Role of Nanoparticles In Modern Drug Delivery Platforms

M Santhosh[1], Dr. G Mariyappan[2]
[1, 2] Dept of PHARMACEUTICS
[1, 2] PALLAVAN PHARMACY COLLEGE,
KOLIVAKKAM, KANCHIPURAM-631502.

Abstract- *Nanotechnology has emerged as a transformative approach in drug delivery, offering innovative solutions for improving the bioavailability, targeting, and therapeutic index of drugs. Among nanotechnological advances, nanoparticles have shown exceptional promise in overcoming physiological barriers and delivering therapeutic agents efficiently to specific sites of action. This review explores the role of nanoparticles in various drug delivery systems, with a focus on ocular, pulmonary, and gastrointestinal applications. It highlights the unique properties of nanoparticles, recent research findings, challenges, and prospects for clinical translation.*

***Keywords*-** Nanoparticles, Drug Delivery Systems, Ocular Delivery, Pulmonary Delivery, Gastrointestinal Delivery, Controlled Release, Targeted Therapy, Nanotechnology

I. INTRODUCTION

Medicine delivery systems(DDS) are pivotal in assessing the remedial efficacity of pharmacological drugs.Traditional delivery ways constantly have disadvantages, similar as low bioavailability, systemic adverse goods, and a lack of focused action.In recent times, nanotechnology has surfaced as a transformational way to addressing these problems, allowing for the development of nanoparticle- grounded drug delivery systems.

Nanoparticles, typically ranging from 1 to 1000 nanometers in size, offer unique physicochemical properties such as high surface area, controlled release profiles, and the ability to target specific tissues or cells.These characteristics make them highly suitable for delivering a wide range of therapeutic agents including small molecules, peptides, proteins, and nucleic acids.

This review explores the different types of nanoparticles used in drug delivery, their mechanisms of action, and their role across various routes of administration.By highlighting recent advancements, challenges, and future prospects, the article aims to provide a comprehensive understanding of the evolving role of nanoparticles in improving drug delivery outcomes.

II. CLASSIFICATION OF NANOPARTICLES IN DRUG DELIVERY

Nanoparticles used in drug delivery can be broadly classified based on their composition, structure, and functional properties.Each type of nanoparticle has distinct advantages and applications in targeted and controlled drug release.

2.1 LIPID-BASED NANOPARTICLES

Liposomes: These spherical vesicles are composed of a couple of phospholipid bilayers.They are capable of covering both lipophilic and hydrophilic drugs.Widely used for cancer therapy and vaccine delivery (e.g., Doxil®).Solid Lipid Nanoparticles (SLNs): Made from solid lipids, offering improved drug stability and controlled release.Nanostructured Lipid Carriers (NLCs): Second-generation lipid nanoparticles with better drug loading capacity and reduced drug expulsion.

2.2 POLYMERIC NANOPARTICLES

Constructed using either synthetic or natural polymers (e.g., chitosan, PLGA). Offer controlled and sustained drug release. Can be surface-functionalized for targeted delivery.

2.3 METAL-BASED NANOPARTICLES

It Include gold (Au), silver (Ag), and iron oxide nanoparticles. Have distinctive optical, magnetic, or thermal qualities. Frequently used in imaging, diagnosis, and cancer treatment.

2.4 DENDRIMERS

Branched, tree-like synthetic macromolecules with a high degree of surface functionality. Ideal for multi-drug loading and precise targeting.

2.5 CARBON-BASED NANOPARTICLES

Includes carbon nanotubes and fullerenes.
High drug loading potential and ability to penetrate cell membranes.

2.6 NANOEMULSIONS AND MICELLES

Nanosized colloidal systems used for enhancing the solubility of poorly soluble drugs.Micelles are especially useful for oral and intravenous drug delivery.Each type of nanoparticle offers specific benefits depending on the route of administration, drug molecule properties, and therapeutic goals.

III. ROLE OF NANOPARTICLES IN VARIOUS DRUG DELIVERY SYSTEMS (SELECTED ROUTES)

Nanoparticles have revolutionized medicine delivery across multiple administration routes by enhancing medicine solubility, bioavailability, and targeting.Below is a focused discussion on their part in optical, pulmonary, and gastrointestinal(GI) medicine delivery.

3.1 OCULAR DRUG DELIVERY

Delivering drugs to ocular tissues poses significant challenges due to anatomical and physiological barriers like the corneal epithelium, lacrimal drainage, and blood-ocular barriers.Nanoparticles help overcome these barriers by enhancing drug retention time, penetration, and controlled release.

Polymeric nanoparticles and liposomes have shown promising results in increasing the ocular bioavailability of antibiotics, anti-inflammatories, and anti-glaucoma agents.

Chitosan-based nanoparticles exhibit mucoadhesive properties, improving precorneal retention.

Example: Cyclosporine-loaded lipid nanoparticles for dry eye syndrome show enhanced corneal absorption with reduced dosing frequency

3.2 PULMONARY DRUG DELIVERY

The lungs offer a large surface area and rich blood supply, making them an attractive route for both local and systemic drug delivery.However, drug retention is restricted by alveolar macrophage absorption and mucociliary clearance.

Nanoparticles, especially those in the size range of 100–300 nm, can evade rapid clearance and penetrate deep into the alveolar region.
Solid lipid nanoparticles and nanoemulsions have been used to deliver anti-tuberculosis drugs, corticosteroids, and anticancer agents directly to the lungs.

Example: Inhalable paclitaxel-loaded nanoparticles for lung cancer therapy have shown improved therapeutic efficacy and reduced systemic toxicity.

3.3 GASTROINTESTINAL (ORAL) DRUG DELIVERY

Oral administration remains the most convenient method, although it confronts challenges such as enzyme breakdown, pH fluctuation, and low drug solubility.

Lipid- grounded nanoparticles(like NLCs and SLNs) enhance oral bioavailability of inadequately answerable medicines by promoting lymphatic immersion.

Polymeric nanoparticles cover sensitive medicines(like peptides) from acidic declination in the stomach.

face- modified nanoparticles(e.g., PEGylated) can repel mucus ruse and ameliorate intestinal uptake.

Example Insulin- loaded chitosan nanoparticles have demonstrated bettered intestinal permeability and bioactivity in experimental studie.

3.4 PARENTERAL DRUG DELIVERY

Parenteral administration distributes medications straight into the systemic circulation, avoiding first-pass digestion.

However, fast clearance and systemic toxicity are frequent downsides.

Polymeric nanoparticles and liposomes facilitate regulated and sustained medication release following intravenous (IV), intramuscular (IM), or subcutaneous (SC) injection.Stealth nanoparticles (PEGylated) prevent opsonization and increase circulation time.

For example, doxorubicin-loaded liposomes (Doxil®) minimize cardiotoxicity and boost tumor targeting in cancer patients.

3.5 TRANSDERMAL DRUG DELIVERY

The stratum corneum (outermost skin layer) serves as a significant barrier to transdermal medication administration. Nanoparticles improve drug penetration and enable regulated distribution via the skin.Solid lipid nanoparticles and nanoemulsions are frequently employed to enhance medication delivery across skin layers.

Flexible liposomes (transfersomes) can pass across intercellular skin gaps to achieve deeper penetration.

For example, diclofenac-loaded SLNs have been shown to have excellent anti-inflammatory properties while also improving skin retention.

3.6 TARGETED DRUG DELIVERY

Targeted delivery tries to target therapeutic medicines to specific tissues, cells, or receptors while reducing systemic exposure and negative effects.Active targeting: Nanoparticles are surface-modified with ligands (such as antibodies or peptides) that bind to sick cells' overexpressed receptors.Passive targeting makes use of the enhanced permeability and retention (EPR) effect, which is particularly effective in tumors and inflamed tissues.Gold and magnetic nanoparticles are being researched for both therapeutic (theranostic) and diagnostic uses.

For example,Folate-conjugated PLGA nanoparticles improve the absorption of anticancer medicines in folate receptor-positive malignancies.

IV. CHALLENGES AND LIMITATIONS OF NANOPARTICLES IN DRUG DELIVERY

While nanoparticles have shown tremendous promise in revolutionizing drug delivery, several scientific, technical, regulatory, and clinical challenges remain. These limitations must be carefully addressed for successful translation from lab to market.

4.1 STABILITY AND SHELF-LIFE

When stored, nanoparticles are vulnerable to drug leakage, sedimentation, and aggregation.Temperature, pH, and humidity can affect nanoparticle structure and drug encapsulation.

Lyophilization (freeze-drying) is commonly used to improve stability, but it may require cryoprotectants.

Example: Liposomes and lipid nanoparticles may fuse over time, leading to inconsistent drug release.

4.2 SCALE-UP AND MANUFACTURING COMPLEXITY

Scaling up nanoparticle production while maintaining uniform particle size, encapsulation efficiency, and reproducibility is a major hurdle.

Batch-to-batch variability and high manufacturing costs limit widespread use.Example: Techniques like microfluidics and spray drying offer promise but require optimization.

4.3 REGULATORY HURDLES

Lack of standardized protocols for characterization, safety testing, and long-term toxicity assessments.

Many regulatory agencies treat nanoparticle formulations on a case-by-case basis.Approval of nanomedicines requires extensive preclinical data, even for well-known drugs.

For example, FDA-approved nanodrugs (such as Doxil®) have undergone extensive pharmacokinetic and immunogenicity testing.

4.4 TOXICITY AND IMMUNOGENICITY

Long-term safety data on accumulation, degradation products, and off-target effects is limited.Some materials (e.g., metallic NPs) may cause oxidative stress, DNA damage, or immune responses.

Surface modifications (like PEGylation) may reduce immunogenicity but may also lead to anti-PEG antibody development over time.

Example: Cationic nanoparticles, while effective for gene delivery, are often cytotoxic at high concentrations.

V. FUTURE PERSPECTIVES AND EMERGING APPLICATIONS

The future of nanoparticle-based medication delivery seems optimistic, because to ongoing advances in materials science, bioengineering, and personalized medicine.Here are some developing trends and prospective directions in this quickly changing industry.

5.1 SMART NANOCARRIERS AND STIMULI-RESPONSIVE SYSTEMS

"Smart" nanoparticles respond to internal (pH, temperature, enzymes, redox conditions) or external (light, magnetic field, ultrasound) triggers for controlled or site-specific drug release.

These systems offer on-demand release, minimizing off-target effects.

Example: pH-sensitive micelles that release anticancer drugs in the acidic tumor microenvironment.

5.2 THERANOSTIC NANOPARTICLES

These multifunctional platforms combine therapy + diagnostics in a single system. used for reaction monitoring, medication tracking, and real-time imaging.. Magnetic nanoparticles (e.g., iron oxide) and gold nanoparticles are widely used.

Example:Gold nanoshells for tumor imaging and photothermal ablation in combination with chemotherapy.

5.3 GENE AND NUCLEIC ACID DELIVERY

To securely and effectively distribute siRNA, miRNA, mRNA, and CRISPR/Cas9 components, nanoparticles are being produced.

Following its application in mRNA-based COVID-19 vaccines, lipid nanoparticles, or LNPs, attracted a lot of attention.

For instance, the FDA-approved Onpattro® (patisiran) delivers siRNA for hereditary transthyretin amyloidosis using lipid nanoparticles.

5.5 ARTIFICIAL INTELLIGENCE (AI) AND PREDICTIVE MODELING

AI tools and machine learning algorithms are being used to predict:

Nanoparticle behavior
Drug loading efficiency
Bio distribution
Toxicity and clearance
Accelerates formulation development and reduces the need for extensive trial-and-error experiments.

VI. FUTURE PERSPECTIVES OF NANOPARTICLES IN DRUG DELIVERY

The landscape of drug delivery is undergoing a transformative shift, with nanoparticles playing a central role in overcoming limitations associated with conventional therapeutic approaches. As the field evolves, several promising trends and innovations are expected to shape the future of nanoparticle-based drug delivery systems.

1. PERSONALIZED NANOMEDICINE

Advances in genomics and biomarker profiling are paving the way for patient-specific nanoparticle formulations. Precision-targeted nanoparticles could be customized based on individual patient profiles, disease state, and pharmacogenetics, maximizing efficacy and minimizing side effects.

2. SMART AND STIMULI-RESPONSIVE NANOCARRIERS

Future nanoparticles will increasingly integrate stimuli-responsive elements that release drugs only under specific conditions—such as pH changes, enzymes, temperature, or redox gradients. For example, tumor-targeted nanoparticles may release their payload only in acidic tumor microenvironments, sparing healthy tissue.

3. MULTIFUNCTIONAL AND THERANOSTIC PLATFORMS

Real-time treatment response monitoring is made possible by theranostic nanoparticles, which integrate therapeutic and diagnostic properties into a single system. Precision in cancer, neurology, and cardiology is improved with image-guided medication administration made possible by integration with imaging agents (MRI, PET, or fluorescence).

4. BIODEGRADABLE AND BIOMIMETIC NANOPARTICLES

Research is moving toward fully biodegradable materials that degrade into non-toxic byproducts, improving safety and reducing long-term side effects. Biomimetic nanoparticles, such as those cloaked in cell membranes (e.g., RBC- or leukocyte-coated NPs), offer immune evasion, prolonged circulation, and enhanced targeting capabilities.

5. ORAL NANOMEDICINE AND NON-INVASIVE ROUTES

Improving oral bioavailability of peptide-based and protein drugs through nanoparticle encapsulation is a key future goal. Efforts are also directed at transdermal, nasal, and buccal nanoparticle systems to enable non-invasive alternatives for vaccines, hormones, and insulin.

6. INTEGRATION WITH ARTIFICIAL INTELLIGENCE (AI) AND MACHINE LEARNING

AI-assisted design and simulation of nanoparticles will accelerate drug formulation, predict in vivo behavior, and personalize therapy regimens. Machine learning models may help optimize parameters such as size, charge, and surface chemistry for maximum therapeutic outcomes.

7. REGULATORY HARMONIZATION AND CLINICAL TRANSLATION

As more nanoparticle-based therapeutics reach clinical trials, regulatory bodies like the FDA, EMA, and WHO are expected to develop clearer frameworks for nanomedicine evaluation. Collaborations between academia, industry, and regulatory agencies will be crucial for scaling up and standardizing manufacturing processes.

8. EXPANDED APPLICATIONS IN EMERGING DISEASES

Nanoparticles hold great potential in emerging infectious diseases, antimicrobial resistance (AMR), neurodegenerative disorders, and gene therapy. The COVID-19 mRNA vaccines, which utilize lipid nanoparticles, have already proven the real-world potential of nanotechnology in global health.

VII. CONCLUSION

Nanoparticles have emerged as powerful and versatile tools in the field of drug delivery, offering unique solutions to overcome the intrinsic limitations of conventional therapeutic systems. By enabling targeted, controlled, and sustained delivery of drugs, they improve therapeutic efficacy while reducing systemic toxicity. The adaptability of nanoparticles to carry a wide range of bioactive molecules—including small-molecule drugs, proteins, peptides, and nucleic acids—makes them highly attractive for a variety of clinical applications.

This review has highlighted the successful integration of nanoparticles in ocular, pulmonary, and gastrointestinal drug delivery systems, showcasing their ability to navigate complex physiological barriers and improve local drug concentration at target sites. Additionally, the ability to modify surface characteristics allows for enhanced permeation, cellular uptake, and immune evasion.

Notwithstanding their apparent benefits, biocompatibility, manufacturing scalability, regulatory approval, and long-term safety are major obstacles for nanoparticle-based drug delivery systems. Due of these constraints, more multidisciplinary research encompassing clinical medicine, materials engineering, pharmaceutical sciences, and regulatory policy is required.

Future developments in tailored, intelligent, and multipurpose nanocarriers that can react to particular biological stimuli and deliver medicines with extreme accuracy are key to the success of nanoparticle-mediated drug delivery. It is anticipated that innovations like theranostic platforms, AI-guided formulation, and biomimetic nanoparticles would completely transform the field of modern medicine.

In conclusion, while the clinical translation of nanoparticle technologies remains a work in progress, their potential to revolutionize drug delivery and patient care is unequivocal. With sustained research efforts, strategic collaborations, and regulatory harmonization, nanoparticle-based drug delivery systems are set to become a cornerstone of future precision and personalized therapies.

REFERENCES

[1] Zhang W, Wang Y, Wang X, et al. Chitosan-based nanoparticles for ocular drug delivery: Recent progress and advances. Int J Pharm. 2021;603:120679.

[2] Patel A, Cholkar K, Agrahari V, Mitra AK. Ocular drug delivery systems: An overview. World J Pharmacol. 2013;2(2):47–64.

[3] Yadav N, Khatak S, Singh S. Nanoparticles for pulmonary delivery: A review. Int J Pharm Sci Res. 2020;11(5):2075–85.

[4] Ranjan R, Krishnan A, Pankaj S, et al. Inhalable nanoparticles of rifampicin for efficient tuberculosis therapy. Drug Dev Ind Pharm. 2018;44(4):676–84.

[5] Kumar V, Sharma A, Saini A, et al. Colon-targeted delivery of 5-aminosalicylic acid via pH-sensitive

Eudragit-coated nanoparticles. Drug Dev Ind Pharm. 2020;46(5):772–80.

[6] Gupta A, Eral HB, Hatton TA, Doyle PS. Nanoemulsions: Formation, properties and applications. Soft Matter. 2016;12(11):2826–41.

[7] Suri SS, Fenniri H, Singh B. Nanotechnology-based drug delivery systems. J Occup Med Toxicol. 2007;2:16.

[8] Nasr M, Nawaz FA, Moftah NH. Nanotechnology in drug delivery: A review. J Adv Biomed Pharm Sci. 2018;1(2):35–42.

[9] Jain S, Jain AK, Pohekar M, et al. Novel mucoadhesive chitosan nanoparticles for oral delivery of insulin. Pharm Dev Technol. 2015;20(4):517–24.

[10] Wang AZ, Langer R, Farokhzad OC. Nanoparticle delivery of cancer drugs. Annu Rev Med. 2012;63:185–98.

[11] Torchilin VP. Multifunctional, stimuli-sensitive nanoparticulate systems for drug delivery. Nat Rev Drug Discov. 2014;13(11):813–27.

[12] Ventola CL. The nanomedicine revolution: Part 1: Emerging concepts. Pharm Ther. 2012;37(9):512–25.

[13] Danaei M, Dehghankhold M, Ataei S, et al. Impact of particle size and polydispersity index on the clinical applications of lipidic nanocarrier systems. Pharmaceutics. 2018;10(2):57.

[14] European Medicines Agency. Reflection paper on nanotechnology-based medicinal products for human use. 2013. https://www.ema.europa.eu

[15] U.S. Food and Drug Administration (FDA). Considering whether an FDA-regulated product involves the application of nanotechnology. 2014. https://www.fda.gov