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ADVANCES IN NANOPARTICLE-BASED DRUG DELIVERY SYSTEMS: TRENDS AND THERAPEUTIC APPLICATIONS

A. E. Dinesh*[1], Dr. V. Kalvimoorthi[2], L. Gopi[3]

[1]M.Pharm First Year Department of Pharmaceutics, [2] Professor Cum Head Department of Pharmaceutics, [3]Assistant Professor Department of Pharmaceutics.

Aadhibhagawan College of Pharmacy, Rantham, Thiruvanamalai, Tamilnadu, India.

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***Corresponding Author: A. E. Dinesh**

M. Pharm First Year Department of Pharmaceutics, Aadhibhagawan College of Pharmacy, Rantham, Thiruvanamalai, Tamilnadu, India.

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ABSTRACT

Nanoparticle-based drug delivery systems (NDDS) have emerged as a transformative approach in modern pharmaceutical sciences due to their ability to improve drug solubility, bioavailability, targeting efficiency, and therapeutic outcomes. Conventional drug delivery methods often suffer from poor pharmacokinetics, low specificity, systemic toxicity, and rapid drug degradation. Nanotechnology-based carriers overcome these limitations through controlled and site-specific drug delivery. Various nanoparticle systems including liposomes, polymeric nanoparticles, dendrimers, solid lipid nanoparticles, metallic nanoparticles, nanogels, and lipid nanoparticles have shown promising applications in cancer therapy, gene delivery, vaccine development, antimicrobial therapy, and neurological disorders. Recent advances involve surface functionalization, stimulus-responsive systems, and AI-assisted nanomedicine design. This review summarizes the recent trends, classifications, mechanisms, therapeutic applications, advantages, limitations, and future perspectives of nanoparticle-based drug delivery systems.

KEYWORDS: Nanoparticles, Drug delivery systems, Nanomedicine, Liposomes, Targeted therapy, Controlled release, Therapeutic applications

1. INTRODUCTION

Drug delivery systems play a vital role in improving therapeutic efficacy and minimizing adverse effects. Traditional dosage forms often exhibit poor drug targeting, low

bioavailability, and frequent dosing requirements. Nanotechnology has revolutionized pharmaceutical sciences by enabling the development of nanoparticle-based drug delivery systems. Nanoparticles are colloidal structures ranging from 1–1000 nm in size and can encapsulate therapeutic agents such as drugs, proteins, genes, and vaccines. Due to their small size and modifiable surface characteristics, nanoparticles can cross biological barriers and deliver drugs selectively to diseased tissues. Recent research has demonstrated significant advancements in nanoparticle engineering, including ligand-mediated targeting, surface decoration, and controlled release technologies. Nanoparticles are now extensively investigated for applications in oncology, infectious diseases, cardiovascular disorders, and neurological diseases.

2. CLASSIFICATION OF NANOPARTICLE-BASED DRUG DELIVERY SYSTEMS:

2.1 Liposomes

Liposomes are spherical vesicles composed of phospholipid bilayers capable of encapsulating hydrophilic and lipophilic drugs.

Advantages

- Biocompatibility
- Reduced toxicity
- Improved pharmacokinetics
- Enhanced drug stability

Applications

- Cancer therapy
- Vaccine delivery
- Gene delivery

Recent advancements in liposomal technology have improved targeted drug delivery and clinical translation.

2.2 Polymeric Nanoparticles

These are prepared from biodegradable polymers such as PLGA, chitosan, and PEG.

Types

- Nanospheres

- Nanocapsules

Advantages

- Controlled drug release
- High drug loading
- Enhanced stability

Applications

- Anticancer drug delivery
- Protein delivery
- Gene therapy

2.3 Solid Lipid Nanoparticles (SLNs):

SLNs are composed of solid lipids stabilized by surfactants.

Advantages

- Improved bioavailability
- Protection of labile drugs
- Controlled release

Limitations

- Low drug loading capacity
- Drug expulsion during storage

2.4 Dendrimers

Dendrimers are highly branched macromolecules with nanoscale dimensions.

Advantages

- Precise molecular structure
- High drug entrapment
- Surface functionalization

Applications

- Targeted chemotherapy
- Diagnostic imaging

- Gene delivery

2.5 Metallic Nanoparticles

Metal nanoparticles include gold, silver, and magnetic nanoparticles.

Applications

- Photothermal therapy
- Imaging
- Antimicrobial therapy

Challenges

- Potential toxicity
- Biocompatibility concerns

2.6 Nanogels

Nanogels are hydrogel nanoparticles capable of swelling in aqueous environments.

Advantages

- High water content
- Stimuli responsiveness
- Controlled drug release

3. MECHANISM OF NANOPARTICLE DRUG DELIVERY:

Drug-loaded nanoparticles reach target tissues through:

- **Passive Targeting:** Based on the Enhanced Permeability and Retention (EPR) effect in tumors
- **Active Targeting:** Surface modification using ligands, antibodies, peptides, or aptamers improves site-specific targeting.
- **Stimuli-Responsive Delivery:** Drug release occurs in response to:

➢ pH
➢ Temperature
➢ Enzymes
➢ Magnetic field
➢ Ultrasound

Surface decoration technologies have significantly enhanced nanoparticle specificity and therapeutic efficiency.

4. RECENT TRENDS IN NANOPARTICLE-BASED DRUG DELIVERY:

4.1 Surface Fictionalization

PEGylation and ligand conjugation improve circulation time and targeting capability.

4.2 Lipid Nanoparticles in mRNA Delivery

Lipid nanoparticles gained major attention during mRNA vaccine development. Programmable lipid nanoparticles are now being explored for precision medicine applications.

4.3 Extracellular Vesicles and Exosomes

Exosomes serve as natural nanocarriers with excellent biocompatibility and tissue penetration. Recent studies highlight their therapeutic potential in gene and protein delivery.

4.4 Nanorobotics and Smart Nanocarriers

Nanorobots and intelligent nanoparticles are emerging technologies for targeted and responsive therapy.

Applications include

- Precision oncology
- Biosensing
- Minimally invasive treatment

4.5 AI-Assisted Nanomedicine Design

Artificial intelligence and machine learning are increasingly used for:

- Nanoparticle optimization
- Drug loading prediction
- Toxicity assessment
- Personalized medicine

5. THERAPEUTIC APPLICATIONS

5.1 Cancer Therapy

Nanoparticles improve tumor targeting while reducing systemic toxicity.

Commonly used nanocarriers

- Liposomes
- Polymeric nanoparticles
- Gold nanoparticles

Applications include

- Chemotherapy
- Immunotherapy
- Photothermal therapy

Recent nanocarrier systems demonstrate improved anticancer efficacy

5.2 Gene Delivery

Nanoparticles efficiently deliver

- DNA
- siRNA
- mRNA
- CRISPR systems

Advantages

- Reduced degradation
- Improved cellular uptake

5.3 Vaccine Delivery

Nanoparticles enhance antigen stability and immune response.

Applications

- mRNA vaccines
- Nasal vaccines
- DNA vaccines

5.4 Antimicrobial Therapy

Silver nanoparticles and nano-antibiotics show strong antimicrobial activity against resistant pathogens.

5.5 Neurological Disorders

- Nanoparticles can cross the blood-brain barrier and improve treatment of Alzheimer's disease
- Parkinson's disease
- Brain tumors

6. ADVANTAGES OF NANOPARTICLE-BASED DRUG DELIVERY SYSTEMS:

- Improved bioavailability
- Controlled and sustained release
- Reduced toxicity
- Site-specific targeting
- Enhanced therapeutic efficacy
- Better patient compliance

7. LIMITATIONS AND CHALLENGES:

Despite significant advancements, several challenges remain:

- Nanotoxicity
- Stability issues
- High production cost
- Scale-up difficulties
- Regulatory barriers
- Limited long-term safety data

Manufacturing and scalability remain critical barriers for commercialization.

8. FUTURE PERSPECTIVES:

Future research focuses on:

- Personalized nanomedicine
- Multifunctional nanoparticles
- AI-integrated drug delivery
- Biodegradable nanocarriers
- Clinical translation and regulatory standardization

Emerging technologies such as smart nanocarriers, exosome engineering, and programmable lipid nanoparticles are expected to revolutionize precision medicine.

9. CONCLUSION

Nanoparticle-based drug delivery systems represent one of the most promising advancements in pharmaceutical technology. Their ability to improve targeting efficiency, reduce toxicity, and enhance therapeutic outcomes has significantly transformed modern medicine. Recent advances in lipid nanoparticles, surface-modified nanocarriers, exosome-based delivery, and intelligent nanomedicine continue to expand therapeutic possibilities. However, issues related to toxicity, scalability, and regulatory approval require further investigation. Continued interdisciplinary research and technological innovation will accelerate the translation of nanoparticle therapeutics from laboratory research to clinical practice.

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