INTERNATIONAL JOURNAL OF PHARMACEUTICAL SCIENCES
[ISSN: 0975-4725; CODEN(USA): IJPS00]
Journal Homepage: https://www.ijpsjournal.com

OPEN ACCESS

Review Article

Application of Nanotechnologies in Pharmaceutical Industry

Rohan Kaswa*, Vedant Bhansali, Sayali Deth, Snehal Tuse

Rasiklal M Dhariwal Institute of Pharmaceuticals Education and Research, Chinchwad, Pimpri-Chinchwad, Maharashtra 411019

ARTICLE INFO

Published: 13 Oct 2025

Keywords:

Nanotechnology, Covid-19, Cancer therapy, Lab on chip, Nanoparticles, Biomarkers

DOI:

10.5281/zenodo.17340743

ABSTRACT

Nanotechnology has rapidly emerged as a transformative force in the pharmaceutical and medical fields, offering innovative solutions for drug delivery, diagnostics, and therapeutic applications. This review highlights the advantages of nanoparticle-based drug delivery systems, including enhanced efficacy, targeted delivery, and reduced adverse effects. Various nano systems-such as carbon nanotubes, dendrimers, liposomes, and solid lipid nanoparticles-are explored along with different fabrication techniques like polymerization, nano-spray drying, and supercritical fluid technology. The study also examines the physicochemical factors influencing nanoparticle performance and stability. Clinical applications span cancer, Alzheimer's disease, tuberculosis, kidney disorders and COVID-19 vaccines. Additionally, nanotechnology's role in diagnostics, wearable devices, and AI-driven biomedicine are discussed. Despite its promise, challenges related to toxicity, scalability and regulation persist. This paper provides a comprehensive overview of current strategies and future directions, serving as a valuable resource for researchers and practitioners in the field.

INTRODUCTION

Nanotechnology refers to the manipulation and application of materials, structures, and systems at the nanoscale-typically between 1 and 100 nanometers-where unique physical and chemical phenomena emerge. This interdisciplinary field bridges science and engineering, enabling the design, characterization, and fabrication of advanced nanoscale technologies. The foundational concept was famously introduced by physicist Richard Feynman in his 1959 lecture, *"There's plenty of room at the bottom,"* where he envisioned the possibility of constructing devices at atomic and molecular scales. Today, nanotechnology is widely recognized as one of the most promising scientific frontiers of the 21st century, particularly in biomedical research. Its rapid evolution is reflected in the surge of public

***Corresponding Author:** Rohan Kaswa

Address: *Rasiklal M Dhariwal Institute of Pharmaceuticals Education and Research, Chinchwad, Pimpri-Chinchwad, Maharashtra 411019*

Email : kaswarohan02@gmail.com

Relevant conflicts of interest/financial disclosures: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

and private investment in nanotech R&D, which has catalysed innovation across healthcare, manufacturing and diagnostics. Beyond its technical contributions, nanotechnology is reshaping societal structures, economic models and the quality of human life by enabling smarter, more efficient solutions to longstanding challenges.

In the pharmaceutical domain, nanotechnology is broadly categorized into two key areas: nanomaterials and nano-devices.

A. Nanomaterials in Drug Delivery and Biomedical Engineering;

Nanomaterials are extensively used in drug delivery systems and biomedical implants. These include:

- **Nanocrystalline materials**, produced via specialized milling techniques, which enhance the solubility and bioavailability of poorly water-soluble drugs. These formulations are suitable for intravenous administration or inhalation as nanosuspensions.
- **Nanostructured materials**, engineered to exhibit unique surface properties and morphologies, are often tailored for controlled drug release and targeted delivery.

Surface modification or coating of these materials improves their biocompatibility, making them ideal for use in dental implants, orthopedic scaffolds, and tissue engineering applications. Their small size and high surface-area-to-volume ratio allow for efficient interaction with biological systems, facilitating applications in:

- Asthma inhalers
- Transdermal hormone delivery
- Ocular drug administration
- Oral and vaccine-based delivery platforms
- Gene therapy
- Cancer treatment

Several pharmaceutical companies have already adopted nanoparticle-based therapies, particularly in oncology, to enhance therapeutic precision and minimize systemic toxicity.

B. Nano Devices in Diagnostics and Therapeutics;

Nano-devices encompass a range of technologies designed to manipulate fluids, detect biomolecules, and perform high-throughput biological analyses. Key examples include:

- **Microfluidic systems**, which control fluid dynamics at micro- to nanoliter scales, enabling precise sample handling and reaction control.
- **Nano and micro-electromechanical systems (NEMS/MEMS)**, which integrate mechanical and electronic components for sensing and actuation at the nanoscale.
- **Microarrays**, which facilitate multiplexed analysis of DNA, proteins, cells, and antibodies, playing a crucial role in genomics, proteomics, and personalized medicine.

C. Liposomes: A Versatile Class of Pharmaceutical Nanoparticles

Liposomes are nanoscale to microscale spherical vesicles composed of one or more phospholipid bilayers, structurally analogous to biological membranes. Their ability to encapsulate both hydrophilic and lipophilic drugs make them highly effective carriers in drug delivery systems.

Key Characteristics

- **Size Range:** Typically, 50–200 nm for nanomedical applications, though they can extend to several microns.
- **Composition:** Primarily phospholipids such as phosphatidylcholine; cholesterol is often included to enhance membrane stability.

Structural Features

1. **Hydrophilic Core:** Ideal for encapsulating water-soluble drugs.
2. **Phospholipid Bilayer:** Accommodates fat-soluble (lipophilic) compounds.
3. **Surface Modifications:** PEGylation (attachment of polyethylene glycol) extends circulation time by reducing immune recognition.

Types of Liposomes;

Table 1

Type	Distinctive Features
Multilamellar Vesicles (MLVs)	Multiple concentric lipid bilayers
Small Unilamellar Vesicles (SUVs)	Single bilayer, typically 20–100 nm
Large Unilamellar Vesicles (LUVs)	Single bilayer, larger than 100 nm
Stealth Liposomes	PEG-coated to evade immune system clearance
Cationic Liposomes	Positively charged; suitable for gene delivery

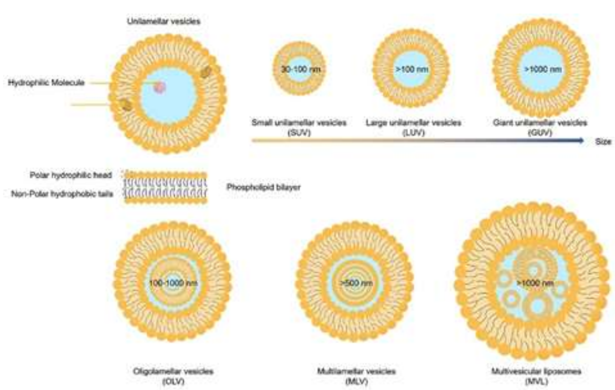


Figure 1

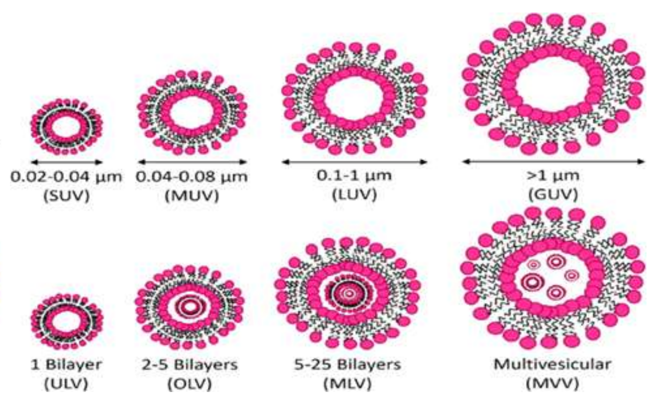


Figure 2

Pharmaceutical Advantages

1. **Enhanced Solubility:** Capable of carrying both hydrophilic and hydrophobic drugs.
2. **Controlled Release:** Enables sustained or delayed drug release profiles.
3. **Targeted Delivery:** Surface ligands can be added to direct liposomes to specific tissues or cells (e.g., tumour sites).
4. **Reduced Toxicity:** Encapsulation minimizes exposure of healthy tissues to toxic agents.
5. **Biocompatibility & Biodegradability:** Constructed from materials compatible with biological systems.

Mechanism of Action;

1. Drug encapsulation during formulation
2. Administration via injection or oral route
3. Systemic circulation
4. Passive or active targeting to diseased tissues
5. Cellular uptake via fusion or endocytosis
6. Intracellular drug release

Therapeutic Applications;

- **Cancer Treatment:**
  Example: Doxil (liposomal doxorubicin) for breast and ovarian cancers
- **Antifungal Therapy:**

Example: AmBisome (liposomal amphotericin B) for systemic fungal infections

- **Vaccination Platforms:**
  Example: Lipid nanoparticles (LNPs) used in mRNA-based COVID-19 vaccines
- **Gene Therapy:**
  Example: Cationic liposomes employed for siRNA and DNA delivery
- **Topical Formulations:**
  Example: Used in dermatological creams and transdermal patches

Challenges in Liposomal Formulation;

- Limited stability during storage
- Short shelf life
- High production costs
- Complex and sensitive manufacturing protocols
- Rapid clearance by the reticuloendothelial system (RES)

Emerging Innovations;

- **Stimuli-responsive liposomes:** Triggered by pH, temperature, or enzymatic activity
- **Ligand-targeted liposomes:** Functionalized with antibodies or peptides for precision targeting
- **Smart liposomes:** Engineered for personalized medicine and adaptive drug release.

D. Nanotechnology and Lab-on-Chip Technology:

Synergistic Advances in Nanotechnology and Lab-on-Chip Systems for Precision Healthcare. The convergence of nanotechnology and Lab-on-Chip (LOC) systems is reshaping the landscape of modern healthcare, offering transformative solutions for diagnostics, targeted therapies, and real-time monitoring. These technologies, when integrated, enable the creation of compact, multifunctional platforms that surpass conventional diagnostic tools in speed, accuracy, and cost-efficiency.

- **Molecular-Level Insights and Disease Profiling;**

LOC devices are increasingly being applied in the detection of viral and oncological diseases, leveraging microfluidic systems to analyze genetic and biochemical markers at the cellular level. Innovations in gene sequencing and fluid-based sampling have further propelled nanotechnology into the realm of precision medicine, enabling the identification of disease signatures that were previously elusive.

- **Lab-on-Nanoparticles: A New Class of Smart Therapeutics;**

The fusion of nanoscale engineering with LOC principles has led to the emergence of Lab-on-Nanoparticles-miniaturized platforms capable of performing simultaneous diagnostic, therapeutic, and monitoring functions. These smart particles are engineered to respond to physiological changes, offering real-time feedback and enabling adaptive treatment strategies. Their nanoscale dimensions allow them to navigate biological environments with high specificity, making them ideal for personalized medicine.

- **Applications in Cancer and Beyond;**

One of the most impactful uses of these technologies is in oncology, where nanoparticles can be functionalized to selectively bind to cancer cells, facilitating early detection and localized drug release. LOC systems complement this by enabling rapid screening for genetic mutations, infectious agents, and metabolic imbalances, often at the point of care.

- **Enhanced Drug Delivery and Pharmacological Precision;**

Nanotechnology has revolutionized drug delivery through systems like nano-liposomes, which can be tailored to release therapeutic agents at specific sites within the body. This targeted approach not only improves drug efficacy but also minimizes systemic toxicity. Future generations of nanoscale diagnostic platforms are expected to incorporate viral detection capabilities and drug release tracking, allowing clinicians to assess treatment performance in real time.

- **Toward Smarter Pharmacokinetics and Pharmacodynamics;**

The overarching goal of these innovations is to optimize the behaviour of drugs within the body-extending their circulation time, enhancing their bioavailability, and ensuring they act precisely where needed. By refining both pharmacokinetic and pharmacodynamic profiles, nanotechnology is paving the way for therapies that are faster, more efficient and tailored to individual patient needs.

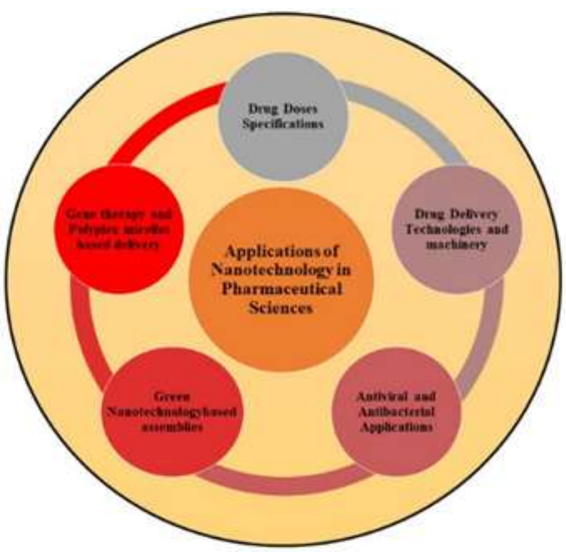


Figure 3. Applications of nanotechnology in pharmaceutical sciences.

E. Nanoscience and Drug Dose Specifications:

Nanoscience in Pharmaceuticals: Precision, Promise, and Emerging Challenges.

Nanoscience has profoundly reshaped the pharmaceutical landscape by enabling the design of therapeutics with superior efficacy and reduced toxicity. Through the use of engineered nanoparticles, drug formulations can be optimized to improve solubility, enhance stability and significantly boost bioavailability. These nanoscale carriers also offer the advantage of targeted delivery, allowing drugs to reach specific tissues or cellular compartments while minimizing systemic side effects.

Pharmacokinetic Complexity and Dosing Considerations;

- The unique physicochemical characteristics of nanoparticles-such as size, shape, surface charge and hydrophobicity-necessitate a highly tailored approach to dosing and administration. Unlike conventional drugs, nanoparticle-based formulations exhibit complex in vivo behaviour, including variable absorption, distribution, metabolism and excretion (ADME) profiles. For example, oral delivery may require higher doses than intravenous routes due to differences in gastrointestinal absorption and first-pass metabolism.

- Determining the optimal dosing regimen for nanomedicines involves balancing therapeutic efficacy with safety. Researchers must carefully evaluate parameters such as dose range, frequency, and duration to ensure sustained therapeutic action without triggering adverse effects. This precision becomes even more critical when dealing with dynamic biological environments and patient-specific variability.

Nano sponges and Detoxification Strategies;

- While nanotechnology has advanced drug delivery, its potential in drug detoxification is gaining traction. One emerging application involves the use of nano sponges-porous, cross-linked polymeric structures designed to absorb and neutralize excess or toxic drug molecules in the bloodstream. These nanoscale absorbents can be engineered to selectively bind harmful compounds, offering a novel approach to managing drug overdoses and mitigating toxicity.

- Recent experimental models have explored squalene-linked nano assemblies capable of sequestering antiviral and anticancer agents. These constructs show promise in enhancing therapeutic selectivity and reducing off-target effects, although most remain in early-stage in vitro development. Their potential to act as dual-function agents-delivering drugs while simultaneously regulating their concentration-marks a significant step toward smarter, responsive nanomedicine platforms.

Regulatory Collaboration and Safety Frameworks;

As nanomedical products become more sophisticated, the need for robust regulatory oversight grows. The development of standardized testing protocols and safety guidelines is essential to ensure that nanoparticle-based therapies are both effective and safe for clinical use. Collaborative efforts between researchers, industry stakeholders, and regulatory bodies are vital to establish frameworks that address the unique challenges posed by nanomaterials - such as long-term biocompatibility, immunogenicity, and environmental impact.

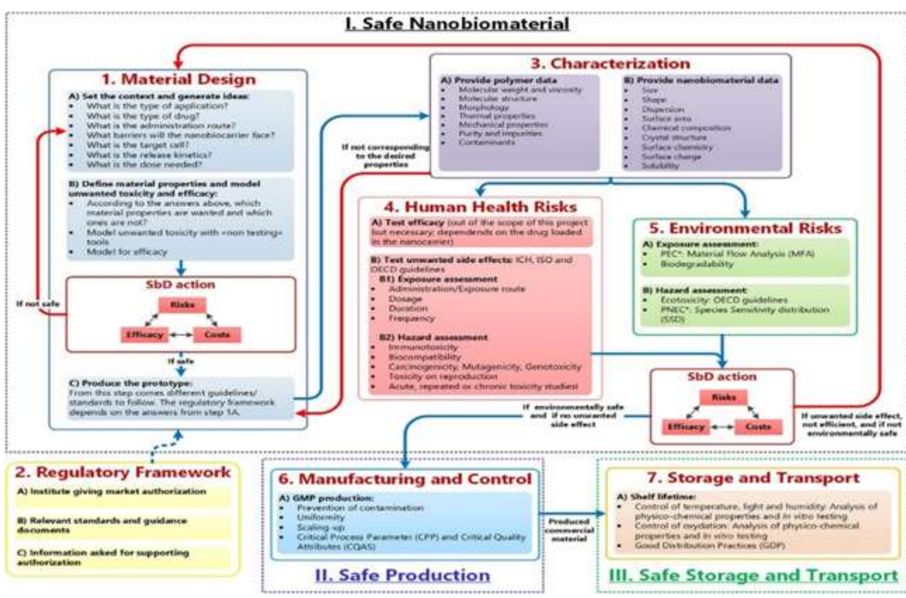


Figure 4

F. Nanotechnology and Drug Delivery Technologies:

Nanotechnology in Drug Delivery: A paradigm shifts toward precision therapeutics.

Nanotechnology has ushered in a transformative era in pharmaceutical sciences, particularly in the realm of drug delivery. By leveraging nanoscale engineering, researchers have developed sophisticated delivery platforms that not only enhance therapeutic precision but also mitigate systemic toxicity. These innovations are reshaping how drugs interact with biological systems, offering new avenues for treating complex diseases.

Targeted Delivery and Pharmacological Optimization;

At the heart of nanotechnology-enabled drug delivery lies the ability to engineer nanoparticles that can navigate biological barriers and selectively accumulate at pathological sites—such as tumours, inflamed tissues, or infected regions. This site-specific targeting reduces off-target effects and allows for lower therapeutic doses, thereby improving patient safety profiles.

Moreover, nanoparticles can be tailored to improve the physicochemical properties of drugs. Poorly soluble or unstable compounds can be encapsulated within nanocarriers, enhancing their solubility, stability, and bioavailability. This not only improves therapeutic outcomes but also expands the range of viable drug candidates that were previously limited by unfavourable pharmacokinetics.

Nanorobotics and Next-Gen Delivery Systems;

Beyond passive delivery systems, the field is rapidly advancing toward active, programmable nanodevices. Experimental nanorobots-microscale machines capable of autonomous movement-are being designed to traverse the circulatory system and deliver therapeutic payloads directly to diseased cells. These innovations are particularly promising in oncology, where precision targeting is critical to avoid damage to healthy tissues.

Researchers are also exploring wireless nanoscale surgical tools capable of intracellular and intranuclear interventions. These tools could revolutionize the treatment of malignancies by enabling minimally invasive manipulation at the cellular level.

One of the most ambitious concepts in this domain is the development of respirocytes-synthetic red blood cell analogs. These nanorobotic constructs are theorized to carry and release oxygen at magnitudes far exceeding natural erythrocytes, potentially offering life-saving support in cases of severe hypoxia, anaemia or trauma. Their application could extend to treating blood-related disorders and enhancing oxygenation in critical care settings.

Future Directions and Clinical Integration;

As nanotechnology continues to evolve, its integration into mainstream drug delivery systems is expected to deepen. The future lies in multifunctional platforms that combine diagnostics, therapeutics and real-time monitoring-ushering in the era of theranostic. These systems will not only deliver drugs but also adapt to patient-specific responses, enabling dynamic and personalized treatment regimens.

However, the path to clinical translation requires rigorous validation. Issues such as long-term biocompatibility, immune interactions and scalable manufacturing must be addressed. Collaborative efforts between scientists, clinicians and regulatory bodies will be essential to establish robust frameworks for safety and efficacy.

G. DNA Nanotechnology and Drug Delivery System:

DNA Nanotechnology in Drug Delivery: A Transformative Frontier

Recent years have witnessed the emergence of DNA-based drug delivery platforms, including

DNA vaccines and gene guns, which leverage the inherent programmability and biocompatibility of nucleic acids. Building on these foundational concepts, the field of **DNA nanotechnology** is rapidly gaining traction within nanomedicine, offering a paradigm shift in how therapeutic agents are delivered and targeted. These nanoscale constructs are capable of **self-assembling into precise architectures**, enabling enhanced specificity in drug targeting while minimizing systemic toxicity—a particularly critical advancement in oncology, where chemotherapeutic agents often pose significant cytotoxic risks to healthy tissues.

Precision Design Through Computational Tools;

Cutting-edge research now integrates computational modelling and in silico design strategies to engineer DNA nanostructures with tailored dimensions, surface functionalities and disease-specific responsiveness. This approach facilitates the development of personalized nanotherapeutics, aligning molecular design with individual patient profiles and disease phenotypes.

Therapeutic Integration and Enhanced Uptake;

Promising results have emerged from the conjugation of potent biomolecules-such as doxorubicin and CpG oligonucleotides-with DNA-based nanocarriers. These hybrid systems demonstrate improved cellular uptake and therapeutic efficacy, underscoring the potential of DNA nanostructures to serve as intelligent delivery vehicles.

RNA-Based Nanomedicine;

The conceptual framework established by DNA nanotechnology is paving the way for RNA-based therapeutic platforms, which may offer similar programmability and disease-targeting capabilities. As this field evolves, it holds immense promise for expanding the toolkit of precision medicine and reshaping the future of drug delivery.

H. Green Nanotechnology-Driven Drug Delivery Assemblies:

Green Nanotechnology in Nanomedicine: A Sustainable Shift

Traditional nanomedicine production has largely relied on chemical and physical techniques to reduce materials to micro-and nanoscale dimensions. While effective, these methods often raise concerns regarding environmental sustainability and potential health hazards due to toxic byproducts. In response, the field is increasingly embracing green chemistry and green engineering principles to guide the development of eco-conscious nanobiomedicine.

The goal of this transition is to engineer biocompatible nanoassemblies that minimize ecological impact and reduce toxicity risks to patients. These green nanoassemblies-when integrated with therapeutic agents, vaccines or diagnostic biomarkers-represent a promising direction for advancing sustainable nanomedical applications.

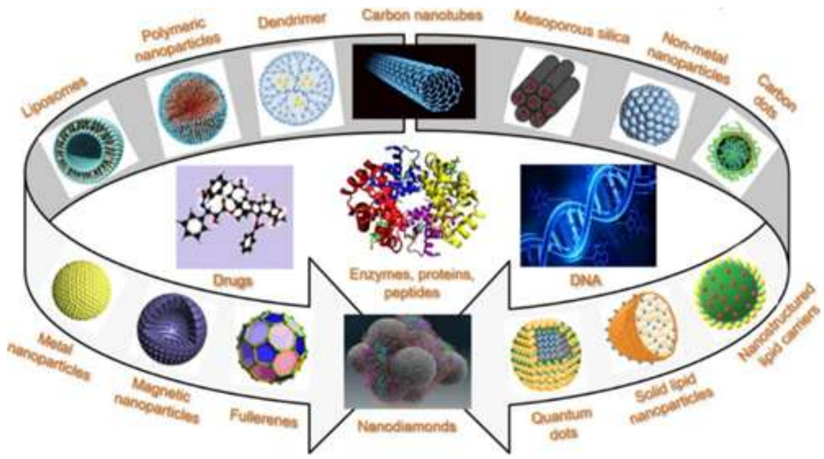


Figure 5

Examples of Green-Engineered Nanostructures;

A variety of inorganic and organic nanostructures have already been synthesized using environmentally friendly approaches. Notable examples include:

Table 2

Type of Nano assembly	Green-Engineered Applications
Gold & Silver Nanoparticles	Drug delivery, imaging, antimicrobial therapies
Quantum Dots	Biosensing, diagnostics
Polymeric Nanoparticles	Controlled drug release, gene delivery
Mesoporous Silica Nanoparticles	Targeted delivery, enzyme immobilization
Dendrimers	Gene therapy, vaccine carriers
Nanostructured Lipid Carriers	Oral and topical drug delivery
Solid Lipid Nanoparticles	Enhanced bioavailability, sustained release formulations

These nanostructures are often functionalized with drugs, nucleic acids (e.g. DNA), enzymes, proteins or peptides, enabling precise therapeutic action and improved pharmacokinetics.

Call for Comparative Research;

Despite the growing adoption of green methodologies, there remains a critical need for comparative studies that evaluate the performance and safety profiles of nanomedicines produced via conventional bioengineering versus those synthesized through green bioengineering frameworks. Such investigations will be instrumental in identifying optimal manufacturing conditions and guiding future innovations in eco-friendly nanotherapeutics.

I. Nanotechnology-Antiviral and Antibacterial Applications:

Nanotechnology: A Precision Tool Against Microscopic Pathogens

Pathogens such as viruses, bacteria, and fungi operate at the microscopic level—making nanoscale interventions a logical and highly effective countermeasure. Nanotechnology has emerged as a transformative platform for both the diagnosis and treatment of a broad spectrum of infectious diseases, offering unprecedented precision and adaptability.

Historically, metals like silver have been used in traditional healing systems, including ancient Greek medicine, for their antimicrobial properties. Modern nanoscience has refined this approach by converting bulk materials into nanoscale formulations, significantly enhancing their biological activity. For instance, research from

Nycryst Pharmaceuticals (Canada) demonstrated that nano silver particles exhibit superior therapeutic efficacy in treating burns and wounds due to their enhanced skin penetration and reactivity at the cellular level.

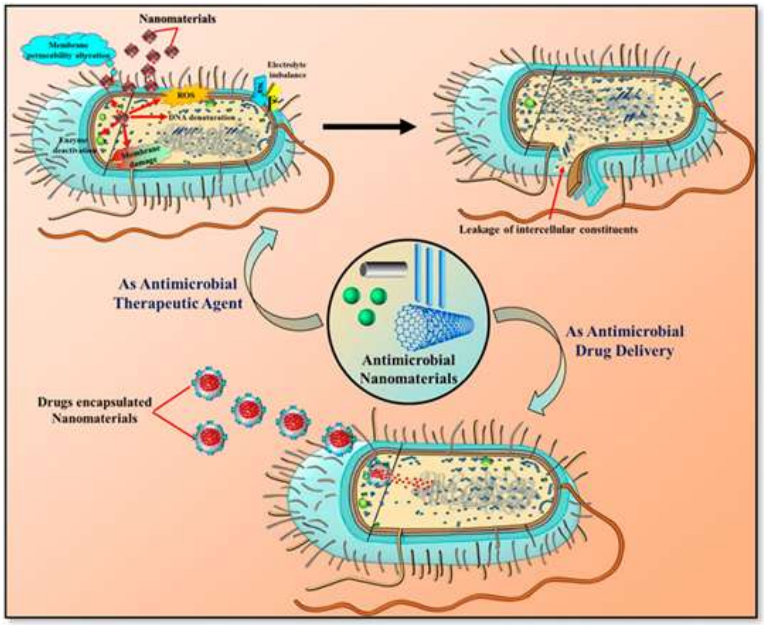


Figure 6

Genomics, Proteomics, and Nano-Enabled Diagnostics;

Advances in genomic and proteomic technologies have already deepened our understanding of disease mechanisms at the molecular level. When integrated with nanotechnology, these fields unlock new possibilities for high-resolution diagnostic tools capable of detecting genetic anomalies and molecular dysfunctions with remarkable sensitivity.

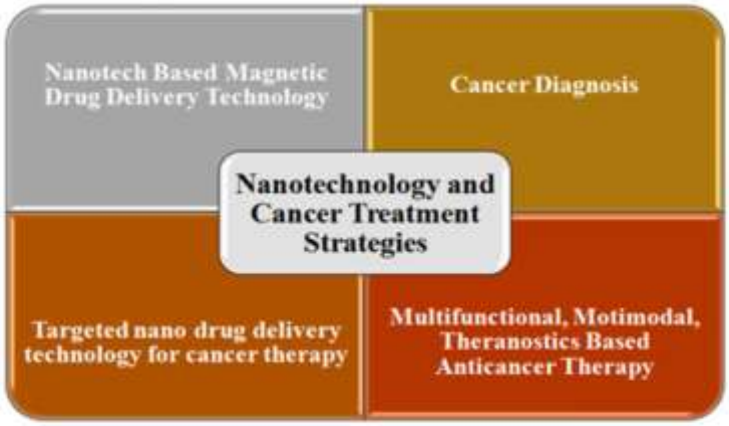
Toward Personalized and Regenerative Nanomedicine;

Emerging research suggests that nanotechnology will soon underpin preventive and regenerative medical strategies, enabling targeted and personalized therapies tailored to individual patient profiles. These nano-enabled systems promise not only enhanced therapeutic outcomes but also greater cost-efficiency and reduced treatment timelines, making them highly attractive for scalable healthcare solutions.

J. Nanotechnology in Cancer Diagnosis:

Nanotechnology in Cancer Diagnosis: A Precision-Driven Revolution

One of the most pressing challenges in oncology is the late-stage detection of cancer, which significantly limits treatment efficacy and patient survival. Most cancers remain undiagnosed until they reach advanced stages-often the third or fourth-where therapeutic options become less effective. To address this diagnostic gap, nanotechnology is being harnessed to enable early and accurate tumour detection across various organ systems.



Nanotechnology offers highly sensitive and specific multiplexed detection capabilities, allowing for the identification of cancer biomarkers both in extracellular environments and through advanced in vivo bioimaging techniques. The nanoscale size of these materials enables them to penetrate cellular membranes and even cross the blood–brain barrier, making them ideal candidates for both targeted drug delivery and precise disease localization.

Targeted Nanoparticles and Biosensors: Emerging Diagnostic Tools

Among the most promising innovations are targeted nanoparticles, engineered to selectively bind to cancer cells. This specificity facilitates early detection, improves monitoring of disease progression and enhances diagnostic accuracy. These nanoparticles can be functionalized to recognize unique surface markers on malignant cells, enabling clinicians to visualize and assess tumors with greater precision.

Complementing this approach is the development of nano-enabled biosensors-miniaturized devices capable of detecting cancer-associated biomarkers in biological fluids such as blood, saliva or urine. These biosensors offer a non-invasive, rapid, and cost-effective means of identifying malignancies at their earliest stages, potentially transforming routine screening and personalized diagnostics.

Toward Non-Invasive, Personalized Cancer Diagnostics;

The integration of nanotechnology into cancer diagnostics holds immense promise for creating more accurate, less invasive, and patient-tailored diagnostic platforms. However, challenges remain in terms of scalability, regulatory approval, and clinical translation. Continued research is essential to refine these technologies, validate their efficacy, and ensure their safe deployment in real-world healthcare settings.

K. Multifunctional, Multimodal, Theranostics-Based Anticancer Therapy:

Multifunctional and Multimodal Theranostics: A Transformative Paradigm in Cancer Therapy

The integration of multifunctional and multimodal strategies within theranostic nanomedicine is reshaping the landscape of cancer treatment. Theranostics-an approach that fuses diagnostic and therapeutic capabilities-leverages the unique physicochemical properties of nanomaterials to enable simultaneous disease detection and intervention. Engineered at the nanoscale, these materials (e.g., nanoparticles, liposomes, dendrimers) can be tailored to perform diverse roles, including targeted drug delivery, molecular imaging and site-specific therapy.

Multifunctionality refers to the capacity of a single nanoplatform to execute multiple tasks-such as transporting chemotherapeutic agents while concurrently enabling real-time imaging. This dual capability enhances precision and minimizes systemic toxicity. Meanwhile, the term multimodal denotes the incorporation of various therapeutic modalities-such as chemotherapy, radiotherapy, photothermal therapy and immunotherapy-into a unified treatment regimen. When embedded within nanocarriers, these modalities benefit from enhanced bioavailability, controlled release, and selective accumulation at tumor sites via mechanisms like the enhanced permeability and retention (EPR) effect.

A key advantage of theranostic nanomaterials lies in their ability to facilitate dynamic monitoring of therapeutic progress. By integrating contrast agents or fluorescent markers, clinicians can visualize drug distribution, assess tumor response, and adapt treatment protocols in real time-ushering in a more personalized and responsive approach to oncology. In essence, the convergence of multifunctional and multimodal capabilities within nanotheranostics holds immense promise. It not only amplifies therapeutic efficacy but also reduces off-target effects, paving the way for more individualized, adaptive and minimally invasive cancer care.

L. Targeted Nano Drug Delivery Technology for Cancer Therapy:

Targeted Nano Drug Delivery Systems in Cancer Therapy: Precision Meets Innovation

Targeted nano drug delivery represents a cutting-edge approach in oncology, utilizing nanoscale carriers to transport therapeutic agents directly to malignant cells. These nanocarriers-engineered to recognize and bind selectively to tumor-specific biomarkers-enable localized drug release at the tumor site, thereby sparing healthy tissues and reducing systemic toxicity. One of the core advantages of this technology lies in its ability to concentrate therapeutic payloads within the tumor microenvironment. This is particularly beneficial for agents with poor solubility or high systemic toxicity, as it allows for elevated local dosing without compromising patient safety. Moreover, encapsulating drugs within nanostructures enhances their pharmacokinetic profiles-improving solubility, stability and circulation time-while also mitigating challenges such as multidrug resistance and poor bioavailability often encountered in conventional chemotherapy.

A diverse array of nanocarriers is under active investigation, including liposomes, polymeric nanoparticles, dendrimers, and carbon nanotubes. These platforms can be functionalized with targeting ligands—such as monoclonal antibodies, peptides, or aptamers—that recognize overexpressed receptors on cancer cells. This molecular targeting facilitates receptor-mediated endocytosis, ensuring efficient cellular uptake and intracellular drug release. Importantly, these delivery systems can be co-loaded with imaging agents, enabling real-time visualization of drug biodistribution, tumor targeting, and therapeutic response. Such theranostic integration supports adaptive treatment strategies, allowing clinicians to monitor efficacy and fine-tune protocols based on dynamic feedback.

In summary, targeted nano drug delivery technologies hold transformative potential for cancer therapy. By enhancing drug specificity, minimizing off-target effects, and enabling personalized treatment regimens, they offer a promising pathway toward more effective and patient-centric oncology care. Nonetheless, continued research is essential to refine these systems, address translational challenges, and ensure their safe and scalable implementation in clinical settings.

M. Nanotech Based Magnetic Drug Delivery Technology and Cancer Therapy:

Integrating Nanotechnology and Magnetic Drug Delivery: A Precision-Driven Frontier in Therapeutics

Nanotechnology and magnetic drug delivery systems represent synergistic innovations in modern medicine, offering refined control over therapeutic distribution and efficacy. Magnetic drug delivery, in particular, harnesses externally applied magnetic fields to steer drug-loaded nanoparticles toward specific pathological sites within the body. These magnetic nanoparticles-often functionalized with therapeutic agents-are administered systemically and then guided to target tissues, such as tumors, through localized magnetic manipulation. This targeted navigation minimizes systemic drug dispersion and significantly reduces off-target toxicity. Parallel advances in nanotechnology have enabled the design of drug carriers with physicochemical properties that surpass conventional delivery platforms. Engineered nanoparticles can be tailored for selective binding to diseased cells or tissues, enhancing drug accumulation at the intended site while mitigating collateral damage to healthy structures. Functionalization with ligands, antibodies or peptides allows for receptor-specific targeting, further refining delivery precision. Beyond targeting, nanocarriers offer protective encapsulation of therapeutic payloads, shielding them from enzymatic degradation and premature clearance. This not only improves drug stability but also facilitates controlled and sustained release, optimizing pharmacodynamics and therapeutic outcomes.

The convergence of nanotechnology with magnetic guidance has demonstrated compelling potential across multiple clinical domains. In oncology, for instance, magnetically responsive nanoparticles can deliver chemotherapeutic agents directly to tumor masses, elevating local drug concentrations while sparing surrounding healthy tissue—thereby enhancing efficacy and reducing adverse effects. Similarly, in neurology, magnetic targeting enables the delivery of neuroactive compounds to discrete brain regions, offering a promising strategy for treating disorders with spatially localized pathology.

Overall, the integration of nanotechnology and magnetic drug delivery systems marks a transformative shift toward precision medicine. By improving site-specific targeting, reducing systemic exposure, and enabling real-time control over drug distribution, these technologies are poised to redefine therapeutic paradigms. Continued interdisciplinary research and translational efforts will be critical to unlocking their full clinical potential.

N. Nanomedicine and COVID-19:

Nanomedicine in the COVID-19 Era: Bridging Nanoscale Innovation with Pandemic Response

The COVID-19 pandemic has catalysed the rapid advancement and deployment of nanomedicine across diagnostics, therapeutics and vaccine delivery. At the heart of this innovation lies the intrinsic compatibility between nanoparticles and viral pathogens like SARS-CoV-2-both of which operate at the nanoscale. This dimensional similarity enables nanoparticles to interact intimately with viral particles, offering unique opportunities for detection, neutralization, and targeted intervention.

Structural and Functional Synergy;

Nanoparticles can be engineered with precise physicochemical properties, allowing them to mimic or complement biological structures. For instance, surface functionalization with ligands or antibodies enables nanoparticles to selectively bind to viral proteins, such as the spike glycoprotein of SARS-CoV-2. This binding capability has been harnessed in diagnostic platforms where nanoparticle-virus interactions trigger optical or fluorescent signals, facilitating rapid and sensitive detection in biological samples like saliva or blood.

Targeted Therapeutics and Drug Delivery;

Beyond diagnostics, nanoparticles serve as intelligent delivery vehicles capable of transporting antiviral agents directly to infected cells. This targeted approach enhances drug bioavailability at the site of infection while minimizing systemic toxicity. Liposomes, polymeric nanoparticles, metallic nanostructures and micelles have all been explored for encapsulating and conjugating antiviral compounds. These nano formulations can inhibit viral entry, replication and assembly, thereby disrupting the infection cycle with heightened pharmacological precision.

Protective Technologies and Vaccine Platforms;

Nanotechnology has also contributed to the development of antiviral protective gear. Face masks embedded with nanoparticle coatings-such as silver or copper nanoparticles-can trap and inactivate viral particles upon contact, offering an additional layer of defense for healthcare workers and the public. In vaccine development, lipid nanoparticles have played a pivotal role in mRNA vaccine delivery, ensuring stability, cellular uptake and controlled release. Emerging platforms, including microneedle patches and intranasal sprays, are being investigated to improve accessibility and immunogenicity, particularly in resource-constrained settings.

Manufacturing and Personalized Applications;

The scalability of nanotechnology has enabled its integration into pharmaceutical manufacturing pipelines, supporting the production of nano-enabled vaccines and therapeutics. Furthermore, personalized medical devices incorporating antiviral nanomaterials are being explored to enhance patient safety and treatment responsiveness. Quantum dots and other nanoscale biosensors are under development for real-time monitoring and diagnostic precision.

Challenges and Future Directions;

Despite its promise, nanomedicine faces critical challenges-particularly regarding nanoparticle-induced cytotoxicity and long-term biocompatibility. Rigorous investigation into safety profiles, biodistribution and immune interactions is essential to ensure clinical translation. Nevertheless, the pandemic has underscored the transformative potential of nanotechnology in infectious disease management.

O. Biomarkers in Nanotechnology – A Deeper Dive:

Nanotechnology has revolutionized how we detect and analyze biomarkers, especially in early disease diagnosis and personalized medicine. Here's a more detailed look at the science and applications:

What Are Biomarkers?

Biomarkers are measurable biological indicators that reflect:

- Normal biological processes
- Pathogenic conditions
- Responses to therapeutic interventions

They can be proteins, nucleic acids, metabolites or even whole cells like circulating tumor cells (CTCs).

Nanotechnology Enhanced Biomarker Detection Nanomaterials offer high sensitivity, specificity and real-time detection capabilities.

1) Functionalization;

Nanoparticles are coated with antibodies, aptamers, or ligands that bind specifically to biomarkers. This enables targeted detection even at ultra-low concentrations.

2) Signal Transduction;

Binding of biomarkers causes changes in optical, electrical, or magnetic properties. These changes are measured using biosensors for quantification.

3) Multiplexing;

Nanodevices can detect multiple biomarkers simultaneously, improving diagnostic accuracy

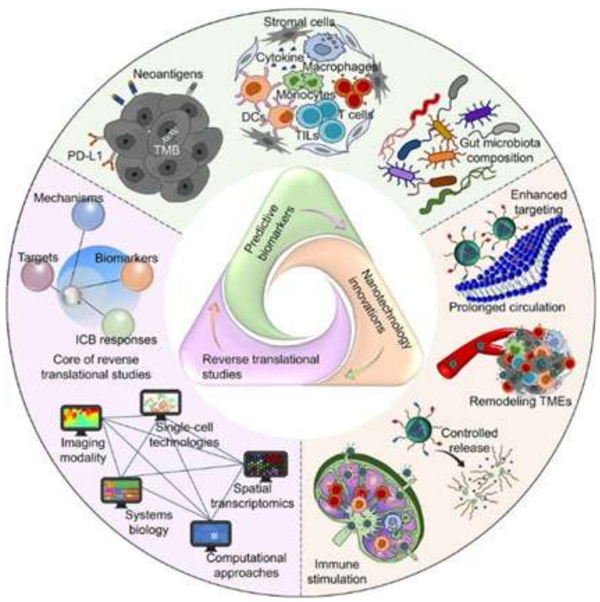


Figure 8

Types of Nanomaterials Used

Table 3

Nanomaterial	Key Feature	Application Example
Gold nanoparticles	Surface plasmon resonance	Cancer biomarker detection
Quantum dots	Bright fluorescence, photostability	Imaging of tumor cells
Carbon nanotubes	High conductivity	Electrochemical biosensors
Magnetic nanoparticles	External field manipulation	Isolation of CTCs from blood
Graphene oxide	Large surface area, conductivity	DNA/RNA biosensors

Applications in Disease Diagnosis;

- Cancer: Detection of PSA, CA-125, CEA, and circulating tumor DNA

- Cardiovascular diseases: Troponin detection for heart attack diagnosis
- Infectious diseases: Rapid detection of viral proteins and bacterial DNA

Advanced Techniques;

- **Electrochemical Sensors:** Offer fast, non-invasive, and precise detection of cancer biomarkers. Nanotechnology is revolutionizing electrochemical sensors by enhancing their sensitivity, selectivity, and portability. Nanomaterials like nanoparticles, nanotubes, and graphene offer increased surface area, improved electron transfer, and unique electrical properties, making them ideal for advanced sensing applications. These advancements have led to more efficient and reliable sensors for various fields, including healthcare, environmental monitoring, and food safety.

- **Surface-Enhanced Raman Spectroscopy (SERS):** Uses nanoparticles to amplify signals from biomarkers.

- **Lab-on-a-chip Devices:** Miniaturized platforms for point-of-care testing. Lab-on-a-chip (LOC) nanotechnology refers to the integration of laboratory functions onto a single chip, typically a few millimetres in size, using microfluidics and electronic components. These devices automate and miniaturize various analytical processes, enabling rapid, cost-effective, and portable diagnostics and research.

Challenges of Biomarkers

- Toxicity of some nanomaterials
- Regulatory hurdles for clinical approval
- Cost and scalability of production

REFERENCES

1. https://scholar.google.com/citations?user=OstsPagAAAAJ&hl=en&oi=sra.
2. https://www.tandfonline.com/doi/abs/10.1517/14712598.3.4.655.
3. Chaturvedi S, and Dave PN (2014). Emerging applications of nanoscience. Paper presented at the Materials Science Forum, 152-159.
4. Maine E, Thomas V, Bliemel M, Murira A, Utterback J. (2014). The emergence of the nanobiotechnology industry. Nature nanotechnology, 9(1): 12-15.
5. Hou, X., Zaks, T., Langer, R., & Dong, Y. (2021). Lipid nanoparticles for mRNA delivery. Nature Reviews Materials. https://doi.org/10.1038/s41578-021-00358-0.
6. Lipid nanoparticles for delivery of RNA therapeutics. (2022). Pharmaceutics / Review (see full text).
7. Comprehensive review of microneedles: types, materials, characterization and applications. (2021). Pharmaceuticals (Open Access). https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8400269/.
8. Donnelly, R. F., & Singh, T. R. R. (2020). Microneedles in drug delivery: progress and challenges. Micromachines, 12(11), 1321. https://doi.org/10.3390/mi12111321.
9. Meng, X., et al. (2025). Recent advances and perspectives of microneedles for biomedical applications. Biophysical Reviews (2025).
10. Das, S., Ng, K., & others. (2020). A brief review on solid lipid nanoparticles. RSC Advances. https://doi.org/10.1039/D0RA03491F.
11. Subroto, E., Andoyo, R., & Indiarto, R. (2023). Solid lipid nanoparticles: review of the current research on encapsulation and delivery systems for active and antioxidant

compounds. Antioxidants, 12, 633. https://doi.org/10.3390/antiox12030633.
12. Kesharwani, P., et al. (2023). Dendrimer: an update on recent developments and future perspectives. Pharmaceutical Reviews / PMC. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10060650/.
13. Engineering PAMAM dendrimers for optimized drug delivery. (2025). Trends in Bioengineering/ Advanced Review.
14. MDPI. (2024). Advances in hydrogel-based drug delivery systems. Polymers/MDPI. https://www.mdpi.com/2310-2861/10/4/262.
15. Fina, F., Goyanes, A., & Gaisford, S. (2023). A review of 3D printing technology in pharmaceutics. Pharmaceutics / PMC9962448. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9962448/.
16. Fina, et al. (2022). The evolution of the 3D-printed drug delivery systems: a review. Pharmaceutics / MDPI. https://www.mdpi.com/1999-4923/14/7/1312.
17. Vamathevan, J., et al. (2024). The role of artificial intelligence in drug discovery and formulation. Nature / Review (see PMC review).
18. ScienceDirect. (2024). Artificial intelligence-driven pharmaceutical industry: a paradigm shift in formulations. (Industry review).
19. Woo PCY, Huang Y, Lau SKP, Yuen KY. Coronavirus genomics and bioinformatics analysis. Viruses Basel. 2010;2(8):1804–1820 doi:10.3390/v2081803
20. Su S, Wong G, Shi W, et al. Epidemiology, genetic recombination, and pathogenesis of coronaviruses. Trends Microbiol. 2016;24(6):490–502. doi:10.1016/j.tim.2016.03.003
21. Wolfe ND, Dunavan CP, Diamond J. Origins of major human infectious diseases. Nature. 2007;447(7142):279–283. doi:10.1038/nature05775
22. Day M. Covid-19: four fifths of cases are asymptomatic, China figures indicate. BMJ. 2020;369:m1375. doi:10.1136/bmj.m1375
23. Sutton D, Fuchs K, D'Alton M, Goffman D. Universal screening for SARS-CoV-2 in women admitted for delivery. N Engl J Med. 2020;382(22):2163–2164. doi:10.1056/NEJMc2009316
24. Mizumoto K, Kagaya K, Zarebski A, Chowell G. Estimating the asymptomatic proportion of coronavirus disease 2019 (COVID-19) cases on board the Diamond Princess cruise ship, Yokohama, Japan, 2020. Euro Surveill. 2020;25(10). doi:10.2807/ 1560-7917.ES.2020.25.10.2000180
25. Sahu KK, Lal A, Mishra AK. Latest updates on COVID-2019: a changing paradigm shift. J Med Virol. 2020;92(6):533–535. doi:10.1002/jmv.25760
26. Drosten C, Gunther S, Preiser W, et al. Identification of a novel coronavirus in patients with severe acute respiratory syndrome. New Engl J Med. 2003;348(20):1967–1976. doi:10.1056/ NEJMoa030747
27. Ksiazek TG, Erdman D, Goldsmith CS, et al. A novel coronavirus associated with severe acute respiratory syndrome. New Engl J Med. 2003;348(20):1953–1966. doi:10.1056/NEJMoa030781
28. G. Pantaleo, C. Graziosi, and A. Fauci, New concepts in the immunopathogenesis of human immunode_ciency virus infection, The New E
29. Gland Journal of Medicine, Vol. 328, 327-335, 1993.
30. S. Crowe, S. Turnbull, R. Oelrichs, and A. Dunne., "Monitoring of human

immunodeficiency virus infection in resource-constrained countries", Clinical Infectious Diseases, Vol. 37, S25-S35, 2003.

31. G. Damhorst, N. N. Watkins, R. Bashir, "Micro and nanotechnology for HIV/AIDS diagnostics in resourcelimited settings", IEEE Transaction of Biomedical Engineering, 60 (3), 715 – 726, 2013.
32. J. Kim, J. Park, S. Yang, J. Baek, B. Kim, S.H. Lee, E.-S. Yoon, K. Chun, and S. Park, "Establishment of a fabrication method for a long-term actuated hybrid cell robot," Lab Chip, vol. 7, pp. 1504-1508, 2007.
33. Freitas RA Jr. Nanomedicine Basic capabilities. 1999;Vol 1 Texas Landes Bioscience Available from: http//www.nanomedicine.com [last accessed on 2000 Sep 26] Georgetown.
34. Nelson B, Rajamani R. Biomedical micro-robotic systemIn: Eighth international conference on medical image computing and computer assised intervention. MICCAI2005 Available from: http://www.miccai2005.org Palm Springs CA: 26-29 Otober 2005.
35. Davis ME, Chen ZG, Shin DM. Nanoparticle therapeutics: an emerging treatment modality for cancer. Nat Rev Drug Discov. 2008;7:771–82. doi: 10.1038/nrd2614.
36. De Jong WH, Borm PJA. Drug delivery and nanoparticles:applications and hazards. Int J Nanomedicine. 2008;3:133–49. doi: 10.2147/ijn.s596. [DOI] [PMC free article] [PubMed] [Google Scholar]
37. Buzea C, Pacheco II, Robbie K. Nanomaterials and nanoparticles: sources and toxicity. Biointerphases. 2007;2:MR17–71. doi: 10.1116/1.2815690. [DOI] [PubMed] [Google Scholar]
38. Kumar V, Toffoli G, Rizzolio F. Fluorescent carbon nanoparticles in medicine for cancer therapy. ACS Med Chem Lett. 2013;4:1012–3. doi: 10.1021/ml400394a. [DOI] [PMC free article] [PubMed] [Google Scholar]
39. Martin TG, Dietz H. Magnesium-free self-assembly of multi-layer DNA objects. Nat Commun. 2012;3:1103. doi: 10.1038/ncomms2095. [DOI] [PMC free article] [PubMed] [Google Scholar]
40. Sobczak JPJ, Martin TG, Gerling T. et al. Rapid folding of DNA into nanoscale shapes at constant temperature. Science. 2012;338:1458–61. doi: 10.1126/science.1229919. [DOI] [PubMed] [Google Scholar]
41. Bellot G, McClintock MA, Lin C. et al. Recovery of intact DNA nanostructures after agarose gel-based separation. Nat Methods. 2011;8:192–4. doi: 10.1038/nmeth0311-192. [DOI] [PMC free article] [PubMed] [Google Scholar]
42. Stahl E, Martin TG, Praetorius F. et al. Facile and Scalable Preparation of Pure and Dense DNA Origami Solutions. Angew Chem Int Ed. 2014;53:12735–40. doi: 10.1002/anie.201405991. [DOI] [PMC free article] [PubMed] [Google Scholar]
43. Shaw A, Benson E, Högberg B. Purification of functionalized DNA origami nanostructures. ACS Nano. 2015;9:4968–75. doi: 10.1021/nn507035g. [DOI] [PubMed]

HOW TO CITE: Rohan Kaswa, Vedant Bhansali, Sayali Deth, Snehal Tuse, Application of Nanotechnologies in Pharmaceutical Industry, Int. J. of Pharm. Sci., 2025, Vol 3, Issue 10, 1253-1270. https://doi.org/10.5281/zenodo.17340743