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Review Paper

Nano-Based Drug Delivery Systems: Recent Advances and Future Perspectives

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ABSTRACT

Nano-based drug delivery systems (NDDS) have emerged as one of the most promising innovations in pharmaceutical sciences. Conventional drug delivery systems often face challenges such as poor aqueous solubility, low bioavailability, non-specific distribution, rapid metabolism, and undesirable side effects. Nanotechnology has revolutionized drug delivery by enabling the development of nanoscale carriers capable of targeted, controlled, and sustained drug release. Various nanocarriers, including liposomes, polymeric nanoparticles, dendrimers, solid lipid nanoparticles, nanostructured lipid carriers, and nanoemulsions, have demonstrated significant potential in enhancing therapeutic efficacy while minimizing toxicity. Recent advances focus on stimuli-responsive systems, targeted delivery, gene therapy applications, and artificial intelligence-assisted nanomedicine. This review discusses the fundamentals of nano-based drug delivery systems, their classifications, advantages, and recent developments, highlighting their future prospects in modern healthcare. NDDS are expected to play a crucial role in precision medicine and personalized therapeutics.

INTRODUCTION

Drug delivery systems are essential components of pharmaceutical therapy because they determine the rate, extent, and site of drug release. Conventional dosage forms such as tablets, capsules, injections, and suspensions often fail to achieve optimal therapeutic outcomes due to poor drug solubility, rapid elimination, instability, and lack of tissue specificity. These limitations can lead to frequent dosing, reduced patient compliance, and increased systemic toxicity.

Nanotechnology has emerged as a revolutionary field that manipulates materials at the nanometer scale, typically ranging from 1 to 1000 nm. The

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application of nanotechnology in drug delivery has enabled the development of sophisticated carriers capable of delivering therapeutic agents directly to target tissues while minimizing adverse effects. Nano-based drug delivery systems have attracted considerable attention due to their ability to improve pharmacokinetic and pharmacodynamic properties of drugs.

The unique physicochemical properties of nanoparticles, including high surface-area-to-volume ratio, tunable surface characteristics, and enhanced permeability, facilitate improved drug loading, prolonged circulation time, and targeted delivery. These advantages have led to extensive applications in cancer therapy, infectious diseases, neurological disorders, cardiovascular diseases, and gene therapy.

Recent developments in nanotechnology have further expanded the scope of drug delivery systems through the incorporation of stimuli-responsive materials, ligand-mediated targeting, theranostic platforms, and artificial intelligence-assisted formulation design. Such advancements are expected to transform conventional therapeutic approaches and pave the way for personalized medicine.

2. Need For Nano-Based Drug Delivery Systems

Several pharmaceutical compounds exhibit poor therapeutic efficacy despite possessing potent pharmacological activity. This discrepancy is often attributed to limitations associated with conventional drug delivery systems.

The major challenges include

2.1 Poor Solubility

Approximately 40–70% of newly discovered drug molecules exhibit poor aqueous solubility, resulting in inadequate absorption and low bioavailability. Nanocarriers enhance dissolution rates by increasing surface area and improving drug dispersion.

2.2 Low Bioavailability

Many drugs undergo extensive first-pass metabolism and degradation before reaching systemic circulation. Nanoformulations protect drug molecules from degradation and enhance absorption.

2.3 Lack of Target Specificity

Traditional dosage forms distribute drugs throughout the body, affecting healthy tissues and causing adverse effects. Nanoparticles facilitate site-specific drug delivery through passive and active targeting mechanisms.

2.4 Frequent Dosing

Rapid drug elimination often necessitates frequent administration. Controlled-release nanocarriers prolong therapeutic action and improve patient compliance.

2.5 Toxicity and Side Effects

Targeted nanocarriers reduce exposure of healthy tissues to therapeutic agents, thereby minimizing systemic toxicity.

3.Advantages of Nano-Based Drug Delivery Systems

Nano-based drug delivery systems offer several advantages over conventional formulations:

1. Enhanced drug solubility and dissolution.
2. Improved bioavailability.
3. Controlled and sustained drug release.
4. Site-specific targeting.
5. Reduced toxicity and side effects.
6. Protection of drugs from enzymatic degradation.
7. Improved pharmacokinetic profile.
8. Enhanced patient compliance.
9. Ability to cross biological barriers such as the blood-brain barrier.
10. Potential for personalized medicine applications.

4.Classification of Nano-Based Drug Delivery Systems

Nano-based drug delivery systems can be broadly classified into:

A. Lipid-Based Nanocarriers

- Liposomes
- Solid Lipid Nanoparticles (SLNs)
- Nanostructured Lipid Carriers (NLCs)
- Nanoemulsions

B. Polymeric Nanocarriers

- Polymeric Nanoparticles
- Polymeric Micelles
- Nanocapsules
- Nanospheres

C. Dendrimer-Based Systems

- PAMAM dendrimers
- Polypropyleneimine dendrimers

D. Inorganic Nanocarriers

- Gold nanoparticles
- Silver nanoparticles
- Magnetic nanoparticles
- Mesoporous silica nanoparticles

E. Biological Nanocarriers

- Exosomes
- Virus-like particles

These systems differ in composition, preparation techniques, drug-loading capacity, and therapeutic applications.

5.Types of Nano-Based Drug Delivery Systems

5.1 Liposomes

Liposomes are spherical vesicles composed of phospholipid bilayers enclosing an aqueous core. They are among the earliest and most extensively studied nanocarriers.

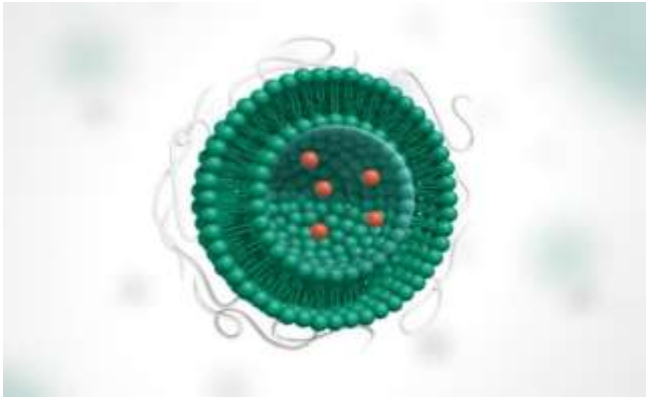

Fig No.1 LIPOSOMES

Characteristics

- Biocompatible and biodegradable.
- Capable of encapsulating both hydrophilic and lipophilic drugs.
- Improve drug stability and circulation time.

Advantages

- Reduced toxicity.
- Enhanced drug accumulation at target sites.
- Improved therapeutic efficacy.

Applications

- Cancer chemotherapy.
- Vaccine delivery.
- Antifungal and antimicrobial therapy.

Several liposomal formulations have received regulatory approval for clinical use, demonstrating the translational potential of nanotechnology in medicine.

5.2 Polymeric Nanoparticles

Polymeric nanoparticles are colloidal systems prepared using biodegradable polymers such as PLGA, chitosan, polylactic acid, and polycaprolactone.

Types

- Nanospheres
- Nanocapsules

Advantages

- Controlled drug release.
- High drug-loading capacity.

- Enhanced stability.
- Surface modification for targeted delivery.

Applications

- Cancer therapy.
- Gene delivery.
- Protein and peptide delivery.

Polymeric nanoparticles are widely investigated because they can be engineered to achieve precise control over drug release kinetics and biodistribution.

5.3 Solid Lipid Nanoparticles (SLNs)

Solid Lipid Nanoparticles (SLNs) are submicron colloidal carriers composed of physiologically compatible lipids that remain solid at both room and body temperatures. They were developed as an alternative to traditional colloidal systems such as emulsions, liposomes, and polymeric nanoparticles.

Composition

SLNs typically consist of:

- Solid lipids (glyceryl monostearate, stearic acid, tristearin)
- Surfactants (Tween 80, Poloxamer 188)
- Aqueous dispersion medium

Advantages

- Improved drug stability
- Controlled and sustained release
- Biocompatibility and biodegradability
- Protection of labile drugs from degradation
- Ease of large-scale production

Limitations

- Limited drug-loading capacity
- Drug expulsion during storage
- Lipid crystallization issues

Applications

- Oral drug delivery
- Topical formulations
- Ocular drug delivery
- Anticancer drug delivery

Recent investigations have demonstrated the utility of SLNs in enhancing the bioavailability of poorly soluble drugs and improving therapeutic outcomes.

5.4 Nanostructured Lipid Carriers (NLCs)

Nanostructured Lipid Carriers (NLCs) are second-generation lipid nanoparticles developed to overcome the limitations of SLNs. They are composed of a mixture of solid and liquid lipids, resulting in an imperfect lipid matrix that accommodates greater amounts of drug molecules.

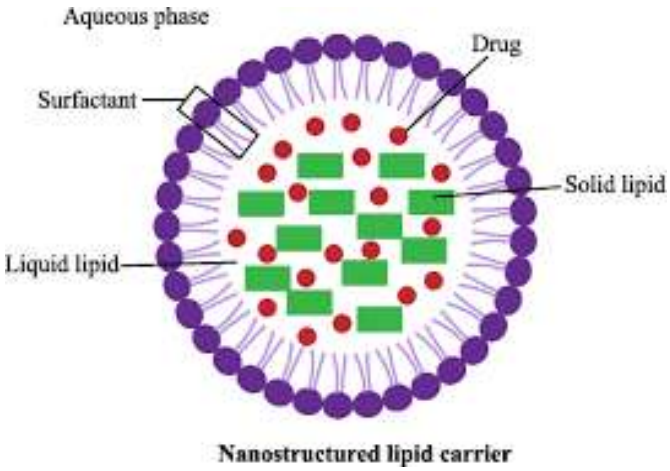

Fig No.2 Nanostructured Lipid Carriers (NLCs)

Advantages

- Higher drug entrapment efficiency
- Reduced drug leakage
- Improved stability
- Better control over drug release

Applications

- Transdermal drug delivery
- Oral formulations
- Anticancer therapy
- Cosmetic preparations

NLCs have gained considerable attention because of their superior drug-loading capacity and long-term stability compared with conventional SLNs.

5.5 Dendrimers

Dendrimers are highly branched, three-dimensional macromolecules with a well-defined structure consisting of a central core, repeated branching units, and multiple terminal functional groups.

Characteristics

- Monodispersed size distribution
- High degree of surface functionality
- Excellent drug encapsulation capacity

Common Types

- Polyamidoamine (PAMAM) dendrimers
- Polypropyleneimine (PPI) dendrimers

Advantages

- Precise molecular architecture
- Controlled drug release
- Enhanced cellular uptake
- Targeted drug delivery

Applications

- Gene delivery
- Cancer therapy
- Antimicrobial therapy
- Diagnostic imaging

Surface modification of dendrimers with targeting ligands significantly improves therapeutic efficacy and reduces systemic toxicity.

5.7 Metallic Nanoparticles

Metallic nanoparticles are inorganic nanocarriers synthesized from metals such as gold, silver, iron oxide, and platinum.

Types

Gold Nanoparticles (AuNPs)

- Excellent biocompatibility
- Easy surface modification
- Photothermal therapy applications

Silver Nanoparticles (AgNPs)

- Potent antimicrobial activity
- Wound healing applications

Magnetic Nanoparticles

- Magnetic targeting capability
- MRI contrast enhancement

Applications

- Cancer diagnosis and treatment
- Drug delivery
- Biosensing
- Medical imaging

The multifunctional nature of metallic nanoparticles has expanded their role in theranostics and personalized medicine.

5.8 Nanoemulsions

Nanoemulsions are thermodynamically stable dispersions consisting of oil, water, surfactants, and co-surfactants, with droplet sizes typically ranging from 20 to 200 nm.

Advantages

- Improved drug solubilization
- Enhanced oral bioavailability
- Ease of formulation
- High physical stability

Applications

- Oral drug delivery
- Topical formulations
- Vaccine delivery
- Nutraceuticals

Nanoemulsions are particularly useful for delivering hydrophobic therapeutic agents with poor aqueous solubility.

6. Recent Advances in Nano-Based Drug Delivery Systems

The last few years have witnessed significant advancements in nano-based drug delivery technologies. Researchers are focusing on developing intelligent nanocarriers capable of

responding to physiological stimuli, improving targeting efficiency, and integrating digital technologies.

6.1 Targeted Drug Delivery

Targeted drug delivery aims to selectively deliver drugs to diseased tissues while minimizing exposure to healthy organs.

Passive Targeting

Passive targeting relies on the Enhanced Permeability and Retention (EPR) effect, particularly in tumor tissues.

Active Targeting

Active targeting involves surface modification of nanoparticles with:

- Antibodies
- Peptides
- Aptamers
- Folic acid
- Transferrin

These ligands recognize specific receptors expressed on target cells, thereby enhancing therapeutic efficacy.

Advantages

- Increased drug concentration at the target site
- Reduced systemic toxicity
- Improved therapeutic outcomes

6.2 Stimuli-Responsive Nanocarriers

Stimuli-responsive or smart nanoparticles release drugs in response to specific internal or external stimuli.

Internal Stimuli

- pH
- Enzymes
- Redox potential

External Stimuli

- Temperature
- Ultrasound
- Magnetic fields
- Light irradiation

Benefits

- Controlled drug release
- Enhanced treatment precision
- Reduced adverse effects

Smart nanocarriers represent one of the fastest-growing areas in nanomedicine.

6.3 Lipid Nanoparticles for Gene and mRNA Delivery

The success of mRNA-based therapeutics has highlighted the importance of lipid nanoparticles (LNPs) as efficient nucleic acid delivery systems.

Functions of LNPs

- Protection of nucleic acids from degradation
- Facilitation of cellular uptake
- Endosomal escape

Applications

- mRNA vaccines
- Gene therapy
- Cancer immunotherapy
- Protein replacement therapies

Lipid nanoparticles are expected to dominate future developments in nucleic acid therapeutics.

6.4 Artificial Intelligence in Nanomedicine

Artificial Intelligence (AI) is increasingly being integrated into pharmaceutical nanotechnology.

Applications

- Formulation optimization
- Prediction of nanoparticle behavior
- Drug-release modeling
- Toxicity prediction
- Personalized treatment planning

Machine learning algorithms can significantly reduce formulation development time while improving accuracy and reproducibility.

6.5 Theranostic Nanoparticles

Theranostics combines therapeutic and diagnostic functions within a single nanoparticle platform.

Benefits

- Simultaneous diagnosis and treatment
- Real-time monitoring of therapeutic response
- Personalized treatment adjustments

Applications

- Cancer imaging and therapy
- Neurological disorders
- Cardiovascular diseases

Theranostic systems represent a major advancement toward precision medicine.

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