeric nanomaterials play a pivotal role in tissue engineering and regenerative medicine by providing scaffolds that mimic the extracellular matrix, promoting cell adhesion, proliferation, and differentiation. Hydrogels and nanofiber meshes, composed of biodegradable polymers like PLGA or polycaprolactone (PCL), serve as matrices for stem cell delivery and tissue repair [21].

 doi:10.20944/preprints202508.1610.v1

Furthermore, PNPs can be loaded with growth factors or cytokines, offering sustained release and localized delivery, which enhances tissue regeneration and healing processes [40].

Polymeric nanomedicines have demonstrated significant promise across various therapeutic areas. Their ability to encapsulate diverse therapeutic agents, target specific tissues, and respond to environmental stimuli positions them at the forefront of modern medicine. Continued research and development are essential to overcome existing challenges and fully realize the potential of polymeric nanomedicines in clinical applications.

Clinical Translation of Polymeric Nanomedicine

Polymeric nanomedicines have shown significant promise in preclinical studies across various therapeutic areas. However, translating these innovations from the laboratory to clinical practice remains a complex and multifaceted challenge. This section delves into the key hurdles impeding the clinical translation of polymeric nanomedicines and discusses strategies to overcome these barriers.

One of the foremost challenges in the clinical translation of polymeric nanomedicines is navigating the regulatory landscape. The unique physicochemical properties of nanoparticles, such as size, shape, surface charge, and composition, necessitate tailored regulatory guidelines. Current regulatory frameworks often lack specific provisions for nanomedicines, leading to uncertainties in approval processes. For instance, while liposomal formulations like Doxil® have gained approval, many other nanoparticle-based therapies face prolonged evaluation periods due to the absence of standardized protocols.

The synthesis of polymeric nanoparticles often involves complex and labor-intensive processes, which can be challenging to scale for commercial production. Variability in batch-to-batch consistency, purity, and reproducibility can affect the quality and safety of the final product. For example, the production of polymeric micelles requires precise control over parameters like polymer concentration and solvent evaporation rates. Such intricacies complicate the transition from laboratory-scale synthesis to large-scale manufacturing, posing significant hurdles for clinical application.

Despite their design to overcome biological barriers, polymeric nanomedicines often encounter challenges in vivo [41]. The reticuloendothelial system (RES) can rapidly clear nanoparticles from circulation, reducing their therapeutic efficacy. Additionally, the blood-brain barrier (BBB) presents a formidable obstacle for delivering therapeutics to the central nervous system. Strategies such as surface modification with polyethylene glycol (PEG) or targeting ligands have been employed to enhance circulation time and specificity. However, these modifications can sometimes lead to immunogenic responses or reduced cellular uptake, complicating their clinical application.

The biocompatibility and long-term safety of polymeric nanomedicines are critical considerations. Accumulation of nanoparticles in organs like the liver and spleen can lead to toxicity. Furthermore, degradation products of biodegradable polymers may elicit inflammatory responses. For instance, poly(lactic-co-glycolic acid) (PLGA) nanoparticles degrade into lactic and glycolic acids, which, if not properly metabolized, can cause acidosis. Comprehensive preclinical studies assessing biodistribution, pharmacokinetics, and potential immunogenicity are essential to ensure the safety of polymeric nanomedicines.

Designing clinical trials for nanomedicines presents unique challenges due to the heterogeneity of nanoparticle formulations and patient populations. Variations in nanoparticle size, surface charge, and drug loading can lead to inconsistent therapeutic outcomes. Moreover, patient-specific factors such as genetic makeup, disease stage, and concurrent medications can influence the efficacy and safety of nanomedicines. Therefore, personalized approaches and biomarker-driven patient stratification are crucial for optimizing clinical trial designs and ensuring the success of polymeric nanomedicines in clinical settings.

The development of polymeric nanomedicines involves intricate formulations and novel technologies, raising concerns regarding intellectual property (IP) rights. Securing patents for unique nanoparticle designs and manufacturing processes is essential to protect innovations. However, the

 doi:10.20944/preprints202508.1610.v1

complex nature of nanomedicines can make patenting challenging, potentially hindering investment and commercialization efforts. Collaborations between academia, industry, and regulatory bodies are vital to navigate the IP landscape and facilitate the successful commercialization of polymeric nanomedicines.

The clinical translation of polymeric nanomedicines is fraught with challenges spanning regulatory, manufacturing, biological, safety, clinical, and commercial domains. Addressing these barriers requires a concerted effort from researchers, clinicians, regulatory agencies, and industry stakeholders. By establishing standardized guidelines, developing scalable manufacturing processes, conducting rigorous safety evaluations, designing personalized clinical trials, and navigating the IP landscape, the path from bench to bedside for polymeric nanomedicines can be significantly improved. Continued interdisciplinary collaboration and innovation are essential to realize the full potential of polymeric nanomedicines in clinical practice.

Future Perspectives

Polymeric nanomedicine stands at the forefront of transformative healthcare, with emerging advancements poised to redefine therapeutic strategies. The integration of personalized approaches, intelligent materials, and cutting-edge technologies heralds a new era in precision medicine. The era of one-size-fits-all treatments is giving way to personalized therapies tailored to individual genetic, molecular, and physiological profiles. Polymeric nanomedicines enable the customization of drug delivery systems, enhancing therapeutic efficacy and minimizing adverse effects. For instance, nanocarriers can be engineered to respond to specific biomarkers, ensuring targeted delivery to diseased tissues while sparing healthy ones. This precision approach not only improves treatment outcomes but also paves the way for individualized treatment regimens, particularly in complex diseases like cancer and genetic disorders.

Advancements in smart polymers have led to the development of next-generation stimuli-responsive carriers capable of responding to specific internal or external triggers such as pH, temperature, light, or enzymatic activity. These intelligent materials allow for precise control over drug release, enhancing therapeutic efficacy and reducing systemic toxicity. For example, semiconducting polymer nano-regulators have been designed to activate upon specific stimuli, enabling targeted drug release and minimizing off-target effects.

The convergence of artificial intelligence (AI) and machine learning (ML) with nanomedicine is revolutionizing the design and optimization of polymeric nanocarriers. AI/ML algorithms can analyze vast datasets to predict the most effective formulations, optimize synthesis processes, and anticipate biological interactions. This data-driven approach accelerates the development of novel nanomedicines, enhances reproducibility, and facilitates the translation of laboratory findings into clinical applications.

Polymeric nanomedicines are increasingly being explored in the realm of immunotherapy. Polymeric systems can deliver immunomodulatory agents, vaccines, or immune checkpoint inhibitors, enhancing the body's immune response against tumors. For instance, polymeric nanoparticles have been utilized to deliver cancer vaccines, improving their stability and immune activation.

Furthermore, hybrid systems combining polymers with lipids or inorganic materials are gaining traction. Polymer-lipid hybrid nanoparticles offer improved stability, controlled release, and the ability to encapsulate a broader range of therapeutic agents. Similarly, polymer-inorganic hybrid systems can provide multifunctionality, such as magnetic targeting or enhanced imaging capabilities, broadening the scope of therapeutic applications. The advancements in polymeric nanomedicine hold significant promise for global healthcare. By enabling targeted and efficient delivery of therapeutics, these innovations can improve treatment outcomes, reduce healthcare costs, and increase accessibility to advanced therapies, particularly in resource-limited settings. For example, nanomedicine has the potential to address global health challenges such as infectious diseases and cancer by providing more effective and affordable treatment options.

 doi:10.20944/preprints202508.1610.v1

In conclusion, the future of polymeric nanomedicine is characterized by personalized therapies, intelligent materials, and the integration of advanced technologies. These developments are set to revolutionize the treatment landscape, offering more effective, targeted, and accessible healthcare solutions worldwide.

Conclusions

Polymeric nanomedicine has emerged as a transformative platform in modern healthcare, offering versatile and tunable strategies for the delivery of therapeutics across a wide range of medical conditions. Over the past two decades, significant advances have been made in the design, functionalization, and application of polymeric nanocarriers, positioning them as a promising alternative to conventional drug delivery systems. Key developments include the engineering of natural and synthetic polymers into nanospheres, nanocapsules, micelles, dendrimers, polymersomes, and nanogels, each tailored to optimize drug loading, stability, and controlled release. Surface functionalization strategies, such as PEGylation and ligand conjugation, have enhanced circulation time, biocompatibility, and active targeting, while stimuli-responsive and smart polymeric systems have enabled precise, on-demand drug release.

Therapeutically, polymeric nanomedicines have demonstrated remarkable potential across cancer therapy, gene therapy, infectious diseases, neurological disorders, and regenerative medicine. In cancer, polymeric carriers improve solubility, reduce off-target toxicity, and enable targeted and theranostic applications. Gene delivery has benefited from cationic polymers and stimuli-responsive systems, facilitating cellular uptake and precise release. Polymeric nanoparticles have also enhanced the efficacy of antimicrobial therapies and immunomodulation strategies, while enabling crossing of biological barriers such as the blood-brain barrier for neurological treatments. In regenerative medicine, polymeric nanocarriers provide scaffolds and controlled growth factors, improving tissue repair and stem cell therapies.

The clinical translation of polymeric nanomedicines remains a complex but achievable goal. Key challenges include regulatory hurdles, scalable manufacturing, biological barriers, safety and toxicity assessments, and individualized patient responses. Despite these obstacles, several polymer-based therapeutics, including PLGA- and PEG-based nanoparticles, have achieved clinical approval, demonstrating the feasibility of translating nanomedicine from bench to bedside. Strategies such as standardized manufacturing protocols, rigorous preclinical testing, and biomarker-guided patient stratification are critical for successful clinical adoption.

Looking ahead, the future of polymeric nanomedicine is highly promising. Personalized and precision nanomedicine, smart stimuli-responsive carriers, and AI-driven design optimization are expected to further enhance therapeutic efficacy and minimize side effects. Emerging areas, including polymeric nano-immunotherapy and hybrid systems (polymer-lipid or polymer-inorganic), offer multifunctional platforms for targeted therapy and real-time monitoring. Collectively, these advances have the potential to reshape clinical practice by providing safer, more effective, and patient-specific treatment options.

In summary, polymeric nanomedicine represents a convergence of material science, molecular biology, and nanotechnology that holds transformative potential for global healthcare. By building on the current advances, addressing translational challenges, and embracing innovative design strategies, polymeric nanomedicine is poised to become an integral component of precision medicine. The roadmap toward widespread clinical adoption involves continued interdisciplinary collaboration, regulatory harmonization, and commitment to safety and efficacy, ultimately enabling a new era of targeted, efficient, and accessible therapeutics for diverse patient populations worldwide.

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