Emerging Trends in Nanotechnology-Based Drug Delivery Systems: A Comprehensive Review

Debjit Goswami[1], Tanuja A M L[2], Dokuparthi Gowthami[3], Nikhil Singh[4], Akanksha Pandey[5], Chandan Sood[6], Govind Kumar[7]

[1]*Birbhum Pharmacy School*

[2] *Assistant Professor (Pharmaceutics Department), Danigond College of Pharmacy Terdal -587315*

[3] *M. Pharmacy, Acharya Nagarjuna University College of Pharmaceutical Sciences*

[4] *Student, Dr. APJ Abdul Kalam Technical University*

[5] *Assistant professor, Vatsalya institute of pharmacy gohaniya prayagraj*

[6] *Assistant Professor, Department of Pharmacology, L.R. Institute of Pharmacy, Jabli-Kyar, Solan, Himachal Pradesh, India 173223*

[7] *Assistant Professor, Shiv Bali Singh Group of Educational and Training Institute College of Pharmacy*

***Abstract*—Nanotechnology has emerged as one of the most promising approaches for overcoming major limitations associated with conventional drug delivery systems, including poor aqueous solubility, low bioavailability, rapid degradation, nonspecific distribution, systemic toxicity, and inadequate drug accumulation at pathological sites. Nanotechnology-based drug delivery systems utilize engineered nanoscale materials to modify the physicochemical, pharmacokinetic, and biological properties of therapeutic agents. A wide range of nanocarriers, including liposomes, lipid nanoparticles, solid lipid nanoparticles, nanostructured lipid carriers, polymeric nanoparticles, polymeric micelles, dendrimers, nanoemulsions, mesoporous silica nanoparticles, metallic nanoparticles, protein-based nanoparticles, and biomimetic systems, have been investigated for controlled and targeted delivery.**

Recent advances have shifted the field from conventional passive drug carriers toward multifunctional, stimuli-responsive, biomimetic, personalized, and precision nanomedicine platforms. Emerging technologies include ligand-mediated active targeting, tumor microenvironment-responsive systems, organelle-specific delivery, cell-membrane-coated nanoparticles, exosome-based delivery, lipid nanoparticles for nucleic acids, theranostic nanoplatforms, artificial intelligence-assisted formulation optimization, and nanocarriers for mRNA, siRNA, CRISPR components, and other advanced therapeutics. These developments have expanded the potential of nanotechnology beyond small-molecule drugs toward biologics and genetic medicines.

Despite considerable progress, clinical translation remains challenging because of nanoparticle heterogeneity, scale-up difficulties, long-term stability, biological variability, immunogenicity, nanotoxicity, manufacturing complexity, and regulatory uncertainties. The U.S. Food and Drug Administration emphasizes that nanomaterial-containing drug products require careful characterization, control of critical quality attributes, and assessment of safety, efficacy, and product-specific properties. This review discusses the evolution, major platforms, emerging trends, mechanisms, therapeutic applications, advantages, limitations, regulatory considerations, and future prospects of nanotechnology-based drug delivery systems, with particular emphasis on technologies that are driving the transition toward precision and personalized medicine.

***Index Terms*—Nanotechnology; Nanomedicine; Nanoparticles; Drug delivery; Targeted delivery; Lipid nanoparticles; Stimuli-responsive systems; Exosomes; Theranostics; Gene delivery; Personalized medicine; Nanotoxicology.**

I. INTRODUCTION

Drug delivery plays a central role in determining the therapeutic success of pharmacological interventions. Although conventional dosage forms have successfully treated numerous diseases, many therapeutic agents exhibit limitations such as poor water solubility, low permeability, instability, rapid metabolism, short biological half-life, nonspecific

tissue distribution, and dose-limiting toxicity. These limitations can result in inadequate drug concentrations at the site of action while exposing healthy tissues to unnecessary pharmacological effects.

Nanotechnology has provided a new approach for addressing these challenges. Nanotechnology-based drug delivery involves the design and utilization of materials with nanoscale dimensions or engineered nanoscale properties to transport therapeutic agents to specific biological locations. At the nanoscale, materials can exhibit physicochemical and biological properties that differ substantially from their bulk counterparts. These properties can be exploited to modify drug solubility, release, distribution, cellular uptake, and therapeutic activity. The FDA notes that nanoscale materials may exhibit dimension-dependent properties relevant to safety, effectiveness, quality, and performance.

Nanocarriers can encapsulate, adsorb, conjugate, or otherwise associate with therapeutic molecules and protect them from premature degradation. Depending on their composition and surface characteristics, they can improve pharmacokinetic behavior, facilitate cellular internalization, provide controlled release, and potentially increase accumulation at diseased tissues.

The development of nanomedicine has progressed from relatively simple drug-loaded particles toward sophisticated multifunctional systems capable of simultaneously performing targeting, drug delivery, imaging, controlled release, and biological response modulation. Recent research particularly emphasizes biodegradable and biocompatible materials, stimulus-responsive systems, nucleic-acid delivery, biomimetic nanoparticles, artificial intelligence-assisted formulation development, and precision nanomedicine. Recent reviews identify targeted delivery, stimulus-responsive nanoparticles, artificial intelligence, real-time imaging, and multifunctional nanoplatforms as important directions in the field[1].

II. FUNDAMENTALS OF NANOTECHNOLOGY-BASED DRUG DELIVERY

Nanotechnology-based drug delivery systems generally consist of a therapeutic payload incorporated into or associated with a nanoscale carrier. The carrier is designed to modify one or more properties of the drug.

2.1 Major objectives

The principal objectives include:

- Increasing aqueous solubility of poorly soluble drugs
- Improving oral or systemic bioavailability
- Protecting drugs from enzymatic or chemical degradation
- Prolonging circulation time
- Providing controlled or sustained drug release
- Enhancing cellular uptake
- Reducing systemic toxicity
- Improving tissue distribution
- Increasing therapeutic index
- Facilitating delivery of proteins, peptides and nucleic acids
- Enabling site-specific or cell-specific delivery
- Combining diagnosis and therapy within a single platform

2.2 Important physicochemical characteristics

The biological behavior of nanoparticles depends strongly on:

Particle size → surface area → protein adsorption → cellular interaction → biodistribution → therapeutic response

Other important characteristics include:

- Particle-size distribution
- Shape
- Surface charge
- Surface chemistry
- Hydrophobicity/hydrophilicity
- Drug-loading capacity
- Encapsulation efficiency
- Release kinetics
- Colloidal stability
- Biodegradability
- Protein corona formation

These parameters can influence circulation, cellular uptake, tissue penetration, immune recognition, and elimination.

III. MAJOR NANOTECHNOLOGY-BASED DRUG DELIVERY SYSTEMS

3.1 Liposomes

Liposomes are spherical vesicular systems composed primarily of phospholipid bilayers surrounding an aqueous core.

They can accommodate:

- Hydrophilic drugs in the aqueous compartment
- Lipophilic drugs within the lipid bilayer

Advantages

- Biocompatibility
- Ability to carry hydrophilic and lipophilic drugs
- Protection of encapsulated drugs
- Possibility of surface modification
- Controlled drug release

PEGylated liposomes can increase circulation time by reducing rapid recognition and clearance by the mononuclear phagocyte system.

Liposome products have also established an important regulatory precedent. The FDA has specific guidance addressing chemistry, manufacturing and controls, pharmacokinetics/bioavailability, and labeling requirements for liposome drug products.

3.2 Lipid Nanoparticles

Lipid nanoparticles have become particularly important for delivery of nucleic acids.

A typical lipid nanoparticle formulation may contain:

1. Ionizable lipid
2. Phospholipid
3. Cholesterol
4. PEG-lipid

Their ability to facilitate intracellular delivery has made them important platforms for RNA-based therapeutics.

Potential applications include:

- mRNA delivery
- siRNA delivery
- Gene editing
- Protein replacement
- Cancer immunotherapy
- Vaccination

3.3 Solid Lipid Nanoparticles

Solid lipid nanoparticles (SLNs) contain a solid lipid matrix stabilized by surfactants.

Advantages

- Controlled drug release
- Improved stability
- Protection against degradation
- Potential enhancement of bioavailability
- Use of relatively biocompatible lipids

Limitations

Drug expulsion during storage and relatively limited drug-loading capacity can occur because of the crystalline nature of the lipid matrix.

3.4 Nanostructured Lipid Carriers

Nanostructured lipid carriers (NLCs) were developed to overcome several limitations associated with SLNs.

They generally contain a mixture of:

Solid lipid + liquid lipid + surfactant

The less ordered lipid matrix can provide improved drug loading and reduce drug expulsion.

3.5 Polymeric Nanoparticles

Polymeric nanoparticles utilize biodegradable or biocompatible polymers such as:

- PLGA
- PLA
- PCL
- Chitosan
- Alginate
- PEG-containing polymers

They can provide controlled degradation and sustained release.

Polymeric systems are particularly attractive for:

- Peptides
- Proteins
- Anticancer drugs
- Vaccines
- Gene delivery

3.6 Polymeric Micelles

Polymeric micelles are self-assembled structures consisting of amphiphilic polymers.

The hydrophobic core can solubilize poorly water-soluble drugs, while the hydrophilic corona improves aqueous dispersibility.

The general mechanism can be represented as:

Poorly soluble drug → micellar encapsulation → improved aqueous dispersion → enhanced systemic exposure[2].

3.7 Dendrimers

Dendrimers are highly branched, nanoscale macromolecules with a well-defined architecture.

Their numerous surface functional groups allow:

- Drug conjugation
- Ligand attachment
- Gene complexation

- Imaging-agent incorporation

However, toxicity related to certain surface chemistries, particularly highly cationic systems, remains an important consideration.

3.8 Nanoemulsions

Nanoemulsions are nanoscale dispersions of oil and water phases stabilized by surfactants.

They can improve:

- Solubilization
- Absorption
- Physical stability
- Bioavailability

They have potential applications in oral, topical, transdermal, ocular, and parenteral delivery.

3.9 Mesoporous Silica Nanoparticles

Mesoporous silica nanoparticles possess highly ordered porous structures.

Their major advantages include:

- High surface area
- High drug-loading potential
- Tunable pore size
- Surface functionalization
- Controlled drug release

They are being investigated for targeted delivery and theranostic applications.

3.10 Metallic Nanoparticles

Gold, silver, iron oxide, and other inorganic nanoparticles have been explored for drug delivery and biomedical applications.

Their properties may enable:

- Drug delivery
- Imaging
- Photothermal therapy
- Magnetic targeting
- Magnetic resonance imaging
- Combination therapy
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However, concerns regarding persistence, degradation, accumulation, and toxicity must be carefully addressed before widespread therapeutic application.

IV. MECHANISMS OF NANOPARTICLE-BASED DRUG DELIVERY

Nanoparticles can improve drug delivery through several mechanisms.

4.1 Passive targeting

Passive targeting exploits differences between diseased and healthy tissues.

In tumors, altered vascular permeability and impaired lymphatic drainage can contribute to nanoparticle accumulation. This phenomenon is commonly described as the enhanced permeability and retention (EPR) effect.

However, the magnitude and reliability of EPR can vary considerably between tumor types, patients, and experimental models. Therefore, modern research increasingly combines passive accumulation with active targeting and biological strategies [3].

4.2 Active targeting

Active targeting involves attaching specific ligands to the nanoparticle surface.

Examples include:

Nanoparticle → ligand → receptor → cellular binding → receptor-mediated internalization

Potential targeting ligands include:

- Antibodies
- Antibody fragments
- Peptides
- Aptamers
- Carbohydrates
- Small molecules

Active targeting can potentially improve cellular specificity and intracellular delivery.

4.3 Stimuli-responsive delivery

Stimuli-responsive nanoparticles release their payload in response to specific environmental signals.

Internal stimuli

- pH
- Enzymes
- Redox conditions
- Reactive oxygen species
- Hypoxia
- Temperature

External stimuli

- Light

- Magnetic field
- Ultrasound
- Electrical stimulation

General concept:

Nanoparticle → circulation → disease-specific stimulus → structural change → drug release → therapeutic action

This approach represents an important transition from passive drug carriers to intelligent drug delivery systems [4].

V. EMERGING TRENDS IN NANOTECHNOLOGY-BASED DRUG DELIVERY

5.1 Stimuli-responsive nanocarriers

Stimuli-responsive systems are increasingly being designed to recognize pathological microenvironments.

For example:

Tumor acidic environment → nanoparticle destabilization → drug release → tumor-cell exposure

Similarly, enzyme-responsive nanoparticles can exploit disease-associated enzymes to trigger payload release.

The objective is to minimize premature drug release while maximizing release at the target site.

5.2 Tumor Microenvironment-Responsive Nanoparticles

Cancer nanomedicine is increasingly focusing on the tumor microenvironment rather than tumor cells alone.

Important characteristics include:

- Low extracellular pH
- High ROS
- Hypoxia
- Abnormal enzyme activity
- Dense extracellular matrix
- Immunosuppressive cells

Nanoparticles can be engineered to respond to these characteristics.

This creates the possibility of:

Disease microenvironment recognition → selective activation → localized therapeutic effect

5.3 Nanoparticles for RNA and Gene Delivery

One of the most important developments in nanomedicine is the transition from small-molecule drug delivery toward nucleic-acid delivery.

Potential payloads include:

- mRNA
- siRNA
- miRNA
- antisense oligonucleotides
- DNA
- CRISPR-associated components

Lipid nanoparticles are particularly important because they can protect nucleic acids from degradation and facilitate cellular uptake.

5.4 CRISPR and Gene-Editing Delivery

Nanocarriers are being explored as vehicles for delivering gene-editing components.

A conceptual pathway is:

Nanocarrier → CRISPR components → cellular uptake → intracellular release → genome editing → therapeutic effect

Nanotechnology may help overcome limitations associated with direct administration of fragile nucleic-acid components.

However, specificity, off-target effects, immunogenicity, long-term safety, and efficient tissue delivery remain major challenges.

VI. EXOSOME-BASED DRUG DELIVERY

Exosomes are naturally occurring extracellular vesicles that participate in intercellular communication.

Their biological origin provides several potentially useful properties:

- Biocompatibility
- Low immunogenicity
- Ability to transport biological molecules
- Potential for tissue-specific interactions
- Natural membrane structure

Exosomes can potentially carry:

- Proteins
- miRNA
- siRNA
- mRNA
- Small-molecule drugs

A major challenge is obtaining reproducible, scalable, standardized, and clinically consistent exosome preparations.

VII. BIOMIMETIC NANOPARTICLES

Biomimetic nanoparticles attempt to reproduce useful characteristics of biological systems.
Examples include:

- Cell-membrane-coated nanoparticles
- Red blood cell membrane-coated nanoparticles
- Platelet membrane-coated nanoparticles
- Cancer-cell membrane-coated nanoparticles
- Hybrid biological–synthetic nanoparticles

General concept:
Synthetic nanoparticle + biological membrane → biomimetic nanocarrier → altered immune interaction and targeting
Such systems may help nanoparticles evade immune clearance or interact preferentially with specific biological environments.

VIII. ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING IN NANOMEDICINE

Artificial intelligence (AI) and machine learning (ML) are emerging as tools for accelerating nanomedicine development.
Potential applications include:
Formulation optimization
AI can analyze relationships between:

- Lipid composition
- Polymer concentration
- Particle size
- Surface charge
- Encapsulation efficiency
- Drug release

Prediction of biological behavior
ML models may assist in predicting:

- Cellular uptake
- Toxicity
- Biodistribution
- Stability
- Drug release
- Targeting efficiency

Conceptual workflow
Formulation variables → experimental data → ML model → prediction → optimized formulation → experimental validation
The integration of AI with nanotechnology may reduce formulation-development time and support more systematic optimization.

IX. PERSONALIZED NANOMEDICINE

Conventional drug delivery often assumes that patients with the same disease will respond similarly.
Nanomedicine increasingly aims to consider individual differences in:

- Disease biology
- Receptor expression
- Tumor microenvironment
- Pharmacokinetics
- Genetic characteristics
- Immune status

The future may therefore involve:
Patient characterization → biomarker identification → personalized nanocarrier → individualized drug dose → monitoring → treatment adjustment
This could be particularly valuable in oncology.

X. THERANOSTIC NANOPARTICLES

Theranostics combines:
Therapy + Diagnosis
A single nanoplatform may incorporate both a therapeutic drug and an imaging component.
For example:
Targeting ligand + imaging agent + therapeutic drug + nanoparticle
This can theoretically enable:

1. Identification of disease
2. Localization of pathological tissue
3. Drug delivery
4. Treatment
5. Monitoring of therapeutic response

Theranostic nanotechnology is particularly attractive for cancer treatment and precision medicine.

XI. ORGANELLE-TARGETED NANOMEDICINE

An emerging direction is targeting intracellular organelles rather than merely targeting cells.
Potential targets include:

- Nucleus
- Mitochondria
- Lysosomes
- Endoplasmic reticulum

For example, mitochondrial targeting may be useful when disease mechanisms involve mitochondrial dysfunction.

The strategy can be represented as:
Nanoparticle → cell → intracellular trafficking → organelle recognition → payload release → molecular target
This may provide greater therapeutic precision than conventional cell-level targeting.

XII. APPLICATIONS OF NANOTECHNOLOGY-BASED DRUG DELIVERY

12.1 Cancer

Cancer remains one of the major applications of nanomedicine.
Nanocarriers can potentially improve:

- Tumor accumulation
- Drug solubility
- Intratumoral exposure
- Combination therapy
- Drug resistance management
- Immunotherapy

Nanomedicine has also been investigated for delivering chemotherapeutics, small interfering RNA, immune modulators, and other biological therapeutics.
Recent reviews emphasize the role of nanoparticles in chemotherapy, immunotherapy, and targeted cancer treatment [5].

12.2 Central Nervous System Disorders

The blood–brain barrier represents a major challenge for CNS drug delivery.
Nanoparticles may potentially improve transport by:

- Modifying drug physicochemical properties
- Facilitating receptor-mediated transport
- Enhancing cellular uptake
- Providing controlled release

Potential applications include:

- Alzheimer's disease
- Parkinson's disease
- Brain tumors
- Neuroinflammation

12.3 Inflammatory Diseases

Nanocarriers can potentially deliver anti-inflammatory agents directly to inflamed tissues.
Potential applications include:

- Rheumatoid arthritis
- Inflammatory bowel disease
- Colitis
- Psoriasis
- Autoimmune disorders

Targeted delivery may help reduce systemic exposure and improve local therapeutic concentrations.

12.4 Cardiovascular Diseases

Nanotechnology has been investigated for:

- Atherosclerosis
- Myocardial infarction
- Thrombosis
- Restenosis
- Vascular inflammation

Nanoparticles can potentially deliver drugs or genetic materials to vascular tissues.

12.5 Infectious Diseases

Nanotechnology can assist in delivering antimicrobial agents and vaccines.
Potential advantages include:

- Improved drug stability
- Increased local concentration
- Controlled release
- Combination delivery
- Improved intracellular delivery

12.6 Ocular Drug Delivery

The eye presents significant barriers to drug delivery, including tear drainage and limited drug penetration.
Nanocarriers may prolong ocular residence time and improve drug penetration.
Potential applications include:

- Glaucoma
- Retinal diseases
- Ocular inflammation
- Corneal disorders

XIII. COMPARISON OF MAJOR NANOCARRIERS

Nanocarrier	Major advantage	Major limitation	Important application
Liposomes	Biocompatibility; versatile drug loading	Stability and manufacturing complexity	Cancer
Lipid nanoparticles	Excellent nucleic-acid delivery	Formulation sensitivity	mRNA/siRNA
SLNs	Controlled release	Drug expulsion	Oral/topical delivery
NLCs	Improved drug loading	Physical stability considerations	Poorly soluble drugs
Polymeric nanoparticles	Controlled degradation	Manufacturing complexity	Sustained delivery
Micelles	Solubilization of hydrophobic drugs	Dilution-related instability	Poorly soluble drugs
Dendrimers	Highly tunable surface	Potential toxicity	Gene/drug delivery
Nanoemulsions	Improved solubilization	Surfactant-related issues	Oral/topical delivery
Mesoporous silica	High loading capacity	Long-term safety concerns	Controlled delivery
Metallic nanoparticles	Imaging/photothermal properties	Potential accumulation/toxicity	Theranostics
Exosomes	Biological origin	Isolation and standardization	RNA/drug delivery
Biomimetic nanoparticles	Biological-like interactions	Complex manufacturing	Targeted delivery

XIV. ADVANTAGES OF NANOTECHNOLOGY-BASED DRUG DELIVERY

Major advantages include:

- Improved solubility
- Enhanced bioavailability
- Controlled drug release
- Prolonged circulation
- Protection of unstable drugs
- Targeted delivery
- Reduced systemic toxicity
- Improved cellular uptake
- Delivery of biological macromolecules
- Possibility of combination therapy
- Integration of diagnosis and therapy

FDA recognizes that nanotechnology can produce product characteristics that differ from conventional formulations and therefore requires consideration of nanomaterial-specific properties during development [6].

XV. LIMITATIONS AND CHALLENGES

Despite substantial progress, several barriers remain.

15.1 Nanotoxicity

Nanoparticles can interact with biological systems in complex ways.

Potential concerns include:

- Oxidative stress
- Inflammation
- Genotoxicity
- Immunotoxicity
- Cytotoxicity
- Organ accumulation
- Long-term persistence

Importantly, nanoparticle safety cannot be generalized across all nanomaterials because toxicity depends strongly on composition, size, surface characteristics, dose, route, and biological interactions.

15.2 Protein Corona

When nanoparticles enter biological fluids, proteins can adsorb onto their surface and form a protein corona.

Nanoparticle → biological fluid → protein adsorption → protein corona → altered cellular interaction

The protein corona may influence:

- Biodistribution
- Cellular uptake
- Immune recognition
- Clearance
- Therapeutic efficacy

15.3 Scale-Up

A formulation that performs well at laboratory scale may behave differently during industrial manufacturing.

Important variables include:

- Mixing
- Temperature
- Shear
- Raw-material variability
- Sterilization
- Batch-to-batch consistency

15.4 Stability

Nanoparticles may undergo:

- Aggregation
- Particle-size changes
- Drug leakage
- Oxidation
- Hydrolysis
- Surface-property changes

The FDA specifically identifies changes in nanoparticle size or size distribution, morphology/solid state, and aggregation or agglomeration as potential stability considerations.

XVI. REGULATORY CONSIDERATIONS

Regulatory assessment represents a major component of successful nanomedicine translation.

The FDA's current guidance emphasizes characterization and control of nanomaterial-containing drug products and notes that nanomaterial properties can influence safety, efficacy, quality, and manufacturing [7].

Important critical quality attributes may include:

- Particle size
- Particle-size distribution
- Morphology
- Surface characteristics
- Composition
- Drug loading
- Encapsulation efficiency
- Release profile
- Impurities
- Stability
- Sterility
- Endotoxin levels

The FDA also notes that nanomaterials can be sensitive to processing and scale-up, making early identification of critical quality attributes particularly important.

Thus, successful development requires integration of:

Nanomaterial design → characterization → manufacturing → quality control → toxicology → pharmacokinetics → efficacy → regulatory evaluation

XVII. FUTURE PERSPECTIVES

The future of nanotechnology-based drug delivery is likely to move toward precision, intelligence, biological mimicry, and patient-specific therapy.

Major future directions include:

17.1 AI-designed nanocarriers

AI may increasingly be used to predict optimal compositions and biological behavior.

17.2 Smart nanoparticles

Future nanoparticles may respond to multiple pathological signals simultaneously.

17.3 Multifunctional systems

One nanoparticle may combine:

Targeting + therapy + imaging + controlled release + biological response modulation

17.4 Gene-editing delivery

Nanocarriers may become increasingly important for delivering CRISPR components and other genetic medicines.

17.5 Exosome–synthetic hybrids

Combining biological vesicles with synthetic nanomaterials may provide improved targeting and engineering flexibility.

17.6 Personalized nanomedicine

Patient-specific biomarkers may determine:

- Nanocarrier composition
- Targeting ligand
- Drug
- Dose
- Administration schedule

17.7 Real-time monitoring

Integration of imaging and therapeutic functions could allow clinicians to monitor distribution and therapeutic response.

XVIII. CONCLUSION

Nanotechnology-based drug delivery has evolved from simple nanoscale drug carriers into sophisticated platforms capable of controlled, targeted, responsive, and multifunctional therapeutic delivery. Liposomes, lipid nanoparticles, polymeric nanoparticles, micelles, dendrimers, nanoemulsions, inorganic nanoparticles, exosomes, and biomimetic systems have demonstrated the ability to overcome several limitations associated with conventional drug delivery.

The current evolution of the field is characterized by stimuli-responsive delivery, active targeting, nucleic-acid therapeutics, tumor-microenvironment-responsive systems, organelle targeting, theranostics, biomimetic nanocarriers, exosome-based delivery, and AI-assisted formulation design. These approaches have the potential to transform nanomedicine from a generalized delivery technology into a precision therapeutic platform.

Nevertheless, the transition from laboratory research to routine clinical application remains challenging. Nanotoxicity, biological variability, manufacturing scalability, stability, reproducibility, characterization, and regulatory requirements must be addressed systematically. Regulatory agencies emphasize that nanomaterial-containing drug products require careful consideration of their unique physicochemical properties, critical quality attributes, manufacturing processes, safety, and efficacy.

Future success will therefore depend not simply on developing smaller particles, but on designing predictable, reproducible, safe, biodegradable, biologically responsive, and clinically scalable nanomedicines. The convergence of nanotechnology with artificial intelligence, molecular biology, gene editing, immunotherapy, biomimetic engineering, and personalized medicine is likely to define the next generation of drug delivery systems [8,9].

Emerging technology	Principle	Therapeutic potential	Major challenge
Stimuli-responsive nanoparticles	Disease-specific stimulus triggers release	Precision drug delivery	Complex formulation
AI-assisted nanomedicine	Computational prediction/optimization	Faster formulation development	Limited high-quality datasets
Lipid nanoparticles	Lipid-mediated intracellular delivery	RNA therapeutics	Stability and tolerability
Exosome delivery	Natural extracellular vesicle transport	RNA/protein/drug delivery	Standardization
Biomimetic nanoparticles	Biological membrane mimicry	Immune evasion/targeting	Manufacturing
Theranostics	Diagnosis + therapy	Personalized oncology	Regulatory complexity
Organelle targeting	Intracellular targeting	Precision molecular therapy	Intracellular trafficking
CRISPR nanodelivery	Nanocarrier-mediated gene editing	Genetic disease/cancer	Off-target effects
Tumor-responsive systems	Tumor microenvironment activation	Cancer therapy	Tumor heterogeneity
Personalized nanomedicine	Patient-specific formulation	Precision medicine	Patient stratification

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