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NANOPARTICLES IN DRUG DELIVERY SYSTEMS: RECENT ADVANCES, TARGETED DELIVERY, THERAPEUTIC APPLICATIONS AND FUTURE PERSPECTIVES

V. V. Lakshmi[1]*, G. Sisira[2], G. Harika[2], G. Mahesh[2], B. Chandrashekar[2], P. Hasya[2]

[1]Associate Professor, Department of Pharmaceutics, Koringa College of Pharmacy, Korangi, Kakinada, Andhra Pradesh, India.

[2]B. Pharmacy 4th Year Students, Koringa College of Pharmacy, Korangi, Kakinada, Andhra Pradesh, India.

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***Corresponding Author: V. V. Lakshmi**
Associate Professor, Department of Pharmaceutics, Koringa College of Pharmacy, Korangi, Kakinada, Andhra Pradesh, India.
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ABSTRACT

Nanoparticle-based drug delivery has emerged as an important approach for improving the therapeutic performance of pharmaceutical agents and overcoming several limitations associated with conventional dosage forms. Problems such as poor aqueous solubility, low bioavailability, premature degradation, non-specific distribution, and frequent administration can restrict effective drug therapy. Nanoparticles provide versatile carrier systems that can protect therapeutic molecules, modify their distribution, enhance drug localization, and regulate drug release. Based on their composition, nanoparticles can be broadly classified into organic, inorganic, lipid-based, polymeric, and hybrid systems. Their biological and pharmaceutical performance is strongly influenced by physicochemical properties such as particle size, morphology, surface charge, surface chemistry, crystallinity, porosity, and colloidal stability. Different preparation techniques, including top-down, bottom-up, and combined approaches, are used to obtain nanoparticles with desired characteristics.

KEYWORDS: Nanoparticles; Drug delivery; Nano carriers; Targeted drug delivery; Controlled release; Lipid nanoparticles; Polymeric nanoparticles; Gene and RNA delivery; Nano medicine.

1. INTRODUCTION

Drug delivery plays an important role in determining the therapeutic effectiveness of a pharmaceutical agent. Conventional dosage forms are often associated with limitations such as poor aqueous solubility, low bioavailability, rapid degradation, non-specific distribution, frequent administration and unwanted systemic effects. These limitations

become more significant when drugs are intended to act on specific organs, tissues or intracellular targets. Therefore, modern pharmaceutical research has increasingly focused on developing drug delivery approaches capable of improving drug stability, controlling drug release and increasing the concentration of therapeutic agents at the desired site of action.

Nanotechnology has emerged as one of the important approaches in this area because nanoscale carriers can be engineered to modify the physicochemical and biological behavior of therapeutic molecules.[1]

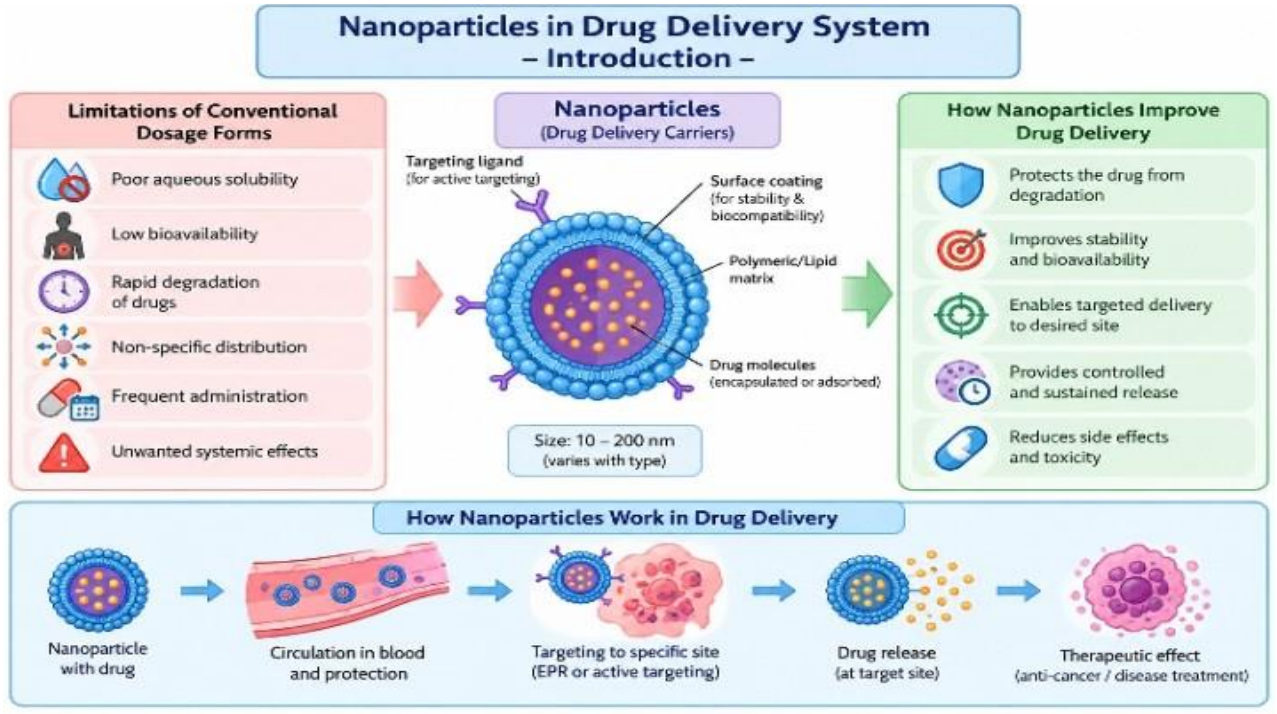


Figure 1: Schematic Representation of nanoparticles in drug delivery systems and their mechanism of action.

Nanoparticles are Nano sized particulate systems that can be used as carriers for therapeutic agents. Depending on the material and preparation method, the drug may be dissolved, entrapped, encapsulated or associated with the nanoparticle matrix.

Nanoparticles can be developed in different structural forms, including Nano spheres and Nano capsules. In Nano spheres, the drug is generally distributed within a matrix, whereas in Nano capsules the therapeutic agent may be contained within a core surrounded by a polymeric or other protective shell. The small dimensions and relatively high surface area of nanoparticles provide opportunities for modifying their surface characteristics and incorporating functional groups that can influence their interaction with biological systems.[2]

The interest in nanoparticle-based drug delivery is closely associated with the ability of these systems to address several problems encountered with conventional drug administration.

Poorly water-soluble drugs may show inadequate dissolution and consequently limited absorption and bioavailability. Encapsulation or incorporation of such drugs into nanoscale carriers can improve their apparent solubility and facilitate

their dispersion in biological fluids. Nanoparticles may also protect incorporated drugs from premature degradation during transport through the body. These characteristics can contribute to improved drug exposure at the intended site and may allow therapeutic effects to be achieved with more controlled drug concentrations.[3]

2. Overview of Nanoparticles

Nanoparticles are nanoscale particulate systems that have gained considerable importance in pharmaceutical and biomedical research because their small dimensions give them properties that differ from those of conventional bulk materials. At the nanoscale, changes in surface area, surface chemistry and other physicochemical characteristics can strongly influence how particles interact with biological systems. Depending on the formulation, a drug may be enclosed within the nanoparticle, incorporated into a polymeric or lipid matrix, attached to the surface, or associated with the carrier thro ugh different physical or chemical interactions. according to the One of the important characteristics of nanoparticles is their relatively large surface area compared with their volume. This feature provides opportunities for surface modification and attachment of functional molecules. The surface of a nanoparticle can be engineered using polymers, biomolecules or targeting ligands to modify its interaction with biological components. Such modifications may influence circulation, cellular uptake, tissue distribution and drug release after administration. The biological performance of nanoparticles is closely related to their physicochemical properties. Particle size, size distribution, morphology, surface charge, composition, hydrophobicity and surface chemistry can affect their behavior in biological environments. For example, changes in particle size can influence bio distribution and cellular uptake, while surface charge can alter interactions with cell membranes and proteins. Consequently, characterization of these properties is an important part of nanoparticle formulation and development.[4]

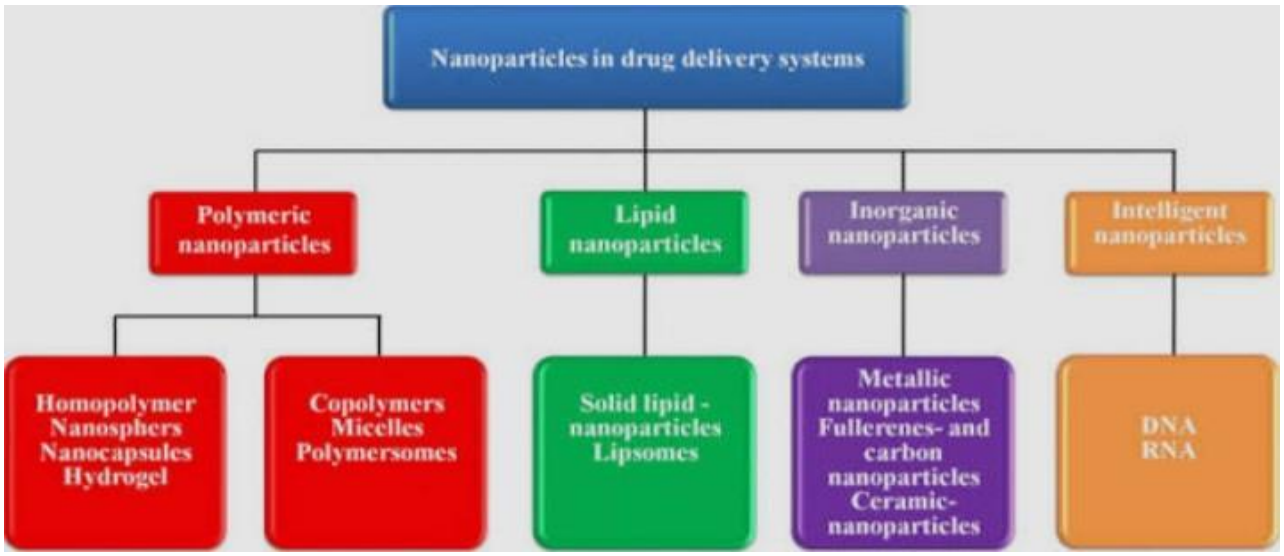


Figure 2: Classification of Nanoparticles used in Drug Delivery systems.

3. Classification of Nanoparticles

Nanoparticles can be classified according to their composition and structural characteristics. In drug delivery, the type of material used to prepare a nanoparticle influences its drug-loading capacity, stability, release behavior and interaction with biological systems. Based on their composition, important groups include organic, inorganic, lipid-based and polymeric nanoparticles.

Organic Nanoparticles

Organic nanoparticles are mainly composed of carbon-containing materials and include systems prepared from lipids, proteins, carbohydrates and other organic substances. Their composition can be modified to obtain desirable properties such as improved drug loading, stability and biological compatibility. Organic Nano carriers have been investigated for the delivery of small-molecule drugs, proteins, peptides and nucleic acids. Examples include micelles, liposomes, dendrites and protein-based nanoparticles.[5]

Inorganic Nanoparticles

Inorganic nanoparticles are prepared from materials such as gold, silver, silica and metal oxides. They possess distinctive optical, magnetic and surface properties, which make them useful not only for drug delivery but also for imaging and combined therapeutic applications.

Mesoporous silica nanoparticles, for example, contain pores that can accommodate therapeutic molecules and can be modified to achieve controlled drug release.[6]

Lipid-Based Nanoparticles

Lipid-based nanoparticles use lipids as their major structural components and include liposomes, solid lipid nanoparticles, nanostructured lipid carriers and lipid nanoparticles.

These systems are widely studied because they can accommodate both hydrophilic and hydrophobic drugs and can improve drug stability and delivery. Liposomes contain an aqueous core surrounded by a lipid bilayer, allowing different types of therapeutic molecules to be incorporated.[7]

Polymeric Nanoparticles

Polymeric nanoparticles are prepared using natural or synthetic polymers and are commonly described as Nano spheres or Nano capsules. Biodegradable polymers such as PLGA, PLA, chitosan and related materials are frequently investigated for pharmaceutical applications. A major advantage of polymeric nanoparticles is their ability to provide controlled and sustained drug release. Their surface can also be modified with polymers or targeting ligands to influence tissue distribution and cellular uptake. However, particle-size control, reproducible manufacturing, stability and toxicity assessment remain important considerations during development.[8]

4. Physicochemical Properties of Nanoparticles

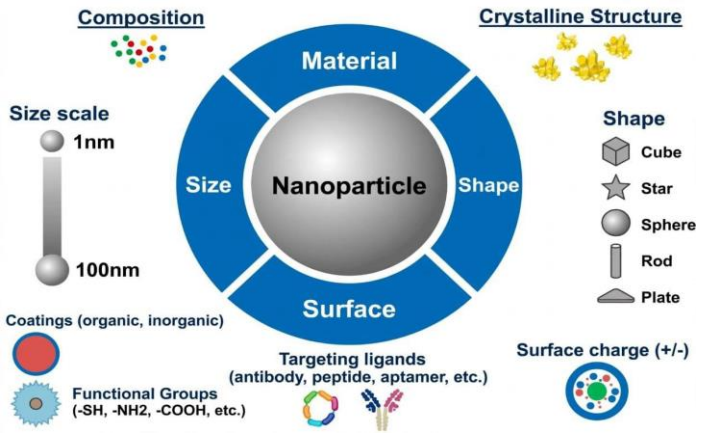


Figure 3: Physicochemical properties and structural characteristics of nanoparticles.

The therapeutic performance of nanoparticle-based drug delivery systems is strongly influenced by their physicochemical characteristics. Properties such as particle size, size distribution, shape, surface charge, surface chemistry, hydrophobicity, morphology, crystallinity, porosity, and colloidal stability determine how nanoparticles interact with drugs, biological fluids, cellular membranes, and target tissues. Therefore, proper control and characterization of these properties are essential for developing reproducible and effective Nano carriers. Particle size and size distribution are among the most important characteristics of nanoparticles. Reduction of particle dimensions increases the surface-area-to-volume ratio, which can influence drug loading, dissolution, cellular interaction, bio distribution, and drug release. Particle size can also affect the circulation and clearance of Nano carriers in the body. However, the biological effect of particle size is not governed by size alone and may also depend on factors such as particle composition, surface characteristics, aggregation, and route of administration.[9]

Overall, the physicochemical properties of nanoparticles are interrelated rather than independent. A change in one characteristic, such as particle size or surface charge, may influence other properties and ultimately alter the biological performance of the Nano carrier. Comprehensive characterization using complementary techniques, including dynamic light scattering, electron microscopy, zeta-potential analysis, X-ray diffraction, and other appropriate methods, is therefore essential before evaluating nanoparticles for pharmaceutical applications.[10]

5. Preparation and Fabrication Techniques

The preparation of nanoparticles is an important step in the development of effective drug delivery systems because the fabrication process can influence particle size, morphology, surface characteristics, drug-loading capacity, stability, and release behavior.

Depending on the starting material and the mechanism used to produce the nanoscale structure, nanoparticle fabrication methods are broadly classified into top-down and bottom-up approaches. In some formulations, both strategies may also be combined to obtain better control over particle characteristics.

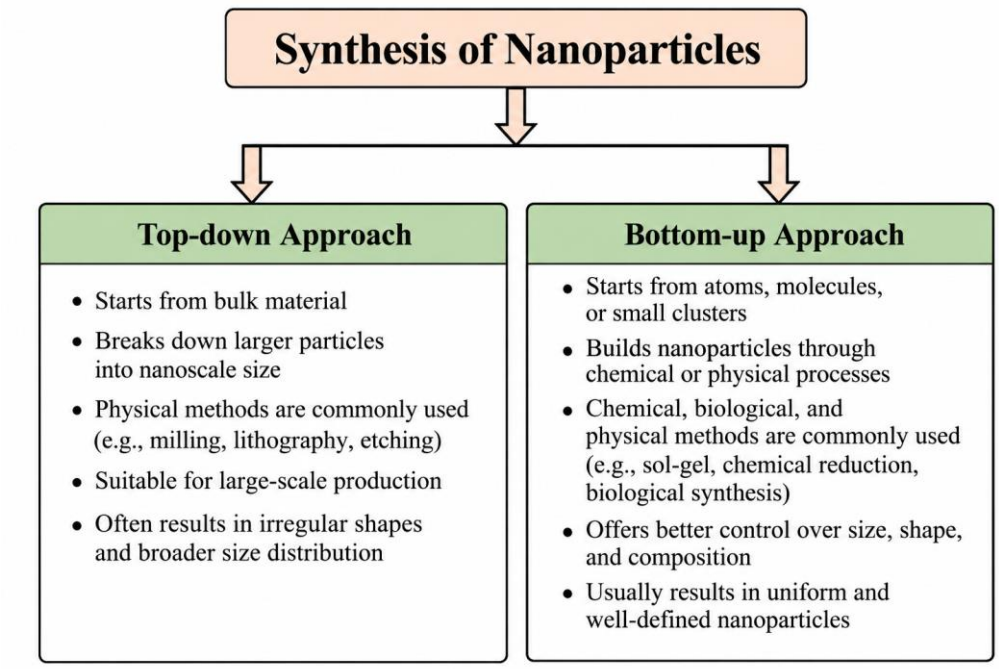
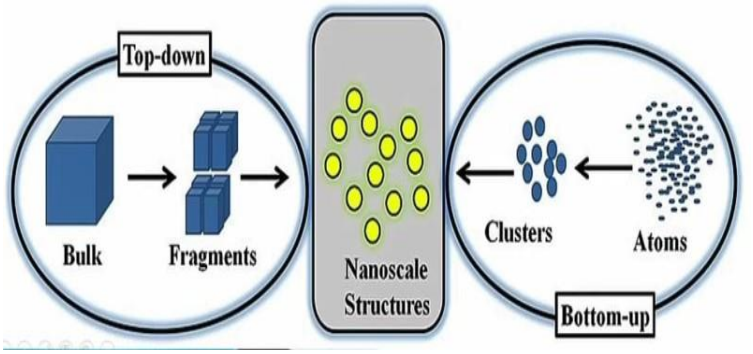


Figure 4: Schematic Representation of Top_Down and Bottom _up Approaches for Nanoparticles.

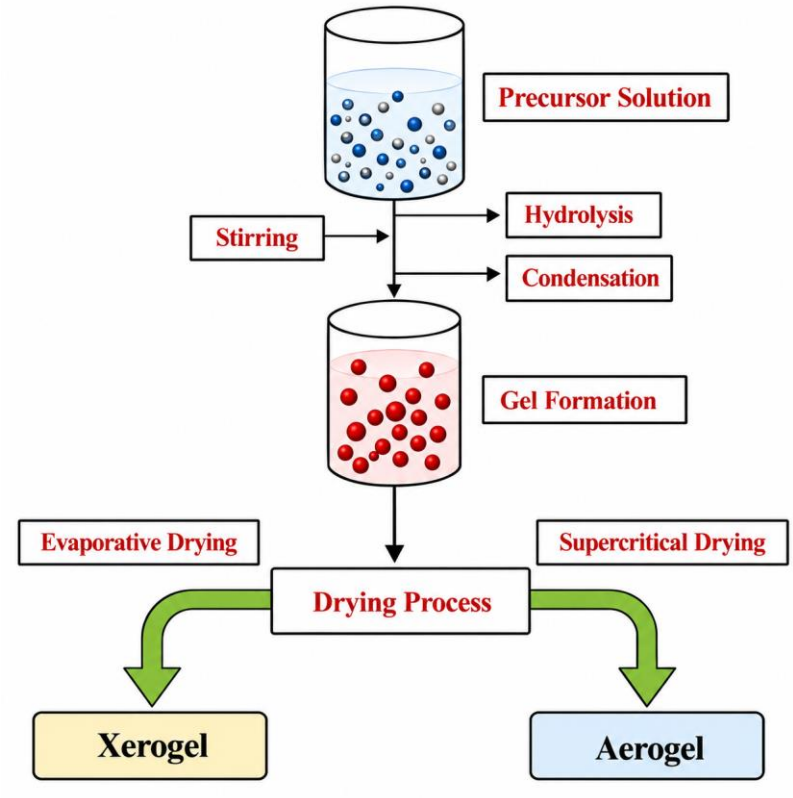
Top-Down Approaches

Top-down techniques involve the conversion of relatively large particles or bulk materials into Nano sized structures by applying mechanical or physical energy. Common techniques include high-pressure homogenization, wet milling, grinding, laser ablation, lithography, and related size-reduction methods. In pharmaceutical applications, wet milling and high-pressure homogenization are particularly important for producing drug nanocrystals and Nano suspensions of poorly water-soluble drugs.During top-down processing, the initial material is progressively reduced in size until nanoparticles or nanocrystals are obtained.

Process parameters such as milling time, applied pressure, temperature, stabilizer concentration, and the mechanical properties of the starting material can affect the final particle size and distribution.[11]



Bottom-Up Approaches



Bottom-up techniques produce nanoparticles by assembling smaller molecular, atomic, or ionic components into larger nanoscale structures. Precipitation, nanoprecipitation, controlled crystallization, sol–gel processes, self-assembly, reduction methods, and certain supercritical-fluid techniques are examples of bottom-up strategies. In drug nanocrystal

preparation, precipitation occurs when a drug solution becomes supersaturated, resulting in nucleation followed by controlled particle growth. The final characteristics of nanoparticles prepared through bottom-up methods depend strongly on factors such as solvent and ant solvent selection, concentration, mixing conditions, temperature, pH, super saturation, and the presence of stabilizing agents.[12]

Combined Approaches

In some cases, top-down and bottom-up strategies can be used together. Such combination Methods can take advantage of the size-reduction capability of top-down processing and The controlled particle formation associated with bottom-up techniques. This approach may Improve control over particle size and distribution while reducing some of the limitations Associated with using either method alone.[13]

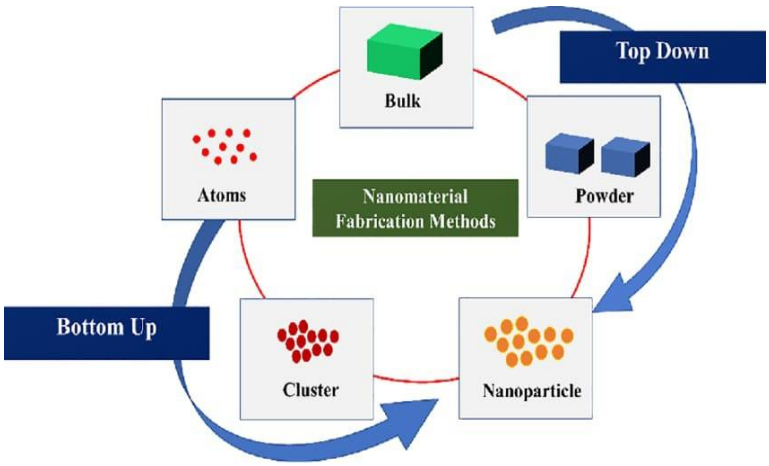


Figure 5: Schematic Representation of Top_Down and Bottom _up Nanomaterial fabrication Metgods.

6. Mechanisms of Drug Loading and Release

The effectiveness of a nanoparticle-based drug delivery system depends not only on the properties of the Nano carrier but also on how efficiently the therapeutic agent is incorporated and subsequently released at the desired site. Drug loading determines the amount of active pharmaceutical ingredient that can be incorporated into the nanoparticle, whereas the release mechanism controls the rate and extent at which the drug becomes available. Depending on the nature of the drug and carrier, loading can occur through physical encapsulation, adsorption, non-covalent interactions, or covalent attachment.

Drug Loading Mechanisms

Physical encapsulation is one of the commonly used approaches for incorporating drugs into nanoparticles. In this method, the drug is entrapped within the core, matrix, pores, or internal compartments of the Nano carrier without forming a permanent chemical bond with the carrier. Hydrophilic and hydrophobic drugs can be incorporated depending on the structure and composition of the nanoparticle. This approach is useful when preservation of the original chemical structure of the drug is important. Adsorption and non-covalent loading involve the association of drug molecules with the surface or internal regions of nanoparticles through relatively weak interactions such as electrostatic forces, hydrogen bonding, hydrophobic interactions, and Vander Waals forces.

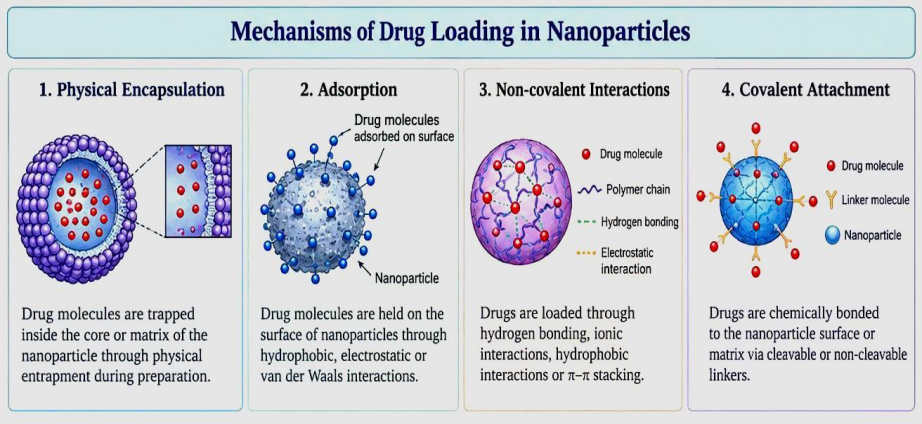


Figure 6: Mechansims of Drug Loading and Release from Nanoparticles.

These interactions can provide relatively simple drug-loading strategies, although the strength of the drug–carrier interaction can influence loading efficiency and release behavior.[14]

Drug Release Mechanism

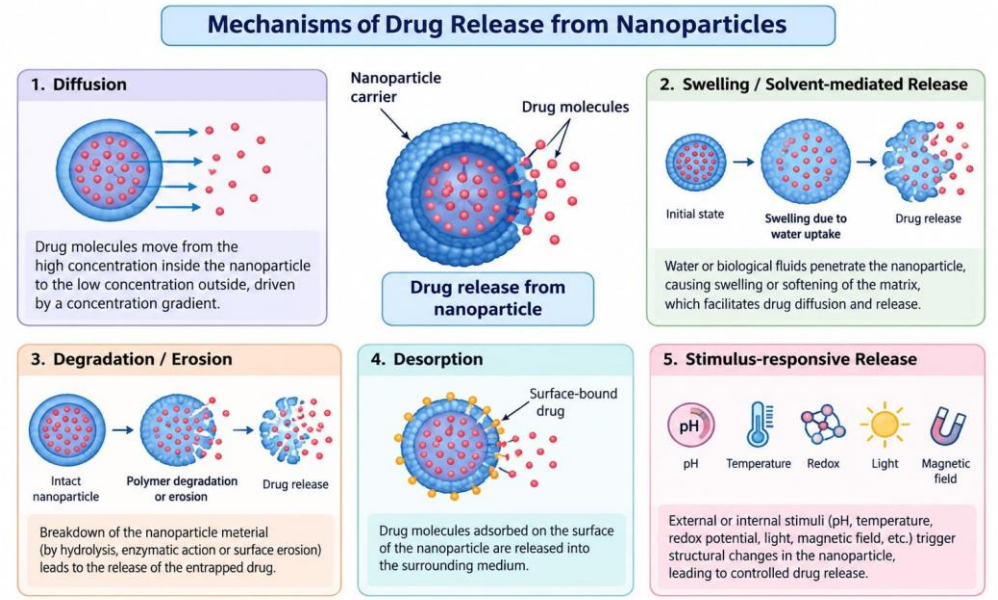


Figure 7: Targeted and stimuli_responsive drug delivery using nanoparticles.

Once nanoparticles reach the biological environment, the incorporated drug can be released through one or more mechanisms. The major mechanisms include diffusion, swelling or solvent-mediated transport, degradation or erosion, desorption, and stimulus-responsive release. In many formulations, more than one mechanism operates simultaneously rather than a single mechanism being responsible for the entire release profile. Diffusion-controlled release occurs when drug molecules move from the nanoparticle toward the surrounding medium because of a concentration gradient. The drug may diffuse through the polymer matrix, pores, or a surrounding membrane. Factors such as particle structure, polymer permeability, drug solubility, and diffusion distance can influence the rate of release.[15]

Overall, drug loading and release are closely interconnected. Strong drug–carrier interactions may improve drug retention but can also slow release, whereas weaker interactions may facilitate rapid release but reduce drug stability

during circulation or storage. Therefore, an appropriate balance between loading efficiency, carrier stability, release rate, and responsiveness to the biological environment is necessary for designing an effective nanoparticle drug delivery system.[16]

7. Recent Advances in Nanoparticle-Based Drug Delivery

Recent advances in nanotechnology have improved the design of nanoparticle-based drug delivery systems by providing better control over particle size, surface properties, drug loading, release, and targeting. Modern nanoparticles are increasingly designed to improve drug solubility, stability, bioavailability, and accumulation at desired tissues while reducing unwanted systemic exposure. Lipid nanoparticles (LNPs) have emerged as important carriers for nucleic-acid therapeutics, particularly mRNA. Their ability to protect fragile RNA molecules and facilitate intracellular delivery has expanded their application from vaccines to gene therapy, cancer treatment, and other therapeutic approaches.[17]

Despite these advances, challenges such as long-term stability, toxicity, bio distribution, reproducible manufacturing, scalability, and clinical translation remain important.

Therefore, current research is increasingly focused on developing safe, reproducible, and precisely engineered nanoparticles suitable for clinical applications. Overall, nanoparticle drug delivery is progressing from conventional carriers toward targeted, multifunctional, stimuli-responsive, and precision-engineered systems, offering opportunities for more effective and controlled therapeutic delivery.[18]

8. Targeted Drug Delivery Using Nanoparticles

Targeted drug delivery using nanoparticles is designed to increase drug accumulation at the desired site while reducing exposure to healthy tissues. Nanoparticles can be engineered by controlling their size, surface properties, composition, and functional groups to improve circulation, tissue accumulation, cellular uptake, and controlled drug release. Targeting strategies are broadly classified into passive targeting, active targeting, and stimuli-responsive targeting.

Passive Targeting

Passive targeting depends mainly on the natural distribution of nanoparticles within the body and differences between diseased and normal tissues. In cancer therapy, the enhanced permeability and retention (EPR) effect may allow appropriately designed nanoparticles to accumulate in tumors because of abnormal vascular permeability and impaired lymphatic drainage. Particle size, shape, surface characteristics, circulation time, and tumor vascular properties can influence this process. However, the extent of passive accumulation can vary considerably between tumors and patients.[19]

Active Targeting

Active targeting involves modifying the nanoparticle surface with specific targeting ligands, such as antibodies, peptides, proteins, a tamers, or carbohydrates. These ligands can recognize receptors or other molecular markers that are more abundant on particular cells or tissues. Following recognition, receptor-mediated interactions may increase cellular internalization and intracellular delivery of the nanoparticle-associated drug. Active targeting is therefore mainly intended to improve cellular or tissue-level localization rather than relying solely on passive accumulation.[20]

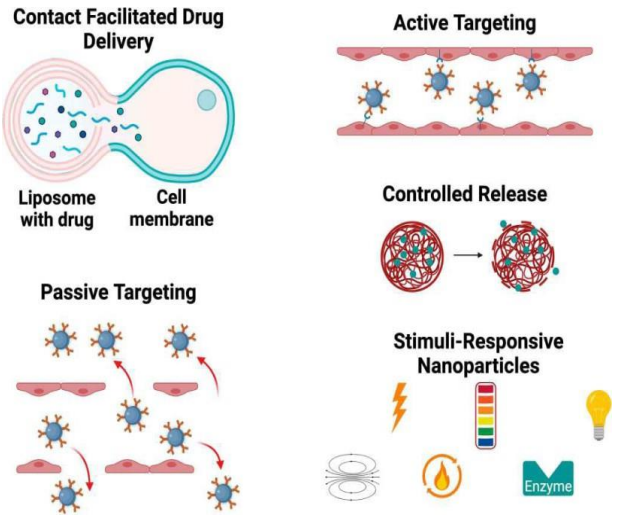


Figure 8: Platelet Membrane _coated Nanoparticles for Targeted Drug delivery and immune evasion.

Stimuli-Responsive Targeting

Stimuli-responsive nanoparticles are designed to alter their properties or release their drug cargo in response to specific biological or externally applied signals. Internal stimuli, including acidic pH, enzymes, and redox conditions, can be used to trigger drug release within particular biological environments Overall, passive, active, and stimuli-responsive approaches can be used individually or in combination. Their integration may improve nanoparticle accumulation, cellular uptake, and controlled drug release, although biological variability, targeting efficiency, stability, and clinical translation remain important challenges.[21]

9. Nanoparticles for Controlled and Sustained Drug Release

Nanoparticles can be designed to control the rate and duration of drug release, thereby maintaining therapeutic drug levels for a longer period and potentially reducing the frequency of administration. Their small size, large surface area, and tunable composition allow drug release to be modified according to the properties of the drug and the intended therapeutic application.

Controlled drug release can occur through different mechanisms, mainly diffusion, polymer degradation, erosion, desorption, and swelling of the carrier.

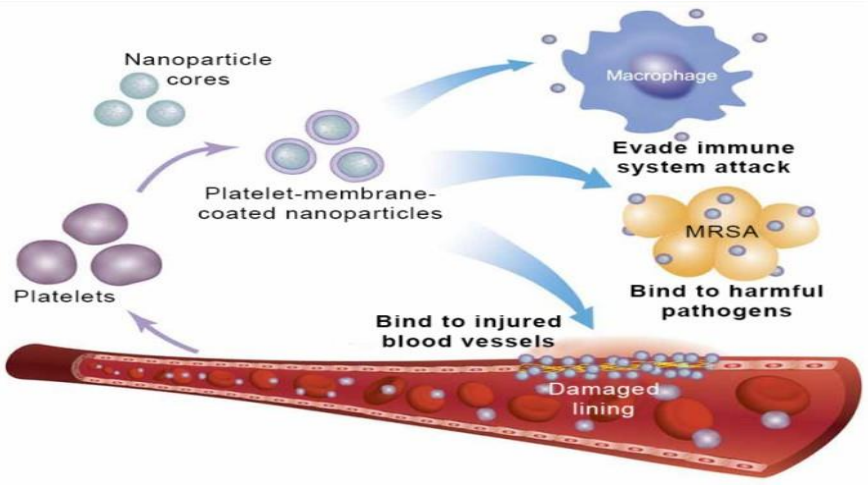


Figure 9: Biological Barriers that Nanoparticles can help overcome.

The composition, particle size, surface properties, drug–carrier interactions, and polymer characteristics can influence the release rate. Polymeric nanoparticles are particularly useful because their degradation and drug diffusion can be adjusted during formulation. Sustained drug release aims to maintain drug availability over an extended period rather than producing a rapid increase in drug concentration. This approach may help reduce fluctuations in drug levels and decrease dosing frequency. Recent approaches use stimuli-responsive and smart nanoparticles in which drug release is influenced by conditions such as pH, enzymes, temperature, redox state, light, ultrasound, or magnetic fields. These systems can provide additional control over the timing and location of drug release and may be combined with targeting strategies.[22]

10. Therapeutic Applications of Nanoparticles

Nanoparticle-based drug delivery systems have been investigated for a wide range of diseases because they can improve drug solubility, stability, bioavailability, targeting, and controlled release. Consequently, nanoparticles are being explored as carriers for small-molecule drugs, proteins, nucleic acids, and other therapeutic agents.

Cancer Therapy

Nanoparticles are widely investigated in cancer treatment for delivering anticancer drugs more selectively to tumor tissues. They can improve the solubility and stability of poorly water-soluble drugs and provide controlled release at the tumor site. Surface functionalization with specific ligands can further support tumor-cell targeting and cellular uptake. Nanoparticles are also being studied for combination therapy, gene delivery, immunotherapy, and transonic applications.

Infectious Diseases

Nanoparticles can improve the delivery of antimicrobial and antiviral agents by protecting drugs from premature degradation and enhancing their distribution to infected tissues. They have been investigated for bacterial, viral, fungal, and parasitic infections. Nano carriers may also facilitate localized delivery and help improve the effectiveness of drugs against microorganisms that are difficult to reach using conventional formulations.[23]

Cardiovascular Diseases

In cardiovascular medicine, nanoparticles are being explored for the targeted delivery of drugs to blood vessels, cardiac tissues, and atherosclerotic lesions. They can improve drug solubility and provide controlled delivery while potentially reducing exposure to non-target tissues. Research has investigated nanoparticle-based approaches for atherosclerosis, myocardial injury, thrombosis, and vascular disorders.

Neurological Disorders

Nanoparticles are being studied for neurological diseases because conventional drugs may have limited access to the brain due to the blood–brain barrier. Appropriately engineered nnanoparticles can potentially improve drug transport toward the central nervous system and support delivery of therapeutic molecules for conditions such as Alzheimer's disease, Parkinson's disease, brain tumors, and other neurological disorders.[24]

Diabetes and Metabolic Disorders

Nanoparticle systems have been investigated for improving the delivery of antidiabetic drugs, peptides, proteins, and nucleic acids. They can help protect sensitive therapeutic molecules from degradation and may provide sustained or

controlled release. Research is also exploring nanoparticle-based approaches for improving insulin delivery and targeting tissues involved in metabolic regulation.

Inflammatory Diseases

Nanoparticles can be used to deliver anti-inflammatory agents directly to sites of inflammation and may improve drug accumulation while reducing systemic exposure. They have been investigated in conditions involving chronic inflammation, autoimmune diseases, and inflammatory disorders. Nano carriers can also be designed to respond to inflammatory micro environmental conditions, providing more localized drug release.[25]

12. Nanoparticles for Vaccine Delivery and Immunotherapy

Nanoparticles have become promising carriers for vaccine delivery because they can protect antigens and other vaccine components from degradation and improve their delivery to immune cells. Their size, surface properties and composition can be modified to influence bio distribution and interaction with antigen-presenting cells Nanoparticle-based vaccines can facilitate the uptake of antigens by dendritic cells and macrophages, which are important antigen-presenting cells. After cellular uptake, the antigen can be processed and presented to T cells, contributing to the development of cellular and humoral immune responses. Nanoparticles can also carry antigens together with adjuvants, allowing both components to be delivered to the same immune cells . Several nanoparticle platforms, including liposomes, polymeric nanoparticles, lipid nanoparticles and inorganic nanoparticles, have been investigated for vaccine development. Lipid nanoparticles are particularly important for nucleic-acid delivery because they can protect RNA molecules and facilitate their intracellular delivery. This has supported the development of nanoparticle-based mRNA vaccine platforms.[26]

13. Role of Nanoparticles in Overcoming Biological Barriers

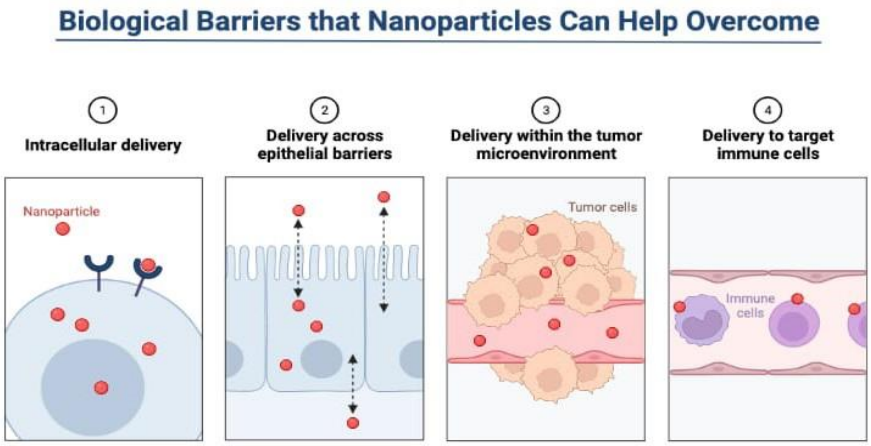


Figure 10: Biological.

Barriers that Nanoparticles can help overcome

Biological barriers can restrict the movement of therapeutic drugs to their intended sites and reduce treatment efficiency. Nanoparticles can help overcome some of these limitations by protecting drugs from degradation, modifying their distribution and improving cellular uptake. The blood-brain barrier (BBB) is one of the major obstacles in delivering drugs to the central nervous system. Its tightly regulated structure limits the entry of many therapeutic molecules into brain tissue. Nanoparticles can be engineered with appropriate size, surface properties and composition

to improve their interaction with the BBB and facilitate transport into the brain Surface modification is another important strategy. Targeting ligands such as peptides, antibodies and receptor-binding molecules can be attached to nanoparticles to promote interactions with specific receptors on barrier-forming cells.[27]

13.1 Advantages of Nanoparticle-Based Drug Delivery Systems

- Improved drug solubility – Nanoparticles can enhance the solubility of poorly water-soluble drugs, improving their therapeutic performance.
- Enhanced bioavailability – They can increase drug absorption and improve the amount of drug reaching systemic circulation.
- Controlled and sustained drug release – Nanoparticles can release drugs gradually over an extended period, reducing the need for frequent dosing.
- Targeted drug delivery – They can deliver drugs preferentially to specific tissues, organs, or cells, thereby improving therapeutic effectiveness.
- Reduced systemic toxicity – Targeted delivery can minimize drug exposure to healthy tissues and reduce unwanted side effects.
- Protection of drugs from degradation – Nanoparticles can protect drugs from chemical, enzymatic, and environmental degradation.

13.2 Challenges and Limitations of Nanoparticle-Based Drug Delivery Systems

Despite their potential, nanoparticle-based drug delivery systems have some important limitations. Safety and toxicity remain major concerns because nanoparticle size, surface charge, composition and accumulation in tissues can influence their biological effects.

Therefore, adequate biocompatibility and long-term safety evaluation are necessary. Another challenge is manufacturing and scale-up. Maintaining consistent particle size, surface properties, drug loading and batch-to-batch quality during large-scale production can be difficult. Complex formulations may also increase production cost and reduce reproducibility. Regulatory requirements and the lack of standardized characterization methods further complicate the development of nanoparticle-based products.[28]

13.3 Safety, Toxicity and Biocompatibility

Safety and biocompatibility are important considerations in nanoparticle-based drug delivery. The biological response to nanoparticles depends on factors such as particle size, shape, surface charge, composition, dose and surface characteristics. Therefore, the safety of one nanoparticle formulation cannot be generalized to all nanoparticle system Nanoparticles may produce unwanted effects through oxidative stress, inflammation, immune reactions, cellular damage and nontoxicity. Proper material selection, surface modification and careful control of nanoparticle properties can help improve safety and reduce toxicity.[29]

13.4 Regulatory Considerations and Clinical Translation

Regulatory evaluation of nanoparticle-based medicines requires careful assessment of quality, safety and efficacy. Important factors include particle size, surface properties, composition, drug loading, stability, manufacturing process and other critical quality attributes. Standardized characterization methods are needed to ensure consistent product quality .Clinical translation can be challenging because laboratory formulations may be difficult to reproduce on a large

scale. Scale-up, batch-to-batch consistency, long-term stability, toxicity evaluation and suitable preclinical models are important before clinical testing. Collaboration between researchers, manufacturers and regulatory agencies can help address these challenges at an early stage.[30]

14. Future Perspectives

The future of nanoparticle-based drug delivery is expected to focus on more precise, personalized and multifunctional delivery systems. Advances in lipid, polymeric and biomimetic nanoparticles may improve delivery of small molecules, proteins, RNA and gene-editing therapeutics while providing better control over bio distribution and drug release Integration of artificial intelligence and machine learning may help researchers predict nanoparticle properties, optimize formulations, improve drug loading and release, and reduce trial-and-error during development. These approaches may also support personalized treatment and prediction of toxicity and therapeutic responses. Future development will also require better scale-up methods, standardized characterization, predictive biological models and regulatory strategies. Improving these areas can help bridge the gap between laboratory research and clinical application and support the development of safer and more reproducible Nano medicines.[31]

15. CONCLUSION

Nanoparticle-based drug delivery has developed into a versatile approach for addressing several limitations associated with conventional pharmaceutical formulations. By appropriately selecting the carrier material and controlling its physicochemical characteristics, nanoparticles can be designed to improve drug solubility, protect sensitive therapeutic molecules, modify their distribution, and regulate the duration and location of drug release. The different classes of nanoparticles provide flexibility for delivering small-molecule drugs as well as proteins, peptides, nucleic acids, and other therapeutic agents.

Targeting and controlled-release strategies have further expanded the potential of these systems. Passive targeting, ligand-mediated active targeting, and stimulus-responsive approaches can be incorporated according to the therapeutic objective. Consequently, nanoparticle systems are being investigated across several areas, including cancer, infectious diseases, cardiovascular and neurological disorders, inflammatory conditions, diabetes, gene and RNA delivery, vaccination, and immunotherapy.

Future research should move toward nanoparticle systems that provide greater precision, improved tissue selectivity, and multifunctional therapeutic capabilities. The incorporation of artificial intelligence and machine-learning approaches may assist in formulation design, prediction of nanoparticle behavior, and optimization of drug loading and release. At the same time, standardized characterization methods, improved scale-up procedures, predictive biological models, and appropriate regulatory strategies will be important for bridging the gap between laboratory research and clinical application.

Overall, nanoparticle technology provides a strong foundation for the development of advanced drug delivery systems. Continued research integrating pharmaceutical science, nanotechnology, biology, safety assessment, manufacturing, and regulatory science will be important for converting promising nanoparticle formulations into reproducible and clinically useful therapeutic products.

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