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NANOTECHNOLOGY-BASED DRUG DELIVERY SYSTEMS: RECENT ADVANCES AND FUTURE PERSPECTIVES

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ABSTRACT

Nanotechnology has emerged as one of the most promising approaches in pharmaceutical sciences, revolutionizing drug delivery systems by enhancing therapeutic efficacy and minimizing adverse effects. Conventional drug delivery systems often suffer from poor bioavailability, non-specific distribution, and rapid degradation of active pharmaceutical ingredients. Nanotechnology-based drug delivery systems (NDDS) overcome these limitations through the use of Nano sized carriers that improve drug solubility, stability, permeability, and targeted delivery. Various Nano carriers including liposomes, polymeric nanoparticles, solid lipid nanoparticles, nanostructured lipid carriers, dendrimers, and polymeric micelles have demonstrated significant potential in improving treatment outcomes for various diseases. Nanotechnology has found applications in cancer therapy, gene delivery, vaccine development, brain targeting, and ocular drug delivery. Despite remarkable advancements, challenges such as toxicity concerns, regulatory barriers, scalability, and manufacturing costs remain significant obstacles to clinical translation. Recent developments in artificial intelligence, personalized medicine, and smart Nano carriers are expected to further enhance the scope of nanotechnology in healthcare. This review highlights the different types of Nano carriers, preparation techniques, pharmaceutical applications, advantages, limitations, and future prospects of nanotechnology-based drug delivery systems.

Keywords: Nanotechnology, Drug Delivery Systems, Nano carriers, Liposomes, Nanoparticles, Targeted Drug Delivery, Controlled Release.

INTRODUCTION

Drug delivery plays a crucial role in determining the therapeutic effectiveness of pharmaceutical formulations. Traditional drug delivery systems often encounter limitations such as poor solubility, inadequate bioavailability, lack of site-specific targeting, and dose-related toxicity. The emergence of nanotechnology has provided innovative solutions to these challenges by enabling the design of nanoscale delivery systems capable of improving drug performance [1].

Nanotechnology refers to the manipulation and application of materials with dimensions ranging from 1 to 1000 nanometers. Due to their small size and unique physicochemical properties, Nano carriers can

efficiently transport therapeutic agents to targeted tissues while minimizing systemic side effects. The integration of nanotechnology into pharmaceutical sciences has led to the development of advanced drug delivery platforms with enhanced efficacy and safety profiles [2].

Nanotechnology-based drug delivery systems have gained widespread attention in cancer treatment, gene therapy, vaccine development, and chronic disease management. The ability of Nano carriers to improve drug stability, prolong circulation time, and provide controlled release has contributed significantly to modern therapeutics [1, 3].

Nanotechnology is a promising and rapidly developing area in the 21st century, which affects various fields of science: physics, chemistry, biology, engineering, microelectronics, and medicine [1]. Nanotechnology is based on the use of materials that, when reduced in size to the Nano-scale, acquire unique structural, optical, mechanical, magnetic, electrical, and biological properties [2, 3]. In the field of medical nanotechnology, various Nano-scaled structures have been developed on the basis of such materials, which can be used as carriers of drugs to improve their bioavailability, reduce systemic side effects, and increase therapeutic efficacy [4]. Such carriers must have a number of properties, such as bio-inertness, biocompatibility, biodegradability, and a lack of toxicity to the organism, and must also protect the drug from degradation and inactivation [5] during transportation to the specific site, allowing for its prolonged release in the target area. In addition, effective medicine Nano-carriers must be easy to obtain, reproducible, and affordable.

According to their origin, drug delivery systems can be divided into polymeric systems, cellular carriers and viruses, and inorganic carriers [6]. Polymer carriers include micelles, liposomes, dendrimers aggregates, hydrogels, etc. [7]. Cells in the body, such as immune cells (macrophages and T-cells), blood cells (erythrocytes and platelets), stem cells, exosomes, and adipocytes, can act as cellular drug carriers [8]. Finally, magnetic and metal nanoparticles, such as iron or gold oxide nanoparticles; carbon-based structures such as fullerenes, graphene sheets, and carbon nanotubes; quantum dots; and silicon dioxide-based nanoparticles are representatives of inorganic Nano-scaled carriers for different therapeutic and diagnostic agent.

Another key feature of nanotechnology-based carriers is that they can deliver biologically active molecules to the tumor area due to their enhanced permeability and retention (EPR) effect. However, this effect only contributes to the accumulation of carriers in tumors, and insufficient intracellular absorption remains a serious problem for effective chemotherapy. To improve and adjust the EPR effect, the surface of the Nano carriers can be modified with a target ligand, which is responsible for the directional transport of the drug in organism. Peptides, antibodies and their fragments, proteins, small molecules, and aptamers can act as ligands, which can selectively bind to receptors or antigens overexpressed on the cell surface, promoting the enhanced accumulation of Nano carriers in tumor tissue and accelerated integration by tumor cells [18, 19]. For example, the iRGD peptide (CRGDKGPDC) is known for its ability to penetrate and accumulate in deep layers of the tumor, and its conjugation with Nano-scaled carriers is a promising approach in cancer therapy [20].

Another approach in Nano technological drug delivery is physically impacting the carrier structure. Physical factors include changes in pH, oxidation-reduction potential, temperature, ultrasound, magnetic field, etc. The essence of this method is that the carrier material reacts to a certain level of impact, leading to a violation of its integrity and, consequently, the intense release of the drug in the desired area [19, 21].

1. **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:

1.1 Poor Solubility:

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

1.2 Low Bioavailability:

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

1.3 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.

1.4 Frequent Dosing:

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

1.5 Toxicity and Side Effects:

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

2. 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.

3. Classification of Nano-Based Drug Delivery Systems:

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

A. Lipid-Based Nano carriers:

- Liposomes
- Solid Lipid Nanoparticles (SLNs)
- Nanostructured Lipid Carriers (NLCs)
- Nano emulsions

B. Polymeric Nano carriers:

- Polymeric Nanoparticles
- Polymeric Micelles
- Nano capsules
- Nano spheres

C. Dendrimer-Based Systems:

- PAMAM dendrimers
- Polypropylene mine dendrimers

D. Inorganic Nano carriers:

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

E. Biological Nano carriers;

- Exosomes
- Virus-like particles

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

4. Types of Nano-Based Drug Delivery Systems:

4.1 Liposomes

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

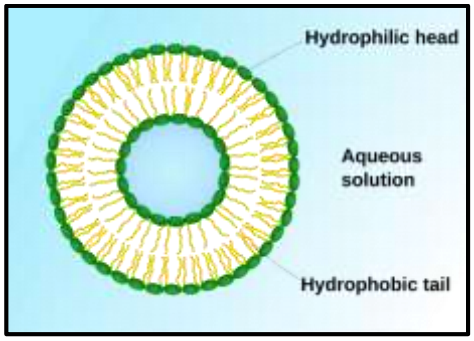

Fig No.1 Basic Structure OF Liposomes

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.

4.2 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.

4.3 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 bio distribution.

4.4 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.

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.

4.5 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.

4.6 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.

4.7 Nano Emulsions:

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

Nano emulsions are particularly useful for delivering hydrophobic therapeutic agents with

poor aqueous solubility.

5. 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 Nano carriers capable of responding to physiological stimuli, improving targeting efficiency, and integrating digital technologies.

5.1 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

5.2 Stimuli-Responsive Nano carriers:

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.

5.4 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.

5.5 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.

5.6 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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