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Nanoparticle-Based Drug Delivery Systems: Recent Advances and Challenges

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Abstract
Nanoparticle-based drug delivery systems have emerged as a transformative approach in modern pharmaceutics, offering improved therapeutic efficacy, enhanced bioavailability, and reduced toxicity compared to conventional dosage forms. These systems utilize nanoscale carriers such as polymeric nanoparticles, liposomes, dendrimers, solid lipid nanoparticles, and metallic nanoparticles to deliver drugs in a controlled and targeted manner. Recent advances have focused on surface modification, ligand-mediated targeting, and stimuli-responsive systems that enable site-specific drug release, particularly in the treatment of cancer, neurological disorders, and infectious diseases. Additionally, innovations in nanotechnology have facilitated the development of multifunctional nanoparticles capable of simultaneous diagnosis and therapy (theragnostic). Despite these promising developments, several challenges remain, including issues related to large-scale manufacturing, stability, toxicity, regulatory approval, and long-term safety. This review highlights the recent progress in nanoparticle-based drug delivery systems, discusses their applications in various therapeutic areas, and addresses the critical challenges that must be overcome for their successful clinical translation.

Keywords: Nanoparticles, Drug Delivery Systems, Targeted Drug Delivery, Nanotechnology, Bioavailability, Controlled Release

Graphical Abstract

Fig 1: Nanoparticles

Introduction

The development of effective drug delivery systems remains a central focus in pharmaceutical research, as conventional dosage forms often suffer from limitations such as poor bioavailability, lack of target specificity, rapid drug degradation, and systemic side effects. To overcome these challenges, advanced drug delivery approaches have been explored, among which nanoparticle-based drug delivery systems have gained significant attention in recent years [1-4].

Nanoparticles are submicron-sized colloidal carriers, typically ranging from 1 to 1000 nm, designed to transport therapeutic agents in a controlled and targeted manner. These systems include a wide range of carriers such as polymeric nanoparticles, liposomes, solid lipid nanoparticles, dendrimers, and metallic nanoparticles. Due to their small size and large surface area,

nanoparticles offer unique physicochemical properties that enhance drug solubility, stability, and permeability across biological barriers [5-8].

One of the major advantages of nanoparticle-based drug delivery is their ability to achieve targeted delivery, either through passive targeting (such as enhanced permeability and retention effect) or active targeting via ligand-receptor interactions. This is particularly beneficial in the treatment of diseases like cancer, where site-specific drug delivery can significantly improve therapeutic outcomes while minimizing toxicity to healthy tissues. Additionally, nanoparticles enable controlled and sustained drug release, thereby reducing dosing frequency and improving patient compliance [9-11].

Recent advances in nanotechnology have further expanded the potential of these systems, including the development of stimuli-responsive nanoparticles that release drugs in response to environmental triggers such as pH, temperature, or enzymes. Moreover, multifunctional nanoparticles have been designed for theragnostic applications, combining diagnostic and therapeutic functions within a single platform [12-15].

Despite these promising advancements, several challenges hinder the widespread clinical application of nanoparticle-based drug delivery systems. Issues such as toxicity, biocompatibility, large-scale production, stability, and regulatory approval need to be carefully addressed. Furthermore, long-term safety and environmental concerns remain areas of ongoing investigation [16-17].

This review aims to provide a comprehensive overview of nanoparticle-based drug delivery systems, focusing on their types, preparation methods, characterization, recent advances, therapeutic applications, and the challenges that must be overcome to ensure successful clinical translation [18].

Literature survey

1. Haji pour and Ghias Vand (2024) reviewed nanoparticle carriers and reported that nanoparticle-based systems enhance drug solubility, bioavailability, and therapeutic efficiency while reducing systemic toxicity compared to conventional drug delivery systems [19].

2. Nikandish *et al.* (2024) highlighted that nanoparticle-based precision drug delivery systems can effectively overcome biological barriers (systemic, cellular, and microenvironmental), enabling targeted and personalized therapy [20].

3. Beach and co-authors (2024) emphasized that polymeric nanoparticles offer excellent control over physicochemical properties such as size, shape, and surface functionality, making them ideal for controlled and sustained drug delivery [21].

4. Gao *et al.* (2024) reported that engineered nanoparticles can successfully cross the blood–brain barrier, providing new opportunities for the treatment of central nervous system disorders [22].

5. Kumarasamy *et al.* (2024) reviewed clinical trials of advanced nanoparticles and found that nanoparticle-based formulations show promising results in cancer and infectious disease treatment [23].

6. Xiaoxia Cheng, Qiong Xie, Yang Sun Reviews nanomaterials for targeted drug delivery, design strategies, therapeutic approaches and challenges in intravascular and extravascular targeting [24].

7. Azeez Yusuf, Awatif Rashed Z. *et al.* (2023) Discusses how nanoparticle properties influence biological interactions and delivery outcomes [25].

8. Mingshan Li, Xiaowei Sun, *et al.* (2023) Co-delivery of drugs and genes using nanoparticles in medical (and agricultural) applications [26].

9. Md. Harun-Or-Rashid *et al.* (2023) Advances in micro/nano carriers based on natural and Md. Harun-Or-Rashid *et al* Advances in micro/nano carriers based on natural and synthetic biomaterials [27].

10. Rouba D. Al Bostami, Waad H. Abuwatfa, Ghaleb A. Husseini *et al*, (2022) Nanocarrier co-delivery systems for improved cancer therapy and the associated challenges [28].

Classification of Nanoparticles:

1. Based on Composition (Most Common Classification)

A. Organic Nanoparticles

Made from carbon-based materials; generally **biodegradable and biocompatible**.

Polymeric Nanoparticles

Made from polymers like PLGA, chitosan

Types:

- Nanospheres
- Nano capsules
- Applications: Controlled drug release, cancer therapy [29-30]

Lipid-Based Nanoparticles

- Liposomes
- Solid Lipid Nanoparticles (SLNs)
- Nanostructured Lipid Carriers (NLCs)
- Advantages: Low toxicity, good drug encapsulation [31]

Dendrimers

- Highly branched, tree-like structures
- Precise size and functional groups [32]

Micelles

- Self-assembled amphiphilic molecules
- Ideal for poorly water-soluble drugs [33]

B. Inorganic Nanoparticles

Made from metals or minerals; often used in imaging and therapy [34, 35].

Metal Nanoparticles

- Gold (Au), Silver (Ag), Platinum
- Applications: Imaging, photothermal therapy

Metal Oxide Nanoparticles

- Iron oxide (Fe_3O_4), Zinc oxide (ZnO)
- Used in MRI, drug targeting

Silica Nanoparticles

- Mesoporous silica
- High drug loading capacity

Quantum Dots

- Semiconductor nanoparticles
- Used in diagnostics and imaging

C. Carbon-Based Nanoparticles

- Carbon nanotubes (CNTs)
- Fullerenes

- Graphene oxide

Applications: Drug delivery, gene delivery, biosensors [36, 37]

2. Based on Structure

Nanospheres

Matrix system (drug uniformly dispersed)

Nano capsules

Core-shell structure (drug enclosed inside)

Nanorods / Nanotubes

Rod-shaped or tubular structures

Nanofibers

Fiber-like structures used in tissue engineering [38-39]

3. Based on Origin [40-42]

Natural Nanoparticles

- . Proteins (albumin nanoparticles)
- . Polysaccharides (chitosan, alginate)

Synthetic Nanoparticles

- Chemically synthesized polymers
- Metals and engineered materials

4. Based on Functionality

Targeted Nanoparticles

Surface modified with ligands/antibodies

Stimuli-Responsive Nanoparticles

Respond to pH, temperature, light, enzymes

Stealth Nanoparticles

PEGylated to avoid immune detection [43-44]

5. Based on Application

- Drug delivery nanoparticles
- Gene delivery systems
- Diagnostic nanoparticles (imaging)
- Theragnostic nanoparticles (therapy + diagnosis) [45]

Methods of Preparation

Nanoparticle-based drug delivery systems (NDDS) are prepared using a variety of physicochemical, biological, and engineering approaches designed to control particle size, drug loading, release, and targeting. Below is a structured, exam-ready overview covering methods of preparation, recent advances, and challenges [46].

1. Methods of Preparation of Nanoparticle-Based Drug Delivery Systems

A. Top-Down Approaches [47, 48]

These methods reduce bulk materials into nanosized particles.

1. High-Pressure Homogenization

- Drug particles are broken down under high pressure.
- Produces **nanocrystals** with improved solubility.
- Widely used in pharmaceutical industries.

2. Milling (Mechanical Attrition)

- Uses grinding media to reduce particle size.
- Simple but may cause contamination and instability.

3. Ultrasonication

- Uses ultrasonic waves to break particles.
- Often combined with emulsification techniques.

B. Bottom-Up Approaches

These involve building nanoparticles from molecular level.

1. Nanoprecipitation (Solvent Displacement)

- Polymer + drug dissolved in solvent → added to non-solvent → nanoparticle formation.
- Simple and widely used for **polymeric nanoparticles**.

2. Emulsification Methods [49, 50]

Emulsion–solvent evaporation

Emulsion–solvent diffusion

Drug is dissolved in organic solvent → emulsified → solvent removed → nanoparticles formed.

3. Salting-Out Method

Uses electrolytes to separate solvent and induce nanoparticle formation.

4. Dialysis Method

Solvent exchange through membrane → controlled nanoparticle formation.

5. Supercritical Fluid Technology

Uses supercritical CO_2 for particle formation.

Produces solvent-free, uniform nanoparticles [49, 50].

C. Polymerization-Based Methods [51]

1. Emulsion Polymerization

Monomers polymerize in emulsion droplets → nanoparticles.

2. Interfacial Polymerization

Polymer forms at interface of two immiscible phases.

3. Controlled/Living Polymerization

Provides precise cont That's what I. rol over molecular weight and structure.

D. Ionic Gelation / Coacervation

Based on electrostatic interaction between polymers (e.g., chitosan).

Mild conditions → suitable for **proteins and genes [52]**.

E. Lipid-Based Nanoparticles Preparation

1. High Shear Homogenization & Ultrasonication

Used for **solid lipid nanoparticles (SLNs)**.

2. Microemulsion Technique

Thermodynamically stable systems → nanoparticle formation after cooling.

3. Solvent Injection Method

Lipids dissolved in solvent → injected into aqueous phase → nanoparticle formation [53, 54].

F. Biological (Green Synthesis) Methods

Use microorganisms, plant extracts, or enzymes.

Eco-friendly and biocompatible [55].

G. Microfluidics-Based Methods (Modern Technique)

- Uses microchannels to precisely control mixing.

- Produces **uniform, reproducible nanoparticles**.
- Reduces batch variability and waste [56].

2. Recent Advances in NDDS

1. Targeted Drug Delivery
- **Passive targeting** (EPR effect)
- **Active targeting** using ligands (antibodies, peptides)

2. Stimuli-Responsive Nanoparticles
- Triggered by:
- pH
- Temperature
- Light
- Enzymes [57-58]
- Enable **controlled and site-specific drug release**

3. Multifunctional Nanoparticles (Theragnostic)
- Combine **therapy + diagnosis**
- Used in cancer imaging and treatment

4. Lipid Nanoparticles (LNPs)
- Widely used in **mRNA delivery systems**
- Improved stability and cellular uptake [59, 60] Cortana A

Gaug. 5. AI and Precision Nanomedicine
- AI used to optimize:
- Particle size
- Drug loading
- Targeting efficiency [61]

6. Surface Functionalization
- PEGylation ("stealth" coating) to avoid immune clearance
- Enhances circulation time [62]

3. Challenges in Nanoparticle Drug Delivery [63, 64]

A. Biological Challenges
- Rapid clearance by **reticuloendothelial system (RES)**
- Poor cellular uptake in some cases
- Biological barriers (blood-brain barrier, tumor microenvironment)

B. Toxicity and Safety
- Long-term toxicity unclear,
- Accumulation in organs (liver, spleen)

C. Manufacturing Challenges
- Scale-up difficulties
- Batch-to-batch variability
- Reproducibility issues

D. Stability Issues
- Aggregation of nanoparticles
- Drug leakage during storage

E. Regulatory Challenges
- Lack of standardized guidelines
- Complex approval process

F. Cost and Commercialization
- High production cost
- Limited industrial translation

Nanoparticle-based drug delivery systems are revolutionizing medicine by enabling targeted, controlled, and efficient drug delivery. A wide range of preparation techniques—from traditional emulsification to advanced microfluidics—are used depending on the application. Despite major advances such as stimuli-responsive systems and precision nanomedicine, challenges like toxicity, scalability, and regulatory barriers must be addressed for widespread clinical adoption [65].

Characterization of Nanoparticles

Characterization of nano particles for these topic Nanoparticle-Based Drug Delivery Systems: Recent Advances and Challenges.

1. Importance of Nanoparticle Characterization

Characterization is essential to ensure quality, safety, and efficiency of nanoparticle drug delivery systems. It determines how nanoparticles behave in biological systems.
.. Nanoparticles typically range from **1–1000 nm** and exhibit unique properties (size, surface, shape) that influence drug delivery performance.
- Key factors affecting drug delivery:
- Size → circulation time & cellular uptake
- Shape → biodistribution
- Surface charge → stability & interaction with cells

2. Key Characterization Parameters

Nanoparticles are characterized based on:

A. Physical Properties
- Particle size & size distribution
- Shape & morphology
- Surface area

B. Chemical Properties
- Composition
- Functional groups
- Drug encapsulation

C. Surface Properties
- Surface charge (zeta potential)
- Surface modification

D. Biological Properties

Drug release behaviour
- Stability
- Biocompatibility [66]

Major Characterization Technique

3.1 Particle Size & Distribution

Dynamic Light Scattering (DLS)
- Measures **hydrodynamic diameter** using Brownian motion
- Fast and widely used for colloidal systems
- Helps detect aggre I. gation and stability
- Principle: Smaller particles move faster than larger ones [67, 68]

3.2 Morphology & Structure

Transmission Electron Microscopy (TEM)
- Provides **high-resolution images**
- Shows shape and exact particle size

Scanning Electron Microscopy (SEM)
- Gives surface morphology and structure

Atomic Force Microscopy (AFM)
- 3D surface imaging at nanoscale [69]

3.3 Surface Charge
Zeta Potential Analysis
- Measures **surface charge of nanoparticles**
- Indicates colloidal stability
- High absolute zeta potential = better stability

3.4 Chemical Composition & Functional Groups
Fourier Transform Infrared Spectroscopy (FTIR)
- Identifies **functional groups and bonding**
- Confirms drug loading and surface modification
- FTIR gives molecular "fingerprint" of nanoparticles [70]

3.5 Crystallinity & Structure
X-ray Diffraction (XRD)
- Determines
- Crystal structure
- Phase purity
- Crystallite size
- Important for solid nanoparticles [71]
- Measures drug

3.6 Drug Loading & Release-Vis Spectroscopy/HPLC
- Concentration
- Determines encapsulation efficiency

***In vitro* Drug Release Studies**
- Evaluates release profile over time [72]

4. Summary Table

Technique	Property	Importance
DLS [73]	Particle size, distribution [73]	Stability delivery efficiency [73]
TEM/SEM [74]	Shape, morphology [74]	Structural analysis [74]
Zeta Potential [75]	Surface charge functional [75]	Colloidal stability [75]
FTIR [76]	Functional groups [76]	Drug loading & bonding [76]
XRD [77]	Crystallinity [77]	Structural integrity [77]
HPLC/UV	Drug content	Dosage accuracy

5. Recent Advances in Characterization
- **FTIR imaging** for 3D chemical mapping
- **SAXS (Small-angle X-ray scattering)** for nanoscale structure
- **Combined techniques** (DLS + TEM + XRD) for better accuracy
- Real-time monitoring of drug release and nanoparticle stability [78]

6. Challenges in Characterization
1. **Complexity of nanostructures**
- No single technique is sufficient

2. **AI. ggregation issues**
- Can distort size measurements (e.g., DLS vs TEM differences)

3. **Reproducibility**
- Variations in preparation methods affect results

4. **Biological environment effects**
- Behaviour changes *in vivo* vs *in vitro*

5. **Cost & instrumentation**
- Advanced tools like TEM are expensive

Characterization of nanoparticles is a multidimensional process involving physical, chemical, and biological analysis. A combination of techniques like DLS, TEM, FTIR, XRD, and zeta **potential** is essential to ensure effective and safe nanoparticle-based drug delivery systems. Despite recent advances, challenges like complexity, cost, and reproducibility still remain [79].

Mechanism of Drug Release:
Mechanism of drug release of these topics Nanoparticle-Based Drug Delivery Systems: Recent Advances and Challenges.
Drug release from nanoparticles is a **controlled and targeted process** designed to deliver drugs at the desired site, rate, and duration. The mechanism depends on:
- Type of nanoparticle (polymeric, lipid-based, metallic)
- Drug–carrier interaction
- Physiological conditions (pH, enzymes, temperature) [80]

Major Mechanisms of Drug Release
- **Diffusion-Controlled Release**
- Drug molecules diffuse from the nanoparticle matrix into surrounding fluid [81]
- Occurs when drug is **physically entrapped**

Types:
- **Matrix diffusion**: drug uniformly dispersed
- **Reservoir diffusion**: drug core surrounded by polymer shell
- Rate depends on:
- Particle size
- Polymer density
- Drug solubility [81]
- **Degradation (Erosion)-Controlled Release**
- Nanoparticles degrade over time, releasing drug

Types:
- **Bulk erosion**: entire matrix degrades uniformly
- **Surface erosion**: outer layer degrades first Common in **biodegradable polymers** (e.g., PLGA)

2.3 Swelling-Controlled Release
- Polymer absorbs water → swells → drug diffuses out

Common in:
- Hydrogels
- Polymer-based nanoparticles

Influenced by:
- pH
- Ionic strength [82]

2.4 Stimuli-Responsive (Triggered) Release
Drug release occurs in response to specific stimuli:
Internal Stimuli:

- pH-sensitive release (tumor tissues are acidic)
- Enzyme-triggered release
- Redox conditions

External Stimuli:
- Temperature
- Light
- Magnetic field
- Ultrasound

Enables targeted and site-specific delivery [83]
- **Dissolution-Controlled Release**
- Drug dissolves first, then diffuses out

Depends on:
- Drug solubility
- Surface area of nanoparticles [84]

2.6 Desorption-Based Release
- Drug adsorbed on nanoparticle surface
- Rapid release when exposed to biological fluids

Often causes:
Initial burst release [85]
Drug Release Profile
Typical nanoparticle drug release shows:
Biphasic Pattern:
1. Initial burst release
- Due to surface-bound drug

2. Sustained release
Controlled diffusion or degradation [86]
Factors Affecting Drug Release
Particle-related factors:
Size (smaller → faster release)
- Surface area
- Porosity

Drug-related factors:
- Solubility
- Molecular weight

I.. Drug-polymer interaction
Environmental factors:
- pH
- Temperature
- Enzymes

Recent Advances in Drug Release Mechanisms
- Smart nanoparticles with multi-stimuli responsiveness
- Targeted release systems (ligand-based targeting)
- Controlled release using nanogels and liposomes
- On-demand drug delivery using external triggers

Challenges
1. **Burst release problem**
2. Leads to toxicity
3. **Incomplete drug release**
4. Drug remains trapped
5. **Poor reproducibility**
6. Variation in synthesis

1. *In vivo* complexity
- Different from lab conditions

2. Stability issues
- Premature drug leakage

Drug release from nanoparticles involves multiple mechanisms such as diffusion, degradation, swelling, and stimuli-triggered release. Modern systems focus on controlled, targeted, and responsive delivery, but challenges like burst release and biological variability still need to be addressed [87, 88].

Challenges and Limitations
1. Toxicity and biocompatibility: - Here's a **clear, structured explanation** of **toxicity and biocompatibility** in *nanoparticle-based drug delivery systems (NDDS)*, along with recent advances and key challenges—useful for assignments, research reviews, or exams.
Toxicity and I. Biocompatibility of Nanoparticle-Based Drug Delivery Systems
1. What is Biocompatibility in NDDS?
Biocompatibility refers to the ability of nanoparticles to interact with biological systems **without causing harmful effects** while performing their therapeutic function.
Key determinants:
- **Size, shape, and surface charge**
- **Material composition (lipid, polymer, metal, etc.)**
- **Surface chemistry and functionalization**
- **Degradation and clearance behaviour**

Nanoparticles must:
- Avoid immune rejection
- Be non-toxic to healthy tissues
- Degrade safely or be excreted

For example, chitosan nanoparticles show good biocompatibility with minimal systemic toxicity and no major side effects at therapeutic doses.
2. Toxicity of Nanoparticles
Despite their benefits, nanoparticles can cause nanotoxicity, which depends on physicochemical properties and exposure conditions.
Major toxicity mechanisms:
a. Oxidative Stress
- Nanoparticles can generate **reactive oxygen species (ROS)**

Leads to:
- DNA damage
- Lipid peroxidation
- Cell death

Metal nanoparticles show **2–10× increase in ROS production**
b. Cellular and Organ Toxicity
Can accumulate in organs:
- Liver
- Kidneys
- Spleen

Long-term accumulation may lead to organ damage or poisoning
c. Immune System Activation
- Triggers:
- Inflammation
- Cytokine release
- I. Allergic reactions

Immune activation can increase cytokine levels up to 3-fold.
d. Genotoxicity & Cellular Penetration
- Nanoparticles can:
- Cross cell membranes
- Enter nucleus

May cause:
- DNA mutations
- Carcinogenic effects

e. Dose-Dependent Toxicity
- Toxicity increases with:
- Concentration
- Exposure duration

Cytotoxicity ranges reported at **10–40 µg/mL** for some nanoparticles.

3. Recent Advances Improving Biocompatibility

a. Surface Modification
- PEGylation (polyethylene glycol coating)
- Ligand functionalization
- Reduces immune recognition
- Improves circulation time

b. Biodegradable Nanoparticles
- Materials:
- Polymers (PLGA)
- Lipids (liposomes)
- Natural polymers (chitosan)
- Break down into **non-toxic byproducts**

c. Targeted Drug Delivery
- Ligand-receptor targeting
- Tumour-specific delivery
- Reduces off-target toxicity
- Improves therapeutic index
- Nanoparticles can significantly reduce systemic toxicity in cancer therapy

d. Biohybrid & Biomimetic Nanoparticles
- Cell membrane-coated nanoparticles
- Exosome-based delivery
- Enhanced immune evasion
- Improved compatibility [89-92]

e. Stimuli-Responsive Systems
- pH-sensitive, temperature-sensitive nanoparticles
- Release drugs only at disease sites
- Minimize side effects

4. Challenges in Toxicity and Biocompatibility

(1) Long-Term Safety Uncertainty
- ack of data on:
- Chronic exposure
- Lifetime accumulation
- Requires **extensive *in vivo* studies**

(2) Biodistribution Issues
- Unpredictable distribution in body
- Accumulation in non-target tissues

(3) Standardization Problems
- No universal protocols for:
- Toxicity testing
- Biocompatibility evaluation [93]

(4) Complex Interaction with Biological Systems
- Protein corona formation
- Changes nanoparticle behaviour *in vivo*

(5) Manufacturing Variability
- Small changes in:
- Size
- Shape
- Surface
- Can significantly alter toxicity and safety

(6) Regulatory Challenges
- Lack of clear guidelines for:
- Approval
- Clinical translation

5. Summary (Exam-Ready Points

Advantages (Biocompatibility Perspective)
- Targeted delivery reduces systemic toxicity
- Controlled drug release
- Improved therapeutic efficiency

Toxicity Concerns
- Oxidative stress and inflammation
- Organ accumulation
- Immune reactions
- Genotoxicity

Key Challenges
- Long-term safety
- Standardized testing
- Scale-up consistency
- Regulatory approval

Nanoparticle-based drug delivery systems offer **revolutionary advantages** in modern medicine, particularly in targeted therapy and reduced systemic toxicity. However, **toxicity and biocompatibility remain critical barriers** to their widespread clinical application. Future research must focus on:
- Safer material design
- Long-term toxicity studies
- Standardized evaluation methods

Conclusion

Nanoparticle-based drug delivery systems have emerged as a transformative approach in modern therapeutics, offering significant advantages such as targeted drug delivery, improved bioavailability, and controlled release of drugs. Recent advances in nanotechnology—including surface modification, biodegradable materials, and stimuli-responsive systems—have greatly enhanced their efficiency and biocompatibility, making them promising tools in the treatment of complex diseases like cancer and neurological disorders.

However, despite these advancements, several challenges remain. Issues related to toxicity, long-term safety, biodistribution, large-scale manufacturing, and regulatory approval continue to limit their widespread clinical application. The interaction of nanoparticles with biological systems is highly complex, and insufficient understanding of their long-term effects raises concerns about potential health risks.

Therefore, future research should focus on developing safer and more biocompatible nanomaterials, establishing standardized evaluation protocols, and addressing regulatory hurdles. With continued innovation and careful assessment, nanoparticle-based drug delivery systems hold immense potential to revolutionize personalized medicine and improve patient outcomes.

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