



Recent Advancements in Functional Nanomaterials for Drug Delivery Systems: An Overview

Ritik R Jamgade ^{1*}, Tina G Shete ², Neha P Sharnagate ³, Rampal P Jadhao ⁴, Sakshi V Bhope ⁵, Sapna U Patel ⁶

¹ Research Scholar, Priyadarshini J. L. College of Pharmacy Nagpu-440016, India

² Assistant Professor, Dr. R.G. Bhoyar Institute of Pharmaceutical Education and Research, Wardha- 442001, India

³ Student, Priyadarshini J.L. College of Pharmacy, Nagpur- 440016, India

⁴ Assistant Professor, Sudhakar Rao Naik Institute of Pharmacy, Pusad- 445204, India

^{5, 6} Assistant Professor, KDK College of Pharmacy and Research Institute, Nagpur- 440024, India

* Corresponding Author: Ritik R Jamgade

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Abstract

Nanotechnology is crucial in electronics, life sciences, and medical sciences. Its applications can be assessed as they involve materials' atomic and molecular design. Nanomaterials have proven to be effective drug delivery agents due to their distinctive morphology, making them valuable for encapsulating pharmaceuticals and enabling precise targeting with controlled drug release. The complexity of certain diseases and the inherent toxicity of some drugs have driven interest in developing and refining drug delivery systems. Due to their adaptability, nanomaterials offer a promising solution for tailoring drug delivery systems to specific needs, improving biocompatibility, and ensuring targeted distribution at active sites. This review highlights recent advancements in functional nanomaterials for drug delivery systems, focusing on those that have demonstrated therapeutic efficacy in human studies. It provides insights into nanocarriers and drug release mechanisms based on both in vitro and in vivo results. Additionally, it explores the advantages and limitations of various nanomaterial types, including polymeric, lipid-based, and inorganic-based systems.

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Introduction

For centuries, humans have relied on the natural world, particularly plants, to develop treatments for various ailments. This practice remains relevant today, with approximately one-quarter of essential medications derived from natural sources. These plant-based compounds provide a foundation for discovering and developing innovative drugs due to their diverse molecular structures and biological properties. Recently, there has been growing interest in synthetic compounds of gold (Au), silver (Ag), silica (Si), and iron (Fe), which resemble their natural counterparts in chemical composition and have potential applications in drug discovery based on natural products or materials ^[1, 2, 3, 4]. Natural compounds are distinguished by their unique chemical structures, biological specificity, availability, and low toxicity.

Nanotechnology in drug delivery

Nanotechnology has revolutionized drug delivery by enabling the synthesis of nanoparticles with distinct physical and chemical properties, significantly improving drug efficacy. The transition from micron-scale to nanometer-scale drug formulations has enhanced therapeutic performance by increasing drug activity and reducing toxicity ^[5]. Historically, drug delivery system development involved extensive trial and error, making the process slow, costly, and inefficient. The advent of artificial intelligence (AI) and machine learning has transformed this approach by allowing researchers to analyze vast datasets, identify patterns, and optimize drug delivery systems.

The role of artificial intelligence in drug delivery

The integration of AI in drug development offers several advantages:

- **Virtual Prototyping:** Computer simulations enable rapid evaluation of various drug delivery systems, saving time and resources.
- **Optimized Design:** AI models analyze data to determine the most effective materials and configurations for targeted drug delivery, enhancing therapeutic benefits while minimizing side effects.
- **Personalized Medicine:** AI facilitates the customization of drug delivery methods to suit individual patient needs, improving treatment efficacy [6, 7].

Computational and experimental studies have contributed to novel drug innovations, including nanomaterial-based drug discovery and delivery, which consider molecular interactions. However, pharmaceutical companies often prioritize synthetic chemical compounds over natural products due to cost and feasibility concerns. Nevertheless, natural substances continue to be investigated for treating severe conditions such as cancer, HIV, diabetes, and microbial infections due to their lower toxicity and therapeutic potential [7, 8]. Despite their advantages, challenges remain in ensuring biocompatibility and managing toxicity.

Experimental and computational approaches

While experimental approaches to synthesizing and optimizing nanomaterials have improved, practical constraints persist. Structural resolution is often challenging, and modifying attributes like composition, size, and surface charge can be costly and time-consuming. As a result, achieving an optimal drug delivery system remains complex. Experimental studies remain vital, as they provide crucial insights into drug behavior, material interactions, and biological responses [9].

Many promising drug delivery systems perform well in vitro but fail in vivo due to limited mechanistic understanding and reliance on empirical methods. Computational modeling offers a solution by providing detailed molecular interaction data, aiding in the rational design of nanocarriers and pharmaceuticals [10].

Controlled drug release systems

The increasing complexity of diseases and drug toxicity necessitates innovative drug delivery methods. Controlled drug release systems regulate dosage, concentration, timing, and release at the active site to maximize efficacy and safety. Unlike immediate drug release, controlled-release mechanisms maintain therapeutic concentrations over extended periods [11]. Since the 1980s, micellar solutions and other nanocarriers have been explored for controlled drug delivery. Designing such systems requires consideration of drug chemistry and the physiological properties of target organs, such as their ability to penetrate biological barriers [12]. Various drug administration routes, including oral, intravenous, and intraperitoneal methods, each have their limitations [13], with systemic delivery often leading to toxicity and requiring high doses for effectiveness.

Central nervous system drug delivery

Central nervous system (CNS) therapies face challenges in achieving therapeutic drug levels. Systemic administration is preferred for ease of use but often results in low CNS concentrations. Localized drug delivery, though more invasive, may be necessary for effective treatment. Modern

drug delivery systems focus on controlled release and targeted delivery to reduce systemic side effects and enhance drug bioavailability [14].

The role of nanotechnology in drug bioavailability

Nanotechnology plays a pivotal role in improving drug bioavailability by enhancing solubility and facilitating membrane permeability. By modifying nanomaterial parameters, drug release can be precisely controlled to maintain therapeutic levels [15]. Additionally, nanocarriers support combination therapies by incorporating multiple active substances. Advances in nanotechnology have also improved the efficacy of biological treatments and immunotherapies, allowing for targeted gene and protein-based drug delivery. Functionalized nanomaterials can precisely locate and act on disease sites, minimizing adverse effects [16]. This capability has significant diagnostic applications, enabling targeted transport and release of therapeutic agents with enhanced solubility and biological compatibility [17].

Materials for nanocarriers

The development of nanomaterial-based drug delivery systems requires selecting biocompatible, degradable, and non-immunogenic materials. Polymers are particularly useful, as their properties can be tailored by selecting appropriate monomers [18].

Types of nanomaterials in drug delivery

This review explores recent advancements in nanomaterials for drug delivery, with a focus on polymeric, lipid-based, and inorganic nanomaterials. Table 1 and Table 2 summarize relevant literature, while Fig. 4 illustrates various nanocarrier applications [19, 20, 21].

Polymeric-based nanomaterials

Polymer-based nanoparticles are widely researched for drug delivery due to their biodegradability and ability to enhance drug bioavailability. These materials address limitations in conventional dosing systems by offering targeted and controlled drug release [6].

Lipid-based nanomaterials

Lipid-based nanomaterials, including phospholipids and liposomes, self-assemble into bilayers and serve as effective nanocarriers for drug delivery [45].

Inorganic-based nanomaterials

Inorganic nanoparticles, such as silica, quantum dots, and iron oxide nanoparticles, enable targeted drug accumulation at disease sites, improving treatment efficacy while minimizing damage to healthy tissues [6, 7].

Toxicity Considerations

Nanomaterials are widely used in diagnostics, drug delivery, and organ regeneration, but concerns remain regarding their safety. Smaller particles tend to be more toxic than their larger counterparts due to their potential to elicit immune responses. Spherical nanomaterials are generally less toxic than other shapes.

Future Perspectives

Nanomaterial-based approaches offer promising alternatives to traditional antibiotics in combating drug-resistant bacteria. While these materials cannot completely replace antibiotics, they provide complementary strategies that enhance antibacterial treatments. Ongoing research aims to refine

nanomaterials for broader biomedical applications, with the ultimate goal of improving drug efficacy and reducing side effects.

Conclusion

The development of nanomaterials has transformed drug delivery systems, enhancing therapeutic efficacy and minimizing toxicity. AI and computational modeling further accelerate drug discovery, enabling virtual prototyping and personalized treatment strategies. Despite these advancements, challenges such as toxicity, biocompatibility, and large-scale manufacturing must be addressed. Future research should focus on optimizing nanomaterial properties, improving targeted delivery mechanisms, and ensuring the safety of these innovations. By overcoming these hurdles, nanotechnology will continue to play a pivotal role in modern medicine, offering groundbreaking solutions for treating complex diseases.

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