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Review

Recent Advances in Nanotechnology for Drug Delivery

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Abstract:

Background: For many years, the mainstay of therapeutic intervention has been traditional drug delivery methods, such as tablets, capsules, injections, and topical formulations. Nevertheless, these methods have significant limitations that ultimately restrict clinical results and patient safety, including inadequate bioavailability, systemic toxicity, lack of regulated release, and poor selectivity. The development of nanotechnology has made it possible to precisely and logically build nanoscale carriers, opening up revolutionary avenues for medication delivery. These nanocarriers—ranging from liposomes and polymeric nanoparticles to dendrimers, inorganic platforms, and biomimetic systems—offer unprecedented control over pharmacokinetics, target-site accumulation, and multifaceted therapy. **Methodology:** This analytical review collates evidence from recent scientific literature—including PubMed, clinical trials, regulatory agency reports, and mainstream research platforms. A systematic approach is used to summarize the evolution of nanocarrier designs, mechanism of action (passive/active targeting, stimuli-responsive release, controlled/sustained delivery), and the diverse applications in cancer therapy, infectious disease management, gene delivery (siRNA, CRISPR), barrier-crossing strategies (e.g., blood–brain barrier), and personalized medicine. The review also critically evaluates recent innovations—such as smart, multifunctional and biodegradable nanocarriers, nanorobots, hybrid theranostic platforms, green synthesis, and clinically translated FDA-approved products—while outlining future opportunities including integration with artificial intelligence, patient-specific profiling, and regenerative medicine. **Results:** Nanotechnology-based drug delivery systems have successfully demonstrated improved bioavailability, reduced systemic toxicity, targeted and responsive drug release, and the ability to cross biological barriers. Major clinical milestones comprise FDA approval of nanomedicines (e.g., Doxil®, Abraxane®), the use of lipid nanoparticles in mRNA COVID-19 vaccines, and promising results in gene and immunotherapies. Smart nanocarriers now allow on-demand, sustained, and site-specific drug release. The rapid integration of AI and machine learning into nanomedicine is enabling optimized, personalized treatments, with green nanotechnology advancing environmental safety and sustainability. Furthermore, nanomaterials are contributing to regenerative medicine and tissue engineering, facilitating precision tissue repair and stem cell modulation. **Conclusion:** Nanotechnology is revolutionizing the landscape of drug delivery by addressing the limitations of traditional systems and advancing medicine towards precision, adaptability, and sustainability. The ongoing progress in smart, multifunctional, and patient-specific nanomedicines, supported by clinical translation and regulatory approvals, underscores the vast therapeutic potential of this field.

Keywords: Nanotechnology, Drug Delivery, Nanocarriers, Cancer Nanomedicine, Stimuli-Responsive Release, Controlled Release.

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1. Introduction

1.1 Limitations of Conventional Drug Delivery Systems

The basis for therapeutic intervention in contemporary medicine has been traditional medication delivery methods, including tablets, capsules, injections, and topical treatments. But these conventional approaches frequently have serious flaws that jeopardise the effectiveness of treatment.(1) One principal challenge is low bioavailability, wherein only a small fraction of the administered drug reaches its intended site of action due to factors like poor absorption, first-pass metabolism, and rapid clearance. This inefficiency can lead to fluctuations in drug concentration within the bloodstream, diminishing therapeutic potency and requiring higher or more frequent dosing for desired effects. Furthermore, most conventional methods are unable to discriminate between healthy and diseased tissues, causing systemic toxicity. (2)This non-specific distribution exposes the entire body to potentially harmful agents, manifesting in adverse side effects and complicating long-term disease management, particularly in oncology and the treatment of chronic ailments. Additional limitations include difficulty in delivering physicochemically challenging drugs, such as those that are poorly water-soluble or macromolecular, and the lack of controlled, sustained, or responsive release profiles needed for optimal patient outcomes(3). These challenges highlight the urgent need for more sophisticated medication delivery systems that are capable of getting beyond these built-in restrictions.

1.2 Emergence of Nanotechnology as a Transformative Approach in Drug Delivery

By taking use of the special properties and behaviours of materials at the nanoscale, which is usually between 1 and 100 nanometres, nanotechnology has quickly transformed medication delivery. The development of nano-sized carriers that may encapsulate or conjugate with medicinal drugs, including liposomes, polymers, dendrimers, micelles, and inorganic nanoparticles, has been made possible by this revolutionary method. These nanocarriers provide better control over drug pharmacokinetics and pharmacodynamics than traditional methods. Improved penetration into target tissues and cells is made possible by characteristics including a larger surface area, adjustable size, and flexible surface chemistry.(4) Nanotechnological innovations have led to substantial leaps in precision medicine, permitting selective targeting of pathological regions (for example, tumors or inflamed tissues) through passive or active mechanisms. As a result, treatment efficacy is maximized, while off-target toxicity is drastically reduced. Nanoparticles can also be engineered for stimuli-responsive release, where drug activation occurs in response to pH, temperature, enzymes, or external triggers, providing even finer control over the therapeutic process. (5)The versatility and modularity of nanotechnology have fueled its clinical translation, with several nano-drug formulations now approved or in advanced stages of development for conditions ranging from cancer and infections to autoimmune and neurodegenerative diseases.

1.3 Importance of Nanoscale Systems in Enhancing Therapeutic Efficacy

The integration of nanoscale systems into drug delivery has fundamentally altered the landscape of therapeutic intervention, marking a pivotal shift towards safer, more effective, and individualized treatments. Nanoscale systems excel in enhancing therapeutic efficacy through multiple avenues. Their ability to bypass biological barriers, such as the blood-brain barrier or dense tumor stroma, vastly improves the concentration of drugs at disease sites, frequently translating to lower required dosages and a minimized profile of adverse reactions. Furthermore, nano-enabled delivery systems can simultaneously transport multiple agents, allowing for combined therapies that synergistically address multifactorial conditions and overcome mechanisms of drug resistance.(6) Advances in nanotechnology have also empowered the field of theranostics, where diagnostic and therapeutic functions are combined within a single nanosystem, allowing for real-time monitoring, targeted intervention, and dose adjustment in response to individual patient needs. Ultimately, the adoption of nanoscale platforms promises not just higher treatment success rates, but also expanded possibilities for delivering challenging molecules—including peptides, nucleic acids, and natural products—that have traditionally been inaccessible via conventional methods. These advances are paving the way for next-generation drug delivery paradigms with profound impacts on patient health and disease outcomes.(7)

The objective of this review is to critically examine the limitations of conventional drug delivery systems and highlight how nanotechnology-based approaches overcome these barriers. It aims to

provide a comprehensive overview of different nanocarrier platforms, their mechanisms, applications, recent innovations, challenges, and future opportunities, thereby underscoring their transformative role in enhancing therapeutic efficacy and advancing precision medicine.

2. Types of Nanocarriers

2.1 Liposomes and Lipid-Based Nanoparticles

Liposomes are spherical vesicles made of phospholipid bilayers that are incredibly adaptable drug delivery vehicles because they can contain both hydrophilic and hydrophobic medicines. Their structural resemblance to biological membranes promotes intracellular drug administration by facilitating biocompatibility, low immunogenicity, and effective fusion with target cells. Polymers such as PEG (polyethylene glycol) can be used to functionalise the lipid bilayer, lengthening circulation and decreasing reticuloendothelial system clearance.(8) Lipid nanoparticles (LNPs), including solid lipid nanoparticles and nanostructured lipid carriers, are advanced lipid-based systems offering improved physical stability and higher drug loading compared to traditional liposomes. These nanocarriers have been successfully used in delivering chemotherapeutics, vaccines (notably mRNA COVID-19 vaccines), antifungal, and antiviral agents.(9) Despite their advantages, lipid-based nanoparticles face challenges, including physical instability, potential drug leakage, complex manufacturing processes, and high production costs, which remain barriers for broader clinical use.

2.2 Polymeric Nanoparticles and Micelles

Solid colloidal particles known as polymeric nanoparticles are created from biodegradable or biocompatible polymers like PEG or PLGA (polylactic-co-glycolic acid). They provide regulated and prolonged release patterns by encasing or adsorbing medications, preventing their breakdown. Amphiphilic block copolymers self-assemble to generate core-shell nanostructures known as polymeric micelles.(10) While the hydrophilic shell stabilises the micelle in aqueous settings, the hydrophobic core solubilises weakly water-soluble medicines, increasing their bioavailability. Targeting ligands or stimuli-responsive components can be added to the surface of both polymeric nanoparticles and micelles to enable site-specific medication release that is activated by pH, temperature, or enzyme activity. Their uses include hydrophobic drug delivery, gene and siRNA delivery, and chemotherapy.(11) However, challenges such as potential polymer toxicity, scale-up reproducibility, and complex synthetic procedures require ongoing research for clinical translation.

2.3 Dendrimers and Nanogels

Dendrimers are monodisperse, highly branched macromolecules that form globules with many surface functional groups that can be used for encapsulation or drug conjugation.This architecture allows precise control over size, shape, and surface chemistry, making dendrimers excellent carriers for drug delivery applications requiring specificity and tunability. Nanogels are hydrogel particles in the nanoscale domain, formed by physically or chemically crosslinked polymer networks capable of absorbing large amounts of water or biological fluids.(12) They combine the high loading capacity of hydrogels with nanoscale delivery advantages, including enhanced permeation and retention in diseased tissues. Together, dendrimer-based nanogels enable stimuli-responsive drug release, prolonged circulation, and reduced toxicity. These carriers have been effectively applied in delivering anticancer drugs, peptides, microbial agents, and as platforms for gene therapy.(13) The disadvantages include synthesis complexity, high production costs, and potential immunogenicity or cytotoxicity depending on surface chemistry.

2.4 Inorganic Nanoparticles

Because of their distinct physicochemical properties, inorganic nanoparticles offer distinct advantages. Gold nanoparticles are valued for their optical properties, biocompatibility, and ease of surface modification, which enable photothermal therapy, in which light-generated localised heat excites the gold nanoparticles to kill cancer cells.(14) Silica nanoparticles provide a highly porous structure facilitating large drug loadings and controlled release, often used for sustained delivery of chemotherapeutics or imaging agents. Magnetic nanoparticles (such as iron oxide) possess superparamagnetic properties, enabling magnetic resonance imaging (MRI) contrast enhancement, magnetic targeting using external fields, and hyperthermia therapy. These multifunctional capabilities enable integration of diagnosis and therapy—theranostics—in one platform.(15) Yet, their inorganic nature raises concerns about long-term biocompatibility, biodegradability, and potential accumulation, making regulatory approval more challenging.

2.5 Exosomes and Biomimetic Nanocarriers

Exosomes are naturally secreted extracellular vesicles (30–150 nm) involved in intercellular communication by transporting proteins, lipids, and nucleic acids. Their innate ability to avoid immune detection and target specific cells based on membrane proteins makes them highly attractive as natural drug delivery systems. Biomimetic nanocarriers are engineered to imitate exosomal properties, combining natural surface features with synthetic modifications for improved targeting, payload capacity, and stability.(16) These carriers excel in delivering genetic material for gene therapy, immunomodulatory agents, and targeted cancer therapies. Key obstacles include difficulties in large-scale production, morphological and compositional heterogeneity, complex isolation/purification methods, and limited yields. Despite these challenges, exosomes and biomimetic carriers represent a frontier in personalized and precision medicine. A comparative table of nanocarriers for drug delivery are listed below in **Table-1**

Nanocarrier Type	Definition / Description	Advantages	Typical Applications	Key Limitations	Ref.
Liposomes & Lipid-Based Nanoparticles	Spherical vesicles composed of phospholipid bilayers encapsulating hydrophilic and lipophilic drugs	Biocompatible; mimic cell membranes; can carry diverse drug types; modifiable for targeting; FDA-approved	Cancer therapy, gene delivery, vaccines, antifungals	Stability issues; potential leakage; high manufacturing costs	(9)
Polymeric Nanoparticles & Micelles	Nano-sized particles or self-assembling core-shell structures from natural/synthetic polymers	Controlled release; high drug loading; solubilize poorly soluble drugs; surface functionalization possible	Chemotherapy, nucleic acid delivery, oral/parenteral use	Potential toxicity; complex synthesis; batch variability	(17)
Dendrimers & Nanogels	Highly branched tree-like polymers (dendrimers) and crosslinked hydrophilic polymeric gels (nanogels)	High drug loading; tunable surfaces; stimuli-responsive release; gene and peptide delivery	Cancer, microbial diseases, glaucoma, gene therapy	Synthetic complexity; cost; possible immunogenicity	(18)
Inorganic Nanoparticles (Gold, Silica, Magnetic)	Nano-sized particles with unique optical and magnetic properties; chemically stable	Multipurpose (imaging and therapy); surface-modifiable; high stability; photothermal and magnetic properties	Theranostics, targeted release, bioimaging	Long-term toxicity; unclear biodegradability; regulatory hurdles	(19)
Exosomes & Biomimetic Nanocarriers	Natural extracellular vesicles or engineered vesicles mimicking exosomes	Natural targeting; minimal immunogenicity; efficient nucleic acid/protein transport	Gene therapy, immunomodulation, targeted cancer therapy	Low yield; complex purification; scalability challenges	(20)

Table 1: A Comparative Table of Nanocarriers for Drug Delivery.

3. Mechanisms of Nanoparticle-Mediated Drug Delivery

3.1 Enhanced Permeability and Retention (EPR) Effect

The EPR effect is a unique phenomenon predominantly observed in solid tumors, and it serves as the foundation for passive targeting of nanoparticles. Tumor tissues, in contrast to healthy tissues, exhibit highly permeable and defective vasculature; newly formed vessels have wide fenestrations with poor alignment and lack normal support or drainage. (21)These abnormalities allow nanocarriers such as liposomes, polymeric nanoparticles, and dendrimers—typically sized between 10–200nm to extravasate preferentially into tumor interstitium. Furthermore, the absence or deficiency of lymphatic drainage in tumor tissues leads to retention of these agents, supporting an accumulation that is rarely achieved in healthy organs. The EPR effect can be further modulated by factors like bradykinin, nitric oxide, VEGF, prostaglandins, and other local signals that increase vascular permeability within the tumor microenvironment.(22) While the EPR-based accumulation enhances tumor-selective drug delivery, the overall degree of selectivity is modest (median 0.7% of an injected nanodose in tumors), and researchers continue to optimize nanocarrier circulation time and local permeability for better outcomes.

3.2 Active Targeting Using Ligands, Antibodies, and Peptides

Active targeting is a major advance in nanoparticle design, wherein the surface of nanocarriers is functionalized with molecular ligands, monoclonal antibodies, or peptides that can bind with high specificity to disease-associated receptors. For example, folate, transferrin, hyaluronic acid, carbohydrates, and various peptides can be attached to nanoparticles to target receptor-rich tumor cells, endothelial cells, or immune populations.(23) Antibody-functionalized nanoparticles enable precision targeting—such as anti-CD20 for lymphoma or anti-EGFR for breast cancer—promoting receptor-mediated endocytosis and robust intracellular delivery. This strategy is also employed for vascular targets (e.g., RGD peptide for integrins, or anti-VEGFR for neovasculature) and in immune or hematologic malignancies. Active targeting improves cellular internalization, can overcome multidrug resistance by bypassing drug efflux pumps, and allows for combined therapeutic and imaging modalities.(24) While both passive and active targeting rely initially on the EPR effect for tissue accumulation, active mechanisms facilitate deeper uptake and selective biodistribution within the targeted diseased population.

3.3 Stimuli-Responsive Drug Release

When certain environmental signals, either internal or external, are present in sick tissue, stimuli-responsive nanoparticles are designed to release their medicinal payload. The presence of overexpressed enzymes elevated reactive oxygen species (ROS), specific redox conditions (glutathione gradients), or the acidic pH of the tumour microenvironment or endosomes are examples of internal triggers. Drug release at the target region can also be induced by external stimuli, such as light, magnetic fields, or temperature changes.(25) Common examples are pH-responsive systems: Utilize polymers or linkers that undergo conformational change or hydrolysis in acidic pH, promoting drug release in tumor tissues or intracellular compartments. Temperature-responsive systems: Use materials like poly(N-isopropylacrylamide) (PNIPAM), which alter solubility or conformation near a specific temperature threshold, aiding release in hyperthermic tumor regions. Enzyme-responsive systems: Are activated by enzymes overexpressed in diseased tissues, such as cathepsins in cancer, creating site-specific activation of drug release. Redox-responsive systems: Exploit high intracellular glutathione concentration in cancer cells to trigger disulfide bond cleavage and release of drugs. (26)These custom designs ensure drugs are delivered in high concentration at the target site with minimal off-target leakage, increasing efficacy and safety.

3.4 Controlled and Sustained Release Strategies

Controlled and sustained release strategies are essential for maintaining therapeutic drug concentrations over time, reducing dosing frequency, and minimizing side effects. Nanoparticles can be engineered for: Diffusion-controlled release: The drug diffuses gradually from the nanocarrier matrix or reservoir, providing a slow, steady supply. Degradation-controlled release: The matrix material (e.g., biodegradable polymers) gradually breaks down, releasing the drug in a controlled fashion. Smart sustained-release systems: Incorporate stimuli-responsive triggers combined with sustained-release matrices to precisely orchestrate drug delivery over hours, days, or even weeks. Combination platforms: Deliver multiple drugs or agents in sequence or combination, maintaining optimal therapeutic levels and

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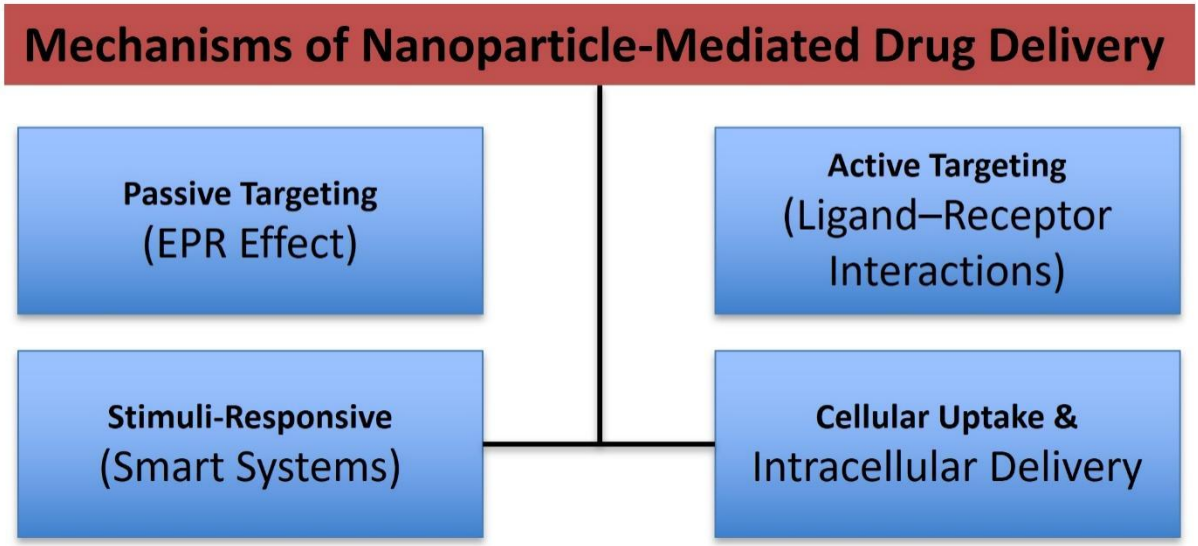
addressing drug resistance or multi-targeted therapy.(27)

The advantages of controlled and sustained nanoparticulate formulations include a reduction of peak-and-valley drug levels, improved patient adherence, fewer administrations, diminished toxicity, and expanded opportunities for combination therapy. The Mechanisms of Nanoparticle-Mediated Drug Delivery is mentioned below in **Figure-1.**

Figure 1: Mechanisms of Nanoparticle-Mediated Drug Delivery.



4. Applications in Therapeutics

4.1 Cancer Nanomedicine: Targeted Delivery and Overcoming Multidrug Resistance

Cancer treatment has long suffered from limitations of conventional chemotherapy, which indiscriminately affects both cancerous and healthy cells, causing significant toxicity and limiting efficacy. Nanotechnology has revolutionized this landscape by enabling targeted delivery of chemotherapeutic agents directly to tumor sites. Nanocarriers—such as liposomes, polymeric nanoparticles, dendrimers, and gold nanoparticles—can be engineered to recognize and bind to specific tumor markers on cancer cells. (28)This is done through the attachment of targeting ligands, antibodies, or peptides on the nanoparticle surface, facilitating receptor-mediated endocytosis and improved cellular uptake. Furthermore, nanocarriers exploit the enhanced permeability and retention (EPR) effect, passively accumulating within tumor tissues due to leaky vasculature and poor lymphatic drainage. A major challenge in cancer therapy is multidrug resistance (MDR), where cancer cells expel drugs, rendering them ineffective. Nanoparticle-based delivery systems can overcome MDR by bypassing efflux pumps, delivering combination therapies, or releasing drugs in response to intracellular triggers. For example, nanoparticles can co-deliver chemotherapy drugs with MDR modulators (such as siRNA targeting resistance pathways) to sensitize cancer cells and restore the effectiveness of treatment. Advanced nanomedicines also enable controlled and sustained drug release, maintaining therapeutic levels over time and minimizing cycles of toxicity and inefficacy. (29)Clinical successes include liposomal doxorubicin, nanoparticle albumin-bound paclitaxel, and antibody-drug conjugates, which have improved patient outcomes and extended survival in several cancer types.

4.2 Nanotechnology in Infectious Diseases

Nanotechnology has expanded possibilities in treating infectious diseases by enhancing the delivery and efficacy of antimicrobial, antifungal, and antiviral drugs. Nano-formulations—such as silver, gold, and polymeric nanoparticles—offer improved stability, solubility, and controlled release of drugs that have challenging properties. Functionalization of nanoparticles with targeting ligands can facilitate the selective delivery of drugs to infected tissues, reducing systemic toxicity and optimizing therapeutic effect. (30)In viral infections, nanocarriers can be designed to interfere with the viral life cycle, for example, blocking viral entry, promoting uptake of antiviral drugs, or serving as adjuvants in vaccines. Their small size, ability to mimic biological structures, and multivalent functionalization enable effective targeting of pathogens or infected cells. For bacterial and fungal infections, nanoparticles can penetrate biofilms or

infected tissues that are difficult to reach with conventional therapies. Furthermore, the ability to simultaneously combine therapeutic and diagnostic agents in nanoparticle formulations supports real-time monitoring of infection and therapeutic response (theranostics), improving patient care.(31) One of the greatest recent breakthroughs was the application of lipid nanoparticles in delivering mRNA vaccines for COVID-19, showing how nanotechnology enables rapid, efficient, and flexible response to emerging infectious threats.

4.3 Gene Delivery Using Nanocarriers: siRNA and CRISPR Systems

The delivery of genetic material is highly promising for addressing diseases with a genetic basis, but naked DNA, RNA, or genome-editing complexes are unstable and easily degraded in the bloodstream. Nanocarriers have tackled these challenges by protecting genetic cargo and facilitating their entry into target cells. Lipid nanoparticles, polymeric nanoparticles, dendrimers, and gold nanostructures are increasingly used for gene delivery applications.(32)

Small interfering RNA (siRNA) can be loaded onto nanoparticles, allowing highly effective gene silencing for cancer and genetic diseases. Similarly, for genome-editing technologies such as CRISPR/Cas9, nanocarriers can transport ribonucleoprotein complexes, plasmids, or mRNA to target cells, enabling precise gene editing while minimizing off-target effects or immune reactions. Surface modification with cell-specific ligands ensures targeting to the right tissues and cell types. Current research is exploring nanoparticles for inherited diseases (e.g., cystic fibrosis, muscular dystrophy), cancer, viral infections, and rare disorders, with early clinical successes fueling optimism for broader applications in human medicine.(33)

4.4 Nanoparticles in Crossing Biological Barriers

The very selective blood–brain barrier (BBB), which keeps most treatments out of the brain, makes medication delivery to the central nervous system (CNS) a difficult task. By taking advantage of transport channels and surface functionalisation, nanoparticles provide answers. Nanoparticles coated with transferrin, lactoferrin, glucose, or antibodies can target receptor-mediated transcytosis, facilitating entry across the BBB. (34)Nanocarriers can also penetrate other biological barriers, such as the mucosal lining of the respiratory or gastrointestinal tract, crossing epithelial surfaces to reach hidden or protected sites of infection or disease. The result is improved therapeutic concentrations in the brain or other target tissues, enhanced efficacy for conditions like glioblastoma, Parkinson's, Alzheimer's, and central nervous system infections, and a dramatic reduction in systemic toxicity. This barrier-crossing ability is one of the most promising aspects of nanomedicine for previously untreatable diseases.(35)

4.5 Personalized Nanomedicine and Precision Drug Delivery

The rise of personalized medicine aligns closely with advances in nanotechnology, enabling the design of tailor-made nanocarriers or drug formulations for individual patients based on genotype, phenotype, and molecular disease profile. Nanoparticles can be functionalized with targeting ligands specific to a patient's cancer or genetic mutation or loaded with the optimum dosing of one or more drugs as indicated by molecular diagnostics. Precision drug delivery with nanomedicine involves real-time responsiveness: smart nanocarriers can release their cargo when exposed to specific internal (enzymes, pH, redox states) or external triggers (light, magnetic fields), ensuring that drugs act only where and when they are needed. This not only enhances efficacy and minimizes adverse effects but also enables stratified medicine, where patient subgroups receive the optimal therapy for their unique disease.(36) In clinical practice, personalized nanomedicine is exemplified by targeted therapies, combination regimens, and nanodiagnostics, all of which are progressing toward routine use for cancer, rare genetic disorders, inflammatory diseases, and other complex conditions.

5. Recent Advances and Innovations

5.1 Smart Nanocarriers and Multifunctional Nanoparticles

The development of smart nanocarriers marks a major shift from simple passive drug carriers to highly responsive and multifunctional platforms. Smart nanoparticles can sense and respond to specific biological cues—such as pH, temperature, enzyme activity, or redox conditions—found at disease sites, enabling on-demand or site-specific payload release. Multimodal nanoparticles integrate multiple therapeutic functions: for example, the combination of chemotherapeutic agents, gene therapies, and imaging molecules within a single carrier. These smart nanosystems often leverage artificial intelligence and computer-aided design to optimize their targeting, release kinetics, and

stability, tailoring their properties to individual patients or disease states.(37) Advanced systems now include nanoparticles capable of switching size and shape in response to tumor microenvironments or external stimuli such as light, further boosting drug penetration and efficacy while minimizing side effects.

5.2 Nanorobots and Micro/Nanomotors for Precise Delivery

Nanorobots and micro/nanomotors represent a futuristic innovation in targeted drug delivery. Unlike conventional nanocarriers, these tiny, motorized vehicles possess the ability to self-propel, navigate complex biological environments, and actively seek out diseased tissues. Propulsion can be powered by chemical energy, magnetic fields, light, ultrasound, or enzymatic reactions. They are engineered to cross biological barriers, penetrate tissues or biofilms, and deliver drugs directly to hard-to-reach sites like tumors or inflamed regions. Numerous studies have demonstrated their ability to enhance delivery efficiency and control drug release using external triggers such as near-infrared light, magnetic fields, or ultrasound—enabling spatiotemporally precise therapy. (38)The field is rapidly advancing, with nanorobots envisioned for not just drug delivery, but also tasks like cell surgery, tissue repair, and biosensing.

5.3 Hybrid Nanoplatforms for Theranostics

Theranostics-focused hybrid nanoplatforms combine therapeutic and diagnostic modalities into a single nanosystem. These systems allow for simultaneous therapy and real-time tracking of drug response and disease progression by combining medications with imaging agents (such as contrast materials for MRI, PET, or optical imaging). Examples include mesoporous silica nanoparticles functionalized for both drug delivery and controlled release, and pH-responsive systems that offer targeted therapy with integrated diagnostic capabilities. Advances in materials chemistry allow organic/inorganic hybrids to be made with tailored responsiveness to physiological or external triggers, enhancing both safety and efficacy while tracking therapeutic outcomes.(39) This approach is particularly beneficial in oncology, where monitoring tumor regression and treatment success enhances personalized and effective care.

5.4 Green Synthesis and Sustainable Nanotechnology Approaches

Sustainability and environmental safety have become central considerations in nanomedicine innovation. Green nanotechnology emphasizes the synthesis of nanoparticles using eco-friendly, non-toxic methods, often employing plant extracts, microorganisms, or biomolecules as natural reducing and stabilizing agents. Green synthesis bypasses traditional chemical methods, reducing hazardous waste, energy consumption, and environmental impact. Plant-derived nanoparticles (PDNPs) show remarkable biocompatibility and biodegradability, often harboring additional therapeutic properties such as antioxidant or anti-inflammatory activity. (40)These nanoparticles provide efficient drug encapsulation, controlled release, and tunable targeting, setting the standard for next-generation, sustainable pharma solutions. Regulatory and ethical frameworks are evolving to support broader adoption, with ongoing research into scaling production and ensuring consistency.

5.5 Clinical Translation and FDA-Approved Nanomedicines

The promise of nano-enabled therapeutics has driven the clinical translation of numerous nanomedicine products. Over 200 nanomaterial-based drugs have passed into clinical studies or reached commercial markets, under the strict regulation of agencies like the FDA. Liposomal and polymeric nanoparticles have the largest share, exemplified by FDA-approved formulations such as Doxil® (liposomal doxorubicin), Abraxane® (albumin-bound paclitaxel), and Vyxeos® (liposomal daunorubicin/cytarabine). These products show superior performance in drug solubility, target abundance, reduced toxicity, and improved patient outcomes, especially in cancer and infectious diseases. (41)The translation process requires robust safety, reproducibility, scalability, and regulatory compliance. Recent years have also seen inorganic nanomedicines—such as iron oxide nanoparticles for imaging—approved for use, broadening the application range. The clinical benefit often comes from reduced toxicity; however, improved efficacy has been documented in newer formulations. Ongoing innovations and clinical trials continue to expand the frontier of nanomedical therapies.

6. Future Directions and Opportunities

6.1 Nanotechnology in Immunotherapy and Vaccine Delivery

The application of nanotechnology in immunotherapy and intelligent vaccination delivery systems is among the most promising opportunities.Nanoparticles can function as carriers

for tumor antigens, adjuvants, and immunomodulatory drugs, thereby enhancing immune responses against cancer and infectious diseases. Nanovaccines based on nanoscale particles can carry multiple antigens, prevent degradation in biological environments, and achieve targeted stimulation of cellular and humoral immune responses. They offer stability, high delivery efficiency, and the ability to tailor immune activation through design of carriers, antigens, and adjuvants, including tumor neoantigens for personalized cancer vaccines. This technology allows for multiple antigen stimulation, greater stability, and prolonged effect in the tumor microenvironment, leading to more effective immunotherapies and vaccines for cancer, infectious diseases, and emerging pandemics.(42) Nanoparticle-mediated immunotherapy can synergize with conventional chemotherapies, angiogenesis inhibitors, and targeted biologics, leading to combination therapies that address tumor immune suppression, overcoming resistance and improving therapeutic efficacy. Innovations include nanoparticle-based delivery of TAM (tumor-associated macrophage) modulators, checkpoint inhibitors, and co-delivery of immunotherapy agents with gene therapies, allowing precise spatial and temporal immune modulation.

6.2 Integration with Artificial Intelligence and Big Data Analytics

The convergence of nanomedicine with artificial intelligence (AI) and big data analytics stands at the frontier of personalized medicine. AI-driven models use patient data, drug parameters, and nanoparticle characteristics to optimize treatment regimens, predict outcomes, and design smarter, safer nanomaterials. Deep learning algorithms can analyze complex imaging and biomarker data to identify ideal nanocarrier attributes, such as composition, size, surface functionalization, and release kinetics for specific patients and diseases.(43) AI facilitates real-time adjustment of nanotherapy by correlating input factors like drug selection, dose, stimuli, and delivery schedule with clinical outcomes. This enables mechanism-independent optimization, rapid identification of effective combinations, and scaling to large, genetically diverse patient populations. AI also aids in improving diagnostic accuracy, individualizing therapy, reducing toxicity, and enabling digital twins—virtual simulations of a patient's response before actual treatment. The interface of nanomedicine and AI promises enhanced accountability, flexibility, and interdisciplinary innovation for next-generation precision medicine.

6.3 Personalized Nanomedicine Through Patient-Specific Profiling

Personalized medicine is rapidly evolving due to molecular profiling and advances in nanotechnology. Patient-specific nanoparticles can deliver drugs, genetic material, or biomolecules matched precisely to a patient's molecular and genetic profile, transforming "one-size-fits-all" therapy into tailored interventions. To maximise effectiveness and minimise off-target effects, nanoparticles are functionalised with ligands, antibodies, or aptamers that target disease characteristics, mutation signatures, or patient-specific biomarkers. (44) Encapsulation of fragile biomolecules such as mRNA, siRNA, or proteins within nanoparticles enhances their bioavailability and protects them from degradation and immune clearance. This is particularly important for rare genetic disorders and targeted cancer therapies where high specificity and adaptability are crucial. As molecular diagnostics and sequencing become more accessible, nanoparticles will be designed for ever more precise targeting, adaptable payloads, and scalable GMP (Good Manufacturing Practices) production for the clinic.

6.4 Next-Generation Stimuli-Responsive and Biodegradable Nanocarriers

Next-generation nanocarriers offer on-demand, controlled drug release triggered by internal (pH, redox, enzymes) or external (magnetic field, light, ultrasound) stimuli. Advances in materials science have produced biodegradable nanocarriers that minimize long-term toxicity and environmental impact while enabling rapid, site-specific drug activation in response to disease microenvironments.Stimuli-responsive nanocarriers increase drug specificity by releasing their payload only in the pathological milieu—such as the acidic microenvironment of tumors or the hypoxic core of infected tissues—thus overcoming multidrug resistance, improving targeting, and realize real-time signal transduction or imaging. The next wave integrates these features with sustained release, self-immolation, and "smart" structural changes (e.g., size and charge conversion), expanding opportunities for both therapeutic and diagnostic applications.(45) Biodegradable carrier design also addresses growing concerns about nanomaterial accumulation and long-term safety, paving the way

for environmentally-consci ous pharmaceutical innovation.

6.5 Potential Role in Regenerative Medicine and Tissue Engineering

Nanotechnology opens previously unheard-of possibilities in tissue engineering and regenerative medicine. Compared to macro-scale materials, nanostructured scaffolds that are molecularly designed more closely resemble the physical, chemical, and biological characteristics of original tissues. Nanoparticle-based scaffolds support cell growth, guide stem cell differentiation, and provide cues for tissue repair while integrating with bioactive molecules, growth factors, or gene therapies for enhanced regeneration. Specific bioactive nanoparticles (gold, titanium dioxide, carbon nanotubes) have shown promise in promoting bone, cardiac, skin, and cartilage regeneration.(46) Nanomaterials enable precise direction of stem cell fate without the use of exogenous growth factors, reducing complications and side effects. Innovations include "dancing molecules" for cartilage repair, conductive nano-scaffolds for axonal regrowth in spinal injuries, and multi-functional materials integrating diagnostics and therapy (theranostics). Safety, toxicity, and mechanistic understanding remain research priorities, but nanotechnology is poised to redefine the practice of regenerative medicine over the coming decades.(47)

These possible avenues for advancement demonstrate how revolutionary nanotechnology may be in the field of medicine. Nanomedicine is poised to elevate beyond simple drug delivery by combining immunotherapy, artificial intelligence (AI), personalised profiles, intelligent biodegradable systems, and regenerative solutions, transforming disease prevention, diagnosis, and cure with accuracy, sustainability, and flexibility.

7. Conclusion:

By getting beyond the significant drawbacks of traditional treatment approaches, nanotechnology has completely changed the medication delivery industry. Nanotechnology makes it possible for precise targeting, enhanced bioavailability, controlled and stimuli-responsive drug release, and the ability to pass through difficult biological barriers by creating a variety of nanocarriers, including liposomes, polymeric nanoparticles, dendrimers, inorganic materials, and biomimetic vesicles. Along with improving treatment efficacy, these developments also lessen systemic toxicity and create new opportunities for personalised medicine and combination therapy. By integrating diagnostic and therapeutic capabilities into a single construct, smart multifunctional systems, nanorobots, and hybrid theranostic platforms significantly broaden the scope of nanomedicine. The development of customised, secure, and efficient medicines for a wide range of ailments, such as cancer, infectious diseases, genetic disorders, and neurodegenerative conditions, is being accelerated by new developments in AI-driven design, sustainable green synthesis, and clinical translation. In the fields of immunotherapy, vaccine research, regenerative medicine, and tissue engineering, nanotechnology holds great promise for a future in healthcare that is patient-centered, highly accurate, and flexible. To fully use nanomedicine and transform the therapeutic landscape for improved global health outcomes, more multidisciplinary research, regulatory backing, and innovation are essential.

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