Journal of Recent Advances in Nanomedicine & Nanotechnology

Research Article
Volume 1 Issue 5 - July 2025

J Recent Adv Nanomed & Nanotech

The Role of Nanotechnology in Driving Some Key Advances in Medicine and Healthcare Fields

Radhakrishnaiah Parachuru*, Lavanya Krishnan and Geethanjali, P

School of Materials Science & Engineering, Georgia Institute of Technology

Submission: June 14, 2025; **Published:** August 18, 2025

***Corresponding author:** Radhakrishnaiah Parachuru, School of Materials Science & Engineering, Georgia Institute of Technology

Introduction

Nanotechnology has revolutionized the medical and healthcare landscape by enabling precision at the molecular level, offering novel solutions for diagnostics, drug delivery, disease monitoring, and therapeutic interventions. Medical field is able to leverage the unique properties of nanoparticles such as their unique size, surface reactivity, and ease of functionalization to overcome biological barriers and deliver site-specific treatments. By enabling site-specific treatment delivery, real-time monitoring, and improved biosensing, it is reshaping healthcare on a global scale. These innovations not only enhance patient outcomes but also support sustainable and scalable healthcare infrastructure worldwide. This paper provides a structured summary of key nanotech-driven advances, their mechanisms, and global implications.

Major Advances and Applications of Nanotechnology in Healthcare

1. Targeted Drug Delivery in Cancer Therapy [1]

- How it works: Nanoparticles (NPs) such as liposomes, dendrimers, and polymeric NPs are engineered to encapsulate anticancer drugs and release them specifically at tumor sites using passive (EPR effect) or active (ligand-receptor) targeting.

- Impact: Improves efficacy while minimizing systemic toxicity; used in drugs like Doxil (liposomal doxorubicin). Expands access to personalized cancer care globally.

2. Nanotechnology in Parkinson's Disease (PD) Management [2]

- How it works: Various nanoparticles (e.g., lipid-based, metallic) are used to deliver neuroprotective drugs across the Blood-Brain Barrier (BBB) to affected dopaminergic neurons. Nanogels and liposomes provide sustained and controlled release.

- Impact: Offers hope for disease-modifying therapies in neurodegenerative diseases; global

implications include better long-term outcomes and lower care costs.

3. Wearable Photonic Nanosensors for Health Monitoring [3]

- How it works: Nanostructured photonic materials integrated into wearables measure physiological and biochemical markers (e.g., glucose, lactate, hydration) non-invasively in real-time.

- Impact: Enables personalized medicine, chronic disease management, and early diagnostics — particularly transformative in under-resourced settings.

4. AI-enhanced Nanomaterial Sensors for Medical Gas Monitoring [4]

- How it works: Metal oxide and carbon-based nanomaterials integrated with AI algorithms enhance detection of gases (e.g., CO_2, O_2, NO) in ICU and surgical settings.

- Impact: Improves patient safety and surgical outcomes; helps prevent gas-related hazards globally, especially in critical care.

Some Top Nanotechnology-Based Drugs that Have Been Recently Approved

Nanotechnology-based drugs, particularly those using nanoparticles for drug delivery, have significantly advanced modern medicine. These FDA-approved nanomedicines offer improved pharmacokinetics, reduced side effects, and enhanced targeting of diseased tissues. The approvals have established nanomedicine as a vital part of modern pharmacotherapy, especially in oncology and rare genetic diseases. Details of some top clinically approved

nanodrugs and their therapeutic roles are given below

1. Doxil® (Liposomal Doxorubicin)

- Application: Cancer (ovarian, multiple myeloma, AIDS-related Kaposi's sarcoma)
- Nanotech Mechanism: Encapsulation of doxorubicin in PEGylated liposomes prolongs circulation time and enhances tumor targeting via the Enhanced Permeability and Retention (EPR) effect.
- Impact: Reduced cardiotoxicity compared to free doxorubicin; set the gold standard for liposomal cancer therapy.

2. Abraxane® (Albumin-bound Paclitaxel)

- Application: Breast, lung, and pancreatic cancer
- Nanotech Mechanism: Paclitaxel is bound to albumin nanoparticles, avoiding solvent-based

carriers that cause hypersensitivity.

- Impact: Enhanced tumor penetration and better patient tolerability.

3. Onpattro® (Patisiran)

- Application: Hereditary transthyretin-mediated amyloidosis
- Nanotech Mechanism: siRNA encapsulated in lipid nanoparticles delivers gene-silencing therapy to the liver.
- Impact: First siRNA-based nanomedicine approved; milestone in genetic disease therapy.

4. Vyxeos® (Liposomal Daunorubicin and Cytarabine)

- Application: Acute Myeloid Leukemia (AML)
- Nanotech Mechanism: Dual-drug liposomal formulation maintains a synergistic molar ratio of drugs and targets bone marrow.
- Impact: Significantly improves survival in secondary AML.

5. DepoCyt® (Liposomal Cytarabine)

- Application: Lymphomatous meningitis
- Nanotech Mechanism: Sustained-release liposomal cytarabine increases cerebrospinal fluid retention.
- Impact: Reduces injection frequency while maintaining therapeutic levels.

Role of Nanotechnology in Facilitating Controlled Drug Supply and Precise Spot Delivery

Nanotechnology transforms drug delivery by enabling precise control over how, when, and where a drug is released in the body. Using engineered Nanoparticles (NPs) such as liposomes, dendrimers, polymeric NPs, and inorganic carriers, it allows drugs to bypass biological barriers, reach specific tissues or cells, and release their contents in a controlled manner. By improving targeting accuracy and pharmacokinetics while minimizing side effects, it has established a new paradigm in personalized medicine and complex disease management. It has demonstrated substantial advantages over conventional drug delivery methods in terms of efficacy, safety, and patient compliance.

1. Targeted Drug Delivery

- Passive Targeting: Exploits the Enhanced Permeability and Retention (EPR) effect in tumors, where leaky vasculature allows NPs to accumulate more in tumor tissue.
- Active Targeting: Functionalization with ligands (e.g., antibodies, peptides) enables binding to specific receptors on target cells, increasing cellular uptake.

2. Controlled Drug Release

- Stimuli-Responsive Systems: Nanocarriers can be engineered to release drugs in response to internal (pH, redox, enzymes) or external (heat, light, magnetic field) stimuli.
- Sustained Release: NPs can be designed to degrade slowly, releasing drugs over days to weeks, minimizing dosing frequency.

3. Overcoming Biological Barriers

- NPs can cross difficult biological barriers such as the Blood-Brain Barrier (BBB) or mucus membranes by tuning surface charge, size, and hydrophilicity.

4. Increased Bioavailability and Solubility

- Many poorly soluble drugs can be loaded into nanocarriers to improve their solubility and absorption.

5. Proof of Nanotechnology's Superiority in Controlled and Localized Drug Delivery

- Cancer therapy: Liposomal Doxorubicin (Doxil) and Albumin-Bound Paclitaxel (Abraxane) reduce off-target toxicity and improve drug concentration at tumor sites.
- Neurodegenerative diseases: Nanoparticles help deliver drugs across the BBB for diseases like Parkinson's and Alzheimer's (Yadav et al., 2025).
- Gene therapy: Lipid Nanoparticles (LNPs) deliver siRNA and mRNA safely to cells, as in Onpattro® and COVID-19 mRNA vaccines.

How to cite this article: Radhakrishnaiah Parachuru, Lavanya Krishnan and Geethanjali P. The Role of Nanotechnology in Driving Some Key Advances in Medicine and Healthcare Fields. J Recent Adv Nanomed & Nanotech. 2025; 1(5): 555572.

Key Nanotechnology-Driven Systems

Nanocarrier	Features	Drug Control Mechanism
Liposomes	Biocompatible, encapsulate hydrophilic & hydrophobic drugs	pH-sensitive release
Polymeric NPs	Biodegradable, tunable release kinetics	Enzyme-responsive degradation
Dendrimers	High loading capacity, multifunctional surface	Surface-bound drug release
Solid Lipid NPs	Stable, controlled release, avoids burst effect	Diffusion and erosion-controlled
Inorganic NPs (e.g., gold, silica)	Imaging + therapy	Light/heat-triggered release

What type of nanoparticles are used in crossing the blood-brain barrier

Crossing the Blood-Brain Barrier (BBB) is one of the greatest challenges in treating neurological diseases. Nanoparticles (NPs) offer unique properties — small size, modifiability, and controlled release — that allow them to traverse the BBB using various mechanisms such as receptor-mediated transcytosis and ultrasound-assisted delivery. A variety of nanoparticle types — from lipid-based to biologically derived vesicles — are now engineered to cross the BBB effectively. Techniques like ultrasound, receptor targeting, and vesicle mimicry enable delivery of complex drugs (like RNA and enzymes) to the brain, opening transformative possibilities in neurodegenerative and rare CNS disorders.

1. Lipid Nanoparticles [5]

- Mechanism: Often rely on focused ultrasound or surface modifications to transiently open the BBB or utilize receptor-mediated transport.
- Use Case: siRNA and mRNA delivery in glioblastoma; delivery efficiency enhanced 6–12× by

ultrasound application.

2. Polymeric Nanoparticles [6]

- Mechanism: Designed with surface ligands for receptor-mediated endocytosis; stable and

biodegradable.

- Use Case: Used in targeting tumors, Alzheimer's, and Parkinson's therapies.

3. Solid Lipid Nanoparticles (SLNs)

- Mechanism: Leverage high lipophilicity to enhance passive diffusion; can be PEGylated for longer circulation.
- Use Case: Non-invasive alternatives for CNS delivery with controlled release profiles.

4. Dendrimers

- Mechanism: Tree-like branched structures with modifiable surfaces; useful in targeted gene delivery.
- Use Case: Targeted delivery of nucleic acids or small molecules to CNS lesions.

5. Nanovesicles [7]

- Mechanism: Engineered to enhance BBB penetration via improved permeability and

encapsulation.

- Use Case: Deliver Cannabidiol (CBD) with higher encapsulation efficiency and sustained release for neurological conditions.

6. Extracellular Vesicles [8]

- Mechanism: Naturally derived carriers (like exosomes) with inherent ability to cross the BBB.
- Use Case: Treat lysosomal storage diseases (e.g., Gaucher, Sanfilippo syndrome) by delivering enzymes or genes.

Summary Table

Type	Mechanism	Key Application
Lipid NPs (LNPs)	Ultrasound-triggered & receptor-mediated	RNA delivery in brain tumors
Polymeric NPs	Receptor-mediated endocytosis	Alzheimer's, gliomas
Solid Lipid NPs	Lipophilic diffusion, PEGylation	Non-invasive CNS delivery
Dendrimers	Targeted binding via surface groups	Gene therapy
Nanovesicles (e.g., Tween 20)	Enhanced stability & release	Neurological drug delivery
Extracellular Vesicles	Natural BBB crossing	Enzyme/gene therapy for LSDs

How to cite this article: Radhakrishnaiah Parachuru, Lavanya Krishnan and Geethanjali P. The Role of Nanotechnology in Driving Some Key Advances in Medicine and Healthcare Fields. J Recent Adv Nanomed & Nanotech. 2025; 1(5): 555572.

Some Known Limitations of Current Nanodrug Delivery Systems?

Nanodrug delivery systems hold enormous promise in improving drug bioavailability, targeting precision, and minimizing side effects. Despite these benefits, several limitations currently hinder their widespread clinical adoption. These issues span biological, technical, regulatory, and economic dimensions, making this an active area of research and innovation. While nanodrug delivery systems have reshaped the therapeutic landscape, their current limitations—ranging from instability and low loading to targeting inefficiency and regulatory challenges—must be resolved for full clinical integration. Addressing these hurdles will require interdisciplinary efforts in nanotechnology, pharmacology, and regulatory science.

Key Limitations of Current Nanodrug Delivery Systems include:

1. Toxicity and Biocompatibility Concerns

- Some nanoparticles (especially inorganic and metallic NPs) can induce cytotoxicity, oxidative stress, or inflammation.
- Long-term accumulation and unknown degradation pathways raise biosafety concerns.

2. Poor Stability and Shelf-Life

- Nanoparticles can aggregate or degrade under physiological conditions or during storage, reducing therapeutic efficacy.
- For example, nano emulsions often face issues in achieving consistent formulation and long shelf stability.

3. Low Drug Loading and Uncontrolled Release [9]

- Many nanocarriers have limited capacity to load active drugs.
- Premature or leaky release of drugs reduces treatment precision and safety, especially in non-covalently conjugated systems.

4. Biological Barriers to Targeted Delivery

- Challenges in crossing the blood-brain barrier, penetrating dense tumor stroma, or achieving endosomal escape inside cells still limit delivery success.
- Receptor expression heterogeneity in patients also reduces the predictability of targeting outcomes.

5. Immunogenicity and Rapid Clearance

- Without surface modification (e.g., PEGylation), nanoparticles are often recognized by the immune system and rapidly cleared from circulation.
- Surface coatings improve stealth but may still provoke complement activation.

6. Scalability and Reproducibility Issues [10]

- Transitioning from lab-scale synthesis to clinical-grade manufacturing remains a bottleneck.
- Batch-to-batch variability and strict quality control are difficult in complex nanocarrier systems

7. Regulatory and Translational Hurdles

- Regulatory frameworks for nanomedicine are still evolving, with no universal standards.
- Lack of long-term human data on safety, efficacy, and pharmacokinetics delays clinical adoption.

Improving the Biocompatibility of Nanoparticles

Improving the biocompatibility of nanoparticles is essential for safe and effective drug delivery, particularly in clinical applications. Biocompatibility refers to the ability of a material to perform with an appropriate host response when applied, without causing adverse effects such as immune reactions, toxicity, or inflammation. Nanoparticles (NPs) must be designed to minimize toxicity, avoid immune recognition, and function harmoniously in the biological environment. To enhance nanoparticle biocompatibility, researchers can modify surface properties, select safe and degradable materials, tune physical

characteristics, and employ bio-inspired coatings. These strategies collectively reduce immunogenicity, toxicity, and improve nanoparticle longevity and performance in clinical settings.

Common strategies to improve nanoparticle biocompatibility include:

1. Surface Modification Techniques

- PEGylation (Polyethylene Glycol Coating):
- Adds a hydrophilic stealth layer that reduces recognition by the immune system (reducing opsonization and phagocytosis).
- Increases circulation time and decreases aggregation.
- Zwitterionic Coatings (e.g., phosphorylcholine)
- Mimics cell membranes to reduce immune activation and protein adsorption.

2. Use of Biodegradable Materials

Natural Polymers:

- Examples: chitosan, gelatin, alginate, hyaluronic acid.
- Advantage: Non-toxic degradation by-products, natural clearance.

Synthetic Biodegradable Polymers:

- Examples: PLGA (poly(lactic-co-glycolic acid)), PLA, PCL.

How to cite this article: Radhakrishnaiah Parachuru, Lavanya Krishnan and Geethanjali P. The Role of Nanotechnology in Driving Some Key Advances in Medicine and Healthcare Fields. J Recent Adv Nanomed & Nanotech. 2025; 1(5): 555572.

- Widely used for FDA-approved nanoparticles due to tunable degradation rates.

3. Tuning Physicochemical Properties

Size Optimization:

- Ideal range: 10–100 nm to avoid rapid renal clearance (<10 nm) and uptake by the spleen or liver (>200 nm).

Surface Charge Adjustment:

- Neutral or slightly negative charge improves compatibility; highly positive particles tend to be cytotoxic.

4. Functionalization with Biomolecules

- Cell membrane coating or biomimetic layers:

- Camouflages NPs as 'self' using red blood cell, platelet, or cancer cell membranes.

5. Avoidance of Toxic Elements

- Replace heavy metals (e.g., cadmium in quantum dots) with safer alternatives or use

organic/inorganic hybrids.

- Use of green synthesis methods to avoid toxic reagents or solvents.

6. Controlled Drug Release and Degradation

- Use of pH-sensitive, enzyme-responsive, or redox-sensitive linkers ensures drugs are released only at target sites, minimizing systemic exposure.

7. Other Approaches

- Stimuli-responsive coatings allow NPs to adapt to the microenvironment of the target tissue, minimizing exposure to healthy cells [11].

- Covalent conjugation methods (e.g., amide, hydrazone bonds) ensure more stable drug attachment, reducing premature release and associated toxicity [12].

References

1. Çiftçi Et Al. (2025) Exploring scape anatomy in Crocus L.: Its role in distinguishing series and species," 15th Symposium on the Flora of Southeastern Serbia and Neighboring Regions, Niš, Nish Serbia pp. 11.
2. Yadav VK, Dhanasekaran S, Choudhary N, Nathiya D, Thakur V, et al. (2025) Recent advances in nanotechnology for Parkinson's disease: diagnosis, treatment, and future perspectives. Front Med (Lausanne) 12: 1535682.
3. Song R, Cho S, Khan S, Park I, Gao W (2025) Lighting the Path to Precision Healthcare: Advances and Applications of Wearable Photonic Sensors. Adv Mater 26: e2419161.
4. Mahapatra C (2025) Recent advances in medical gas sensing with artificial intelligence–enabled technology. Medical Gas Research 15(2): 318-326.
5. Elbaz J, Haslam A, Prasad V (2025) Surrogate end points in oncology: aligning drug development incentives and patient needs Nature Reviews Clinical Oncology.
6. Razavi R, Khajouei G, Divsalar F, Dawi E, Amiri M (2025) Recent advances on brain drug delivery via nanoparticles: alternative future materials for neuroscience applications; a review. Rev Neurosci 36(4): 405-430.
7. Grifoni L, Landucci E, Pieraccini G, Mazzantini C, Bergonzi MC, et al. (2025) Development and Blood–Brain Barrier Penetration of Nanovesicles Loaded with Cannabidiol. Pharmaceuticals 18(2): 160.
8. Lerussi G, Araya VV, Moltó-Abad M, del Toro M, Pintos-Morell G, et al. (2025) Extracellular Vesicles as Tools for Crossing the Blood–Brain Barrier to Treat Lysosomal Storage Diseases. Reproductive and Developmental Biology 15(1): 70.
9. Abbas T, Kanwar F, Tariq H, Malik MR (2025) Nanoparticles in Drug Delivery Systems: Challenges, Innovations, And Surface Modification for Targeted Therapeutics. Indus Journal of Bioscience Research 3(1): 325-336.
10. Imantay A, Mashurov N, Zhaisanbayeva BA, Mun EA (2025) Doxorubicin-Conjugated Nanoparticles for Potential Use as Drug Delivery Systems. Nanomaterials (Basel) 15(2): 133.
11. Abbas T, Kanwar F, Tariq H, Malik MR (2025) Nanoparticles in Drug Delivery Systems: Challenges, Innovations, And Surface Modification for Targeted Therapeutics. Indus Journal of Bioscience Research 3(1): 325-336.
12. Imantay A, Mashurov N, Zhaisanbayeva BA, Mun EA (2025) Doxorubicin-Conjugated Nanoparticles for Potential Use as Drug Delivery Systems. Nanomaterials 15(2): 133.

How to cite this article: Radhakrishnaiah Parachuru, Lavanya Krishnan and Geethanjali P. The Role of Nanotechnology in Driving Some Key Advances in Medicine and Healthcare Fields. J Recent Adv Nanomed & Nanotech. 2025; 1(5): 555572.

How to cite this article: Radhakrishnaiah Parachuru, Lavanya Krishnan and Geethanjali P. The Role of Nanotechnology in Driving Some Key Advances in Medicine and Healthcare Fields. J Recent Adv Nanomed & Nanotech. 2025; 1(5): 555572.