

# Nanotechnology-Based Drug Delivery: A Modern Approach in Pharmaceutical Sciences

<sup>1</sup>Dr S.K. Verma, <sup>2</sup>Ritu Suryavanshi, <sup>3</sup>Dr K.K. Daryani

*1. Professor E-Meritus, Deptt. Of Anatomy, Sukh Sagar Medical College, Jabalpur M.P.*

*2. Lecturer, DBM College of Pharmacy, Champa, C.G.*

*3. Professor E-Meritus, Deptt. Of Pharmacology, Sukh Sagar Medical College, Jabalpur M.P.*

*Corresponding Author: Dr Siddharth Verma, Associate Professor, CSSCP, Prayagraj, U.P.*

Date of Submission: 01-09-2025

Date of Acceptance: 10-09-2025

## ABSTRACT

Drug delivery remains a critical challenge in pharmaceutical sciences due to the inherent limitations of conventional dosage forms. Traditional tablets, capsules, and injectable formulations often suffer from poor solubility, limited bioavailability, rapid metabolism, and lack of site specificity, leading to reduced therapeutic outcomes and increased side effects. Over the past three decades, nanotechnology has emerged as a promising platform to overcome these limitations. Nanotechnology-based drug delivery systems (NDDS) utilize carriers at the nanoscale (1–100 nm) to enhance solubility, improve pharmacokinetics, achieve targeted delivery, and minimize systemic toxicity.

This review article explores the fundamental principles of nanotechnology in drug delivery, classification of nanocarriers, and their mechanisms of action. It highlights liposomes, niosomes, polymeric nanoparticles, dendrimers, nanoemulsions, solid lipid nanoparticles (SLNs), nanostructured lipid carriers (NLCs), carbon nanotubes, and metallic nanoparticles. The advantages of NDDS—such as improved patient compliance, sustained release, and targeted therapy—are compared with their limitations, including stability issues, high production costs, and regulatory hurdles.

Current applications are discussed with case studies in oncology (Doxil®, Abraxane®), neurology (nanoparticles for blood–brain barrier crossing), infectious diseases (Amphotericin B lipid formulations), and vaccine technology (COVID-19 mRNA vaccines using lipid nanoparticles). The review also explores future prospects, including theranostics, personalized nanomedicine, and AI-assisted nanocarrier design.

Overall, nanotechnology represents a transformative advancement in pharmaceutical sciences, with the potential to revolutionize therapy across multiple disease areas. Continuous research,

standardized regulatory guidelines, and careful toxicity assessments will be critical in realizing the full clinical potential of NDDS.

## I. INTRODUCTION

The success of a drug in treating disease depends not only on its pharmacological activity but also on how effectively it reaches the intended site of action in the body. Traditional drug delivery systems, such as tablets, capsules, injections, and topical formulations, are widely used because of their simplicity and cost-effectiveness. However, these dosage forms face significant drawbacks. Many drugs exhibit poor solubility, which leads to low absorption in the gastrointestinal tract. Some drugs are rapidly metabolized by the liver (first-pass effect), reducing their therapeutic concentrations in systemic circulation. Others may distribute non-specifically throughout the body, causing toxicity in healthy tissues.

To address these issues, researchers have explored advanced drug delivery strategies, and one of the most promising among them is nanotechnology. Nanotechnology deals with the manipulation of matter at the nanoscale (1–100 nanometers), where unique physicochemical properties emerge. Materials at this scale exhibit altered solubility, surface charge, and reactivity compared to their bulk counterparts, making them suitable for novel biomedical applications.

The concept of using nanosized carriers in drug delivery was introduced in the 1970s with the development of liposomes. Since then, the field has expanded significantly, and today, nanotechnology has been successfully applied in cancer therapy, infectious disease management, neurological disorders, and vaccine formulations. The growing global nanomedicine market reflects its increasing acceptance, with several nano-formulations already approved for clinical use.

This review aims to provide pharmacy students and researchers with an overview of

nanotechnology-based drug delivery systems (NDDS), their principles, classification, advantages, limitations, and real-world applications. It also highlights future directions in this exciting area of pharmaceutical research.

## II. PRINCIPLES OF NANOTECHNOLOGY IN DRUG DELIVERY

Nanotechnology involves designing carriers in the size range of 1–100 nm. At this nanoscale, materials exhibit properties that are not observed at the macroscopic level. These include:

- **Enhanced Surface Area-to-Volume Ratio:** Smaller particles have greater surface area, increasing drug loading and interaction with biological membranes.
- **Improved Solubility:** Nanoparticles can improve the solubility of poorly water-soluble drugs, enhancing absorption.
- **Controlled and Sustained Release:** Drugs can be encapsulated or bound to nanoparticles, enabling controlled release over time.
- **Targeted Delivery:** Nanocarriers can be engineered to accumulate in specific tissues either by passive targeting (Enhanced Permeability and Retention, or EPR effect, common in tumors) or active targeting (using ligands, antibodies, or peptides).
- **Ability to Cross Biological Barriers:** Some nanocarriers can cross challenging barriers like the blood–brain barrier (BBB), opening new possibilities in neurological therapy.

### MECHANISMS OF DRUG RELEASE FROM NANOCARRIERS

- **Diffusion:** Drug molecules slowly diffuse out of the carrier matrix.
- **Degradation:** Biodegradable polymers gradually break down, releasing the drug.
- **Stimuli-Responsive Release:** Release triggered by pH, temperature, enzymes, or external signals (e.g., light, magnetic field).

## III. CLASSIFICATION OF NANOTECHNOLOGY-BASED DRUG DELIVERY SYSTEMS

Nanocarriers can be classified based on their composition, structure, and drug-loading method.

### 3.1 Liposomes

Liposomes are spherical vesicles composed of phospholipid bilayers surrounding an

aqueous core. They can encapsulate both hydrophilic (in the core) and hydrophobic drugs (in the bilayer). Liposomes improve drug stability, reduce toxicity, and allow controlled release. Example: Doxil® (liposomal doxorubicin), approved for ovarian cancer and Kaposi's sarcoma.

### 3.2 Niosomes

Niosomes are similar to liposomes but made of non-ionic surfactants, making them more stable and cost-effective. They are widely explored in cosmetics and transdermal drug delivery.

### 3.3 Polymeric Nanoparticles

Made from biodegradable polymers like PLA (polylactic acid) and PLGA (polylactic-co-glycolic acid), these nanoparticles provide sustained release and biocompatibility. Drugs can be entrapped inside or adsorbed on the surface.

### 3.4 Metallic Nanoparticles

Gold and silver nanoparticles are widely studied for imaging and photothermal therapy. Gold nanoparticles, for instance, can convert light energy into heat, making them useful in cancer treatment.

### 3.5 Nanoemulsions

Nanoemulsions are oil-in-water or water-in-oil dispersions stabilized by surfactants. They enhance the solubility and bioavailability of hydrophobic drugs.

### 3.6 Dendrimers

Dendrimers are highly branched, tree-like macromolecules with multiple functional groups. They allow multivalent drug conjugation and are promising for gene and peptide delivery.

### 3.7 Solid Lipid Nanoparticles (SLNs) and Nanostructured Lipid Carriers (NLCs)

SLNs consist of solid lipids, while NLCs are mixtures of solid and liquid lipids. They combine the benefits of liposomes and polymeric nanoparticles, offering high stability and controlled drug release.

### 3.8 Carbon Nanotubes (CNTs)

CNTs are cylindrical nanostructures composed of carbon. They have unique electrical and mechanical properties and can carry drugs, proteins, or genes. However, toxicity concerns remain.

**TABLE 1. CLASSIFICATION OF NANOCARRIERS WITH EXAMPLES**

Nanocarrier	Composition	Examples	Applications
Liposomes	Phospholipid bilayers	Doxil®	Cancer therapy
Niosomes	Non-ionic surfactants	Cosmetic products	Transdermal delivery
Polymeric nanoparticles	PLA, PLGA polymers	Genexol-PM®	Sustained release
Metallic nanoparticles	Gold, silver, iron oxide	AuNPs, AgNPs	Imaging, photothermal therapy
Nanoemulsions	Oil, surfactants, water	Vitamin E emulsion	Oral, topical drug delivery
Dendrimers	Branched polymers	PAMAM dendrimers	Gene delivery, peptide transport
SLNs & NLCs	Solid + liquid lipids	Various formulations	Oral/IV drug delivery
Carbon Nanotubes (CNTs)	Carbon cylinders	CNT conjugates	Gene delivery (experimental)

**IV. ADVANTAGES VS. LIMITATIONS**

**Advantages of NDDS**

- Improved solubility and bioavailability
- Targeted delivery to specific sites
- Sustained and controlled release
- Reduction in dose frequency
- Reduced systemic side effects
- Possibility of crossing biological barriers
- Enhanced patient compliance

**Limitations of NDDS**

- High production and development cost
- Stability issues during storage
- Scale-up difficulties in manufacturing
- Regulatory challenges and lack of standardized guidelines
- Potential long-term toxicity and unknown safety concerns
- Limited availability of suitable excipients

TABLE 2. ADVANTAGES VS. LIMITATIONS

Table 2. Advantages vs. Limitations	
Advantages	Limitations
High bioavailability	High cost of production
Targeted and sustained release	Regulatory hurdles
Reduced toxicity	Stability issues
Improved compliance	Scale-up challenges
Can cross BBB	Potential long-term toxicity

## V. CURRENT APPLICATIONS WITH CASE STUDIES

### 5.1 Cancer Therapy

Cancer treatment requires selective targeting of tumor cells while sparing healthy tissues. Liposomal doxorubicin (Doxil®) is one of the most successful nanomedicine formulations, providing targeted delivery and reduced cardiotoxicity. Another example is Abraxane® (albumin-bound paclitaxel nanoparticles), which enhances solubility and reduces the need for toxic solvents.

### 5.2 Neurological Disorders

The blood–brain barrier (BBB) is a major obstacle for CNS drug delivery. Nanocarriers such as polymeric nanoparticles and liposomes can cross the BBB, enabling treatment of diseases like Alzheimer’s and Parkinson’s. Research on curcumin-loaded nanoparticles has shown promise in improving memory and reducing neuroinflammation.

### 5.3 Infectious Diseases

Lipid-based formulations of Amphotericin B (e.g., Ambisome®) have significantly reduced the nephrotoxicity associated with conventional formulations. Silver nanoparticles also show antimicrobial activity against resistant bacteria.

### 5.4 Vaccines

Nanoparticles play a pivotal role in vaccine delivery. The Pfizer-BioNTech and Moderna COVID-19 vaccines used lipid nanoparticles to deliver mRNA encoding the spike protein, demonstrating how nanotechnology can transform global healthcare.

### 5.5 Dermatology and Cosmetics

Nanoemulsions and liposomes are used in sunscreens, moisturizers, and anti-aging creams for improved skin penetration.

## VI. FUTURE PROSPECTS

Nanotechnology in drug delivery is advancing toward:

- Personalized Nanomedicine: Tailoring nanocarriers based on patient genetics and disease profile.
- Theranostics: Combining therapeutic and diagnostic functions in a single nanocarrier.
- AI and Machine Learning in Nanocarrier Design: Predicting nanoparticle interactions and optimizing formulations.
- Gene Therapy: Delivering DNA, RNA, and CRISPR components safely via nanocarriers.
- Regulatory Harmonization: Development of global guidelines for nanomedicine approval.

## VII. CONCLUSION

Nanotechnology-based drug delivery systems represent a significant advancement in pharmaceutical sciences. They address the limitations of conventional dosage forms by improving solubility, targeting, and patient outcomes. While regulatory and safety challenges remain, the potential applications in cancer, neurology, infectious diseases, and vaccine technology make NDDS a cornerstone of future medicine. With interdisciplinary research and clinical validation, nanotechnology has the potential to revolutionize the way we design and deliver medicines.

## REFERENCES

- [1]. Allen TM, Cullis PR. Drug Delivery Systems: Entering the Mainstream. *Science*. 2004;303(5665):1818-1822.
- [2]. Torchilin VP. Recent Advances with Liposomes as Pharmaceutical Carriers. *Nat Rev Drug Discov*. 2005;4(2):145-160.
- [3]. Sahoo SK, Labhasetwar V. Nanotech Approaches to Drug Delivery and Imaging. *Drug Discov Today*. 2003;8(24):1112-1120.
- [4]. Bawa R. Nanoparticle-Based Therapeutics in Humans: A Survey. *Nanotechnology Law & Business*. 2008;5:135-155.
- [5]. Jain KK. Nanomedicine: Application of Nanobiotechnology in Medical Practice. *Med Princ Pract*. 2008;17(2):89-101.
- [6]. Ventola CL. Progress in Nanomedicine: Approved and Investigational Nanodrugs. *Pharmacy and Therapeutics*. 2017;42(12):742-755.
- [7]. Pattni BS, Chupin VV, Torchilin VP. New Developments in Liposomal Drug Delivery. *Chem Rev*. 2015;115(19):10938-10966.
- [8]. Barenholz Y. Doxil®—The First FDA-Approved Nanodrug: Lessons Learned. *J Controlled Release*. 2012;160(2):117-134.
- [9]. Duncan R. The Dawning Era of Polymer Therapeutics. *Nat Rev Drug Discov*. 2003;2:347-360.
- [10]. Sharma A, Garg T, Rath G, Goyal AK. Nanotechnology-Based Approaches for Anti-Cancer Drug Delivery. *Life Sci*. 2016;146:265-275.
- [11]. Shi J, Kantoff PW, Wooster R, Farokhzad OC. Cancer Nanomedicine: Progress, Challenges and Opportunities. *Nat Rev Cancer*. 2017;17(1):20-37.
- [12]. Danaei M, et al. Lipid Nanoparticles for Drug Delivery. *Int J Pharm*. 2018;548(1):70-85.
- [13]. Bobo D, et al. Nanoparticle-Based Medicines: Clinical Applications and Perspectives. *Nanomedicine*. 2016;12(3):314-329.
- [14]. Lammers T, Kiessling F, Hennink WE, Storm G. Nanotheranostics and Image-Guided Drug Delivery: Current Concepts and Future Directions. *Mol Pharm*. 2010;7(6):1899-1912.
- [15]. Rzigalinski BA, Strobl JS. Cadmium-Containing Nanoparticles: Perspectives on Pharmacology and Toxicology of Quantum Dots. *Toxicol Appl Pharmacol*. 2009;238(3):280-288.
- [16]. Mehnert W, Mäder K. Solid Lipid Nanoparticles: Production, Characterization and Applications. *Adv Drug Deliv Rev*. 2001;47(2-3):165-196.
- [17]. Kim BY, Rutka JT, Chan WC. Nanomedicine. *N Engl J Med*. 2010;363(25):2434-2443.
- [18]. Mitragotri S, Burke PA, Langer R. Overcoming the Challenges in Administering Biopharmaceuticals: Formulation and Delivery Strategies. *Nat Rev Drug Discov*. 2014;13(9):655-672.
- [19]. Zhang L, Gu FX, Chan JM, Wang AZ, Langer RS, Farokhzad OC. Nanoparticles in Medicine: Therapeutic Applications and Developments. *Clin Pharmacol Ther*. 2008;83(5):761-769.
- [20]. Alavi M, et al. Applications of Nanocarriers for Drug Delivery in Cancer Therapy. *J Cell Physiol*. 2019;234(10):16724-16736.