



Nanobiotechnology Innovations Enhancing Targeted Drug Delivery and Precision Therapeutics for Human Diseases Globally: A Comprehensive Review

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ABSTRACT

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Nanobiotechnology integrates nanoscience, molecular biology, pharmacology, materials science, biotechnology, and medicine to improve the delivery, diagnosis, and treatment of human diseases. Conventional drug delivery systems may be limited by poor aqueous solubility, premature degradation, rapid clearance, nonspecific biodistribution, inadequate tissue penetration, and dose-limiting toxicity. Nanomedicine provides a broad range of platforms, including liposomes, lipid nanoparticles, polymeric nanoparticles, polymeric micelles, dendrimers, nanogels, inorganic nanoparticles, protein-based systems, extracellular-vesicle-inspired systems, and hybrid nanocarriers, that can modify pharmacokinetics, protect therapeutic cargo, improve cellular uptake, and enable controlled or stimuli-responsive release. Recent advances have incorporated targeting ligands, biomimetic membranes, nucleic-acid delivery, molecular imaging, and theranostic functions into nanomedicine platforms. Targeted nanomedicine has been extensively investigated in oncology and is increasingly being explored for neurological, cardiovascular, metabolic, infectious, inflammatory, and genetic diseases. Brain-targeted delivery remains particularly challenging because the blood–brain barrier restricts the entry of many therapeutic agents. Precision nanomedicine seeks to tailor nanocarrier physicochemical properties, targeting strategies, and drug release characteristics according to disease biomarkers, tissue microenvironments, receptor expression, and patient-specific therapeutic requirements. This review was developed as a structured narrative review of peer-reviewed literature published in English from January 2014 to December 2025. Literature was identified through PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar and synthesized thematically across nanocarrier design, targeting strategies, disease-specific applications, precision nanomedicine, theranostics, safety, manufacturing, regulation, and clinical translation. Major translational barriers include biological heterogeneity, protein-corona formation, nanoparticle clearance, manufacturing complexity and reproducibility, immunogenicity, long-term toxicity, regulatory requirements, and differences between preclinical models and human biology. Overall, advances in nanobiotechnology are expanding the potential for more precise and controlled therapeutic delivery, although robust clinical validation, scalable manufacturing, regulatory harmonization, and equitable global access remain essential for broader clinical implementation.

Keywords: Nanobiotechnology; Targeted drug delivery; Nanomedicine; Precision therapeutics; Nanocarriers.

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INTRODUCTION

To develop effective medicines, it is not enough to identify biologically active therapeutic molecules, it is also important to ensure the delivery of these molecules to the right anatomical and cellular environment and at therapeutic concentrations.

Traditional methods of drug delivery often deliver the drugs to the entire body, not specifically to targeted diseased tissues. This can diminish the therapeutic effectiveness and cause dose-limiting side effects. To overcome these drawbacks, nanobiotechnology has developed into a promising approach to designing nanoscale systems that will enable the delivery, protection, transport and controlled release of therapeutic agents [1–4].

Nanomedicine is the application of engineered materials at the nanometer scale to medical applications such as drug delivery, molecular imaging, diagnostics, regenerative medicine and therapeutics. When incorporated into nanocarriers, the pharmacokinetic and pharmacodynamic characteristics of the drugs can be modified due to the changes in their biodistribution, circulation time, solubility, cellular uptake and release properties [3,5]. In the last few years, nanomedicine has been developed from the relatively simple drug encapsulation systems to more complex platforms, which are able to actively target, sense the environment, traverse cellular interiors, release drugs, and even diagnose and treat at the same time.

Precision therapeutics is the targeting or designing of therapeutics based on the biological properties of individual patients, disease, tissue, and/or molecular target. Nanotechnology fits into this idea as the size, shape, surface chemistry, charge, degradation, and drug-loading capacity of nanoparticles can be systematically tailored. Thus, the physicochemical characteristics of these nanoparticles can be tailored for specific organs, disease microenvironments or patient needs [4,5,22]. Recent studies have focused on the importance of controlling the properties of the nanoparticles, not thinking of them as interchangeable drug carriers.

In the field of oncology, targeted nanomedicine is particularly developed. Nanocarriers have been explored for the delivery of chemotherapeutic drugs, nucleic-acids, proteins, immunotherapeutics and combination therapies. Passive accumulation, receptor-mediated active targeting, cell-membrane camouflage, organelle targeting and stimuli-responsive delivery are all strategies employed [7,8]. The field has progressed beyond the concept that tumour accumulation alone is sufficient. Multistage targeting seeks to maximize circulation, tumour penetration, cell internalization and intracytoplasmic drug release.

But the uses of nanobiotechnology go beyond cancer. Applications for nanocarriers in neurological disorders, cardiovascular diseases, diabetes, infectious diseases, inflammatory disorders, genetic diseases, and other diseases, where the conventional drug delivery is limited by biological barriers or unfavorable pharmacokinetics, are being investigated [12-15,17,20]. Brain targeted delivery is a significant challenge due to the blood–brain barrier which prevents the penetration of many small molecule, protein, nucleic-acid and other therapeutics. Specific surface ligands and physicochemical properties have therefore been used to design nanomaterials that can be transported to the brain via receptor-mediated transport and other routes.

The main innovations in nanobiotechnology changing the landscape of targeted drug delivery and precision therapeutics are reviewed, highlighting novel approaches to nanocarrier design, targeting, disease-specific applications, theranostics, personalized nanomedicine, safety, regulatory aspects and future global opportunities.

Review Methodology

The retrieved literature was screened for relevance and synthesized narratively according to major thematic areas, including nanocarrier platforms, targeting strategies, disease-specific applications, precision nanomedicine, theranostics, safety, manufacturing, regulatory issues, and global clinical translation. Because this article is a narrative review rather than a systematic review or meta-analysis, no quantitative meta-analysis was performed. The reporting and methodological transparency of the review were informed by established guidance for narrative reviews, particularly the Scale for the Assessment of Narrative Review Articles (SANRA) [23].

Priority was given to recent systematic reviews, narrative reviews, translational studies, clinical evidence, and key primary studies that provided clinically or scientifically relevant information on nanocarrier design, targeting mechanisms, therapeutic applications, safety, manufacturing, regulatory considerations, and clinical translation. Reference lists of relevant articles were also examined to identify additional publications of importance. Studies were considered eligible when they directly addressed the development, targeting, therapeutic use, precision applications, safety, or translational challenges of nanotechnology-based drug delivery systems. Publications that were unrelated to therapeutic drug delivery or lacked sufficient relevance to the scope of the review were excluded.

This review was developed as a structured narrative review of contemporary evidence on nanobiotechnology-enabled targeted drug delivery and precision therapeutics. A structured literature search was undertaken using PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar to identify relevant peer-reviewed literature published in English from January 2014 through December 2025. The search strategy combined terms related to nanobiotechnology, nanomedicine, nanoparticles, nanocarriers, targeted drug delivery, precision medicine, personalized therapeutics, stimuli-responsive delivery, theranostics, biomimetic nanoparticles, nucleic-acid delivery, and disease-specific applications, using Boolean operators where appropriate.

Nanobiotechnology and the Evolution of Drug Delivery

Traditional drug delivery approaches, such as oral, intravenous, intramuscular, subcutaneous, transdermal, and inhalation are still essential in clinical medicine, but their effectiveness is hindered by low bioavailability, degradation, rapid

clearance, distribution to the wrong tissues, poor penetration to tissues, and toxicity. Nanobiotechnology has enabled the development of nanoscale carriers which can be used to encapsulate, adsorb or conjugate therapeutic molecules and alter their pharmacokinetic and pharmacodynamic characteristics. Nanocarriers can have different compositions and designs, which allow for better solubility of poorly water-soluble drugs, facilitate protection of therapeutic molecules that are prone to degradation in systemic circulation, extend systemic circulation time, improve delivery to tissue and cellular uptake, facilitate controlled or sustained drug release, limit exposure of healthy tissue, allow for intracellular delivery of therapeutic molecules, and enable co-delivery of multiple therapeutic molecules. In addition, advanced nanocarriers can incorporate targeting ligands, imaging agents, and stimuli-responsive components that can cause the release of the drug when stimulated by pH, enzymes, redox conditions, temperature, light, magnetic fields, and other biological and external stimuli [2,3]. These advances open the door to moving beyond the traditional passive drug encapsulation towards programmable, multifunctional therapeutic delivery systems that can sense and respond to biological signals associated with disease and provide more precise and controlled therapy in space and time [2,3].

Major Nanocarrier Platforms

Nanocarrier platforms are a variety of nanoscale platforms that can enhance the delivery, stability, targeting and therapeutic activity of drugs and biological molecules. The biocompatibility, the versatility of drug-loading capacity, the protection and the possibility of surface modification with polyethylene glycol or targeting ligands have made liposomes clinically important systems for cancer therapy, antimicrobial treatment, vaccine delivery, and delivery of nucleic-acids [3,8]. For nucleic-acid therapeutics, lipid nanoparticles (LNPs) are gaining significant relevance due to their ability to efficiently encapsulate and protect RNA molecules, as well as provide intracellular delivery with minimal enzymatic degradation, and are used in mRNA therapeutics, vaccines, cancer vaccines, gene regulation, and protein expression; while the tissue specificity and stability of LNPs, and the interaction with immune cells, are important challenges. Biodegradable or biocompatible polymeric nanoparticles can be synthesized using a variety of polymers to control the degradation rate of the nanoparticles, drug release, the cellular uptake, and targeting of the drug and are appropriate for sustained delivery of small molecules, proteins, peptides, and nucleic-acids. Polymeric micelles are self-assembled aggregates of amphiphilic polymers with a hydrophobic core and a hydrophilic shell that are especially effective in enhancing the solubility of poorly soluble drugs in water and that can be modified with targeting ligands. Highly branched nanoscale macromolecules with many functional groups on their surface, dendrimers can be used for attaching therapeutic agents, imaging molecules, and targeting ligands to the surface; applications include drug delivery, gene delivery, imaging and diagnostics. Nanogels are nanoscale cross-linked polymeric networks that bind to a large quantity of water; their soft, hydrated, and environment-sensitive structures are appealing for delivery of proteins, peptides, nucleic-acids, and small molecule therapeutics. The inorganic nanoparticles, including gold, iron oxide, silica, quantum dots, etc., have unique physicochemical properties including magnetic responsiveness, optical activity, photothermal conversion and imaging properties which enable them to be used for both therapeutic and diagnostic purposes. Lastly, biomimetic nanoparticles composed of synthetic nanoparticle cores coated with naturally derived biological membranes could have improved biocompatibility, immune evasion, and biological targeting properties, and could facilitate drug delivery, phototherapy, immunotherapy, and cancer therapy applications [6,17]. Together these platforms illustrate the versatility of nanobiotechnology and offer complementary strategies to control, target and deliver multiple therapeutic functions.

Targeting Strategies in Nanomedicine

There are a number of complementary targeting approaches in nanomedicine to enhance therapeutic agent delivery to diseased tissues and specific intracellular and cellular targets. Passive targeting is based on the differences between healthy and diseased tissues, in particular the difference in the vasculature and vascular permeability of the tumours that may allow the accumulation of nanoparticles, but is less predictable than was first thought because of tumour heterogeneity and the differences between experimental models and human tumours [7]. Active targeting relies on the functionalization of the surface of nanoparticles with ligands like antibody, peptides, aptamers, carbohydrates, folate, transferrin, and other recognition molecules which recognize receptors or molecular markers on target cells which might increase receptor mediated endocytosis and intracellular drug levels. However, factors such as ligand density, receptor heterogeneity, steric interactions, protein-corona formation and biological accessibility of target receptors can affect its efficacy. To increase targeting, the therapeutic cargo can be released from the nanoparticles in response to the disease-associated stimuli (acidic pH, enzymes, ROS, redox conditions, hypoxia, abnormal metabolites, etc.) or to external stimuli (light, ultrasound, magnetic field and heat). The nanoparticles are more and more being crafted with several responsive properties to allow for control and site-specific release of therapeutic agents [3,8].

The process of hierarchical targeting is an advanced method, which needs the nanoparticles to pass through multiple biological barriers sequentially, survive in the circulation, accumulate in diseased tissues, enter the pathological microenvironment, cross into target cells and deliver their cargo to specific intracellular compartments. Multistage and hierarchical targeting is an important targeting approach to the development of more complex and effective nanotherapeutics, as each stage can have its own or even conflicting physicochemical requirements [7].

Nanobiotechnology in Cancer Treatment

Despite the significant advances in cancer research and treatment, cancer is still a major cause of morbidity and mortality worldwide, and conventional chemotherapy is hampered by nonspecific cytotoxicity, lack of selectivity between malignant and normal cells, systemic side effects, and insufficient delivery of drugs to tumour sites. The ultimate goal of nanobiotechnology and nanomedicine is to enhance the therapeutic index of anticancer drugs, through modification of their

pharmacokinetic behaviour, increase in the accumulation in the tumour, increase in cellular internalization, and controlled intracellular release. Chemotherapy, Immunotherapy, Gene Therapy, RNA delivery, Photodynamic Therapy, Photothermal Therapy and Combination Therapy have been explored using nanoparticle based systems [1,7,17].

After loading into the tumours, nanocarriers can enter tumour cells and unload therapeutic agents to specific intracellular sites such as the cytoplasm, nucleus, mitochondria, and other organelles. The use of nanomedicine in chemotherapy involves the potential of improving the water solubility of anticancer drugs, preventing untimely degradation of therapeutic molecules, modifying circulation time and decreasing non-specific exposure to healthy tissues; however, an important challenge is to provide reliable active targeting to the tumour [7]. Another major application is the delivery of nucleic-acids, such as RNA interference, messenger RNA, microRNA, antisense oligonucleotides and gene-editing technologies, which need to be efficiently protected from enzymatic degradation and efficiently transported into the cytoplasm and across the cellular membranes; lipid nanoparticles have gained special importance for this application because of their ability to encapsulate nucleic-acids and facilitate their delivery into the cytoplasm and across the cellular membranes [8,9].

Nanotechnology can also be utilized to deliver tumour antigens, adjuvants, cytokines, nucleic-acids, and immune-modulating agents to improve the localization and allow combinations of different therapies. In photothermal therapy and photodynamic therapy, gold nanoparticles and other optically active nanoparticles can be used to focus external light and generate heat at the target area, while for photodynamic therapy, these nanoparticles could also carry photosensitizers that would facilitate delivery and activation of the PDT agents and can be combined with chemotherapy or immunotherapy to increase the effectiveness of the therapy in killing cancer cells [1,7,17]. Moreover, targeting the tumour-microenvironment takes advantage of specific biochemical and cellular features of tumours such as the presence of acidic pH, hypoxia, abnormal composition of the extracellular-matrix, enzymatic alterations, and heterogeneous populations of immune-cells. Nanoparticles that target these features can be designed to release therapeutic agents in a disease-associated and spatially controlled manner and could enhance the therapeutic selectivity. These applications collectively illustrate that nanobiotechnology is moving from the traditional realm of drug encapsulation to the future landscape of integrated, multifunctional therapeutic agents for cancer targeting, transport, release, imaging, immune modulation and combination therapy delivered in a single nanoscale platform.

Nanobiotechnology for Neurological Diseases

The blood-brain barrier (BBB) has a significant effect on the delivery of many therapeutic molecules across the BBB, which poses a major challenge for therapeutic development. The BBB consists of specialized endothelial cells, pericytes, astrocyte parts, basement membranes and associated cellular structures that help to tightly control the movement of molecules between the systemic circulation and brain tissue [12,13,18]. These limitations can be overcome or circumvented with several strategies in nanobiotechnology: receptor-mediated transcytosis, adsorptive-mediated transport, transporter-mediated delivery, cell-mediated transport, intranasal administration and functionalization of nanoparticle surfaces by brain-targeting ligands. The size, shape, surface charge, composition, stability and targeting ligands of nanoparticles are important physicochemical properties that play a key role in determining the biodistribution, cellular uptake, BBB penetration and clearance of nanomedicine, and need to be carefully taken into consideration for effective brain-targeted nanomedicine [12,13,18].

Nanocarriers have also been investigated for the delivery of anti-amyloid agents, anti-inflammatory compounds, antioxidants, and gene-based therapeutics in Alzheimer's disease, with the potential to increase brain exposure and provide controlled or sustained release. Nanoparticle systems might be used in Parkinson's disease to deliver dopaminergic drugs, to deliver neuroprotective compounds, to deliver genetic therapeutics and other therapeutic molecules, and might limit systemic exposure while localizing molecules in the brain. Another promising application is in the case of brain tumours, where the BBB and tumour-associated barriers can significantly hinder drug delivery, and multifunctional nanoparticles with targeting peptides and therapeutic agents and imaging agents are developed for integrated diagnosis and treatment [12,13,18].

Nanoparticles have been explored in the context of stroke for targeted delivery of anti-inflammatory, antioxidant, neuroprotective and regenerative agents, and are potentially interesting for the modulation of secondary injury and tissue recovery, but therapeutic timing, biodistribution, vascular safety, biodegradation and clearance need to be carefully considered for successful clinical translation. All of these suggest the possibility of nanobiotechnology's potential to enhance therapeutic access to the CNS and to treat neurological diseases with greater precision, but the complexity of the BBB, the heterogeneity of diseases, long-term safety, manufacturing challenges, and clinical translation are still significant hurdles.

Therapeutic Applications, Precision Strategies, and Translational Challenges of Nanobiotechnology

With the potential of delivering more precise, controlled and personalized therapy across a range of cardiovascular, metabolic, infectious, genetic, neurological and oncological disease areas, nanobiotechnology has become a versatile platform to enhance therapeutic delivery. Lipid-, polymer- and inorganic-based nanoparticles have been investigated for the modification of drug biodistribution and for controlled delivery in atherosclerotic plaques, myocardial infarction, thrombosis, hypertension, vascular inflammation, restenosis and cardiac injury or regeneration, targeted delivery of anti-inflammatory and antiproliferative agents may prove particularly useful in diseased vascular tissue [14]. Nanoparticles, liposomes, dendrimers, niosomes, micelles and other systems have been studied in diabetes and metabolic disorders for the

delivery of insulin and other antidiabetic drugs orally, as well as for the protection of the therapeutic proteins from degradation, increasing the bioavailability, extending drug action and improving treatment adherence [15,16,20].

Glucose-responsive nanocarriers are also under development which change their response in the presence of glucose and are able to control drug release; however significant research efforts remain before such nanocarriers are used in the clinic on a large scale. For infectious diseases, nanocarriers can solve a number of issues linked to antimicrobial resistance, poor tissue permeation, intracellular pathogens, systemic toxicity, and insufficient drug levels, including: enhance the solubility of drugs, protect unstable drugs and drug molecules, prolong drug circulation, increase drug uptake into cells, improve delivery to infected tissues, facilitate combination therapy, and minimize systemic exposure; and the use of nanotechnology to deliver antiviral nucleic-acids, vaccines, antimicrobial peptides, and immunomodulatory agents. Another important application is genetic and rare diseases, where the delivery of DNA, messenger RNA, small interfering RNA, antisense molecules, or gene editing components to specific cells is necessary for successful gene therapy, and which could benefit from nonviral delivery systems, such as lipid nanoparticles, polymeric nanoparticles, dendrimers, and hybrid systems, having the advantages of cargo flexibility, scalability, and manufacturing. The combination of molecular diagnostics with targeted nanoparticle delivery could one day lead to treatment choice based on an individual's genetic makeup. Theranostic nanomedicine integrates therapeutic and diagnostic elements within a single platform, designed to include both drugs and imaging or diagnostic agents, and to deliver information about biodistribution, target-site accumulation, drug release, treatment response, disease progression and treatment resistance, especially in the case of cancer targeted approaches, where molecular and functional imaging are particularly critical. A key example of biomimetic nanotechnology is the development of cell-membrane-coated nanoparticles in which the synthetic cores of nanoparticles are decorated with naturally derived cell membranes, which could offer extended circulation properties, interactions with blood vessels in the vascular lesions, and homotypic targeting properties for cancer cells; however, the membrane's consistency, purification, storage, and regulatory characterization, along with the large-scale production of such nanoparticles, are challenges [6,17].

The possibilities extend further with the incorporation of artificial intelligence (AI) and precision nanomedicine as machine-learning algorithms can potentially capture complex relationships between nanoparticle size, shape, surface chemistry, drug loading, drug release, biodistribution, toxicity, targeting ligand selection, pharmacokinetic modeling, image-based monitoring of therapy, and patient-specific therapeutic selection. However, there are a number of fundamental requirements for reliable AI-aided nanomedicine, such as high-quality data, standardized experiments, independent validation, and clinically relevant data. The personalized nanomedicine approach involves tailoring or optimising the design of therapeutic nanoparticles to address patient-specific disease conditions, such as genetic alterations, receptor expression, disease phenotype, immune status, disease stage, organ function, drug sensitivity, nanoparticle biodistribution, and treatment response, as well as optimizing their physicochemical properties based on their individual disease biology, such as nanoparticle size, shape, surface chemistry, and charge [4,5,22].

Another significant advancement made by nanobiotechnology is the control and stimuli-responsive release of therapeutic agents which can be achieved by the engineering of nanocarriers in such a way that the therapeutic agent is released in response to the internal stimuli such as acidic pH, increased enzymatic activity, oxidative stress, hypoxia, glutathione concentrations, and disease-associated metabolites or external stimuli such as light, ultrasound, magnetic field, temperature, radiation, and focused energy, thus providing higher spatial and temporal control over therapeutic agent exposure. Although the biological barriers have been overcome in many cases, overcoming them is still necessary as nanoparticles have to pass through the mucus, extracellular matrix, endothelial barrier, immune surveillance, cell membranes, endosomal compartments, and renal or hepatic clearance mechanisms after their administration. However, biological fluids can alter the identity, biodistribution, cellular uptake and targeting ability of nanoparticles through the formation of a protein corona, which could result in significant differences in properties of nanoparticles as determined under the formulation conditions compared to those in biological conditions. Therefore, biodistribution and clearance control are essential factors for clinical translation since animal models do not always predict human nanoparticle distribution and elimination [2].

Safety, toxicity, and biocompatibility are equally as critical as functionality, because the administration of particles may result in oxidative stress, inflammation, activation of the complement system, immunotoxicity, organ-specific accumulation, interaction with various blood components, genotoxicity, mitochondrial dysfunction, persistence in vivo for an extended period of time, or impact on the environment, depending upon their characteristics, particle size, surface chemistry, dosage, administration route, degradation profile, and exposure time. This requires full assessment not only with regard to acute toxicity and immediate effects on target tissue, but also in terms of long-term pharmacokinetic, biodistribution and degradation profiles, inflammatory and immune responses, and reproductive, teratogenic, and repeated-dose toxicity. Lastly, challenges at the manufacturing and regulatory fronts are significant hurdles to achieving clinical application of nanobiotechnology products as particle size distribution, polydispersity, surface charge, morphology, drug loading, encapsulation efficiency, release kinetics, sterility, storage stability, and batch-to-batch uniformity may affect the therapeutic performance, and scale-up manufacture may change nanoparticle characteristics without affecting even the nominal formulation. An evaluation strategy must then address both the payload and the nanocarrier itself, which, particularly with complex nanosystems- necessitates comprehensive physicochemical and biological characterization. Development of universally accepted analytical methods, scalable and reliable manufacturing processes and quality assurance, as well as internationally harmonized regulations, are crucial for bringing this technology from research laboratory to clinical use as safe, efficient, and widely available precision medicines.

Clinical Translation, Global Perspectives, and Future Directions

Although nanomedicine has moved from basic science research towards clinically applicable therapies, especially in the field of oncology and nucleic-acid delivery, the success rate of clinical translation is much lower than that of laboratory-based development. While various types of nanocarriers have been produced and explored in cancer treatment, for effective active targeting they still require overcoming difficulties arising from intra-tumoural heterogeneity and the uneven nanoparticle biodistribution (and biological barriers and intra-cellular trafficking) throughout normal physiology, variations in nanoformulation synthesis and manufacturing. Also, advanced nanoformulations often need the use of expensive raw materials to produce, the assistance of specialized factories, trained scientists and high-level quality controlling, and they mostly require refrigeration or a cold chain. Hence for global application, affordable raw materials, mass-producible and reproducible nanoformulations, a shelf-life suitable formulation, simple methods of delivery and storage, regional production capabilities and standardised quality-controlling procedures as well as simplified procedures of approval are all required to enable the equal and convenient access to new advanced nanomatter-medicine to patients worldwide; future of nanobiotechnology will likely focus on functional, responsive and tailored nanotherapeutics that are able to react to local diseases conditions, and self-assemble nano-drugs are expected to offer alternative means for improved circulation and tissue-specific effects. Using AI for designing nanoparticles can assist prediction-based design and decrease, to some extent, experimental requirements through predictive correlations with the physics of nanoparticle physico-chemical properties and nano-bio-interactions/pharmacokinetics/bio-distributions and toxicity/therapeutics in general [7].

RNA and gene-editing systems, especially lipid nanoparticles, will likely stay as central delivery mechanisms for mRNA, siRNA, miRNA, antisense and gene-editing drugs; while nanomedicine brain-targeting is supposed to be enabled by better understanding the receptor-mediated transport and BBB physiology as well as region/cell-specific targeting agents and will enable new treatment options to be explored for neurodegenerative disorders and brain tumours; meanwhile, patient-specific nano-drug delivery means its physicochemical properties would be modulated by individual health status which can address the heterogeneous biological and physiological conditions of individuals. Ultimately, self-assembled responsive and integrated, yet individually-tailored nanotheranostic systems that enable detection, targeting, real-time monitoring and precise treatment, would take nanobiotechnology beyond the traditional concept of drug carrier systems toward intelligently orchestrated and individually adjusted therapy platforms which can truly be widely accessible across the global disparity in access to medical technologies and ensure equity.

Table 1. Major Nanocarrier Platforms and Their Principal Roles in Targeted Drug Delivery

Nanocarrier platform	Key characteristics	Principal role in drug delivery
Liposomes	Phospholipid-based vesicles capable of carrying hydrophilic and hydrophobic drugs; surface modification is possible	Improved solubility, prolonged circulation, targeted delivery, and reduced systemic toxicity
Lipid nanoparticles (LNPs)	Ionizable lipid-containing systems with high nucleic-acid loading capacity	Delivery of mRNA, siRNA, and other nucleic-acid therapeutics
Polymeric nanoparticles	Biodegradable or biocompatible polymers with tunable size and surface properties	Controlled release, protection of therapeutic cargo, and tissue/cellular targeting
Polymeric micelles	Amphiphilic polymer assemblies with hydrophobic cores	Solubilization and delivery of poorly water-soluble drugs
Dendrimers	Highly branched, monodisperse macromolecules with multiple functional surface groups	Drug conjugation, gene delivery, and ligand-mediated targeting
Nanogels	Hydrophilic, cross-linked nanoscale polymer networks	Encapsulation of drugs and biomolecules with controlled or stimuli-responsive release
Inorganic nanoparticles	Include gold, silica, iron oxide, and other inorganic materials with tunable physicochemical properties	Imaging, photothermal therapy, magnetic targeting, and drug delivery
Protein-based nanoparticles	Constructed from natural or engineered proteins with favorable biological compatibility	Delivery of therapeutic molecules and biomolecules
Extracellular-vesicle-inspired systems	Biomimetic systems designed to reproduce selected properties of extracellular vesicles	Biocompatible delivery and transport of biological therapeutics
Hybrid nanocarriers	Combine two or more material classes to integrate complementary functions	Multifunctional delivery, targeting, imaging, and combination therapy

This table summarizes the major nanocarrier platforms discussed in the review, their key characteristics, and their principal roles in targeted therapeutic delivery.

Table 2. Targeting Strategies Used in Nanobiotechnology-Enabled Drug Delivery

Targeting strategy	Mechanism/principle	Potential therapeutic advantage
Passive targeting	Exploits pathological vascular and tissue characteristics to promote preferential nanoparticle accumulation	Increased localization at diseased tissues without requiring a specific targeting ligand
Active targeting	Surface ligands interact with receptors or biomarkers expressed on target cells	Enhanced cellular recognition, binding, and internalization
Receptor-mediated targeting	Ligands bind specific receptors that facilitate cellular uptake through endocytosis	Improved intracellular delivery of therapeutic cargo
Biomimetic targeting	Nanoparticles are modified with cell membranes or membrane-derived components	Enhanced biological recognition, immune evasion, and tissue-specific interactions
Organelle targeting	Nanocarriers incorporate features that promote localization to specific intracellular organelles	Improved subcellular delivery and therapeutic activity
Stimuli-responsive targeting	Drug release is triggered by endogenous or external stimuli such as pH, enzymes, redox conditions, temperature, light, or magnetic fields	Spatially and temporally controlled drug release
Multistage targeting	Combines sequential delivery processes such as circulation, tissue penetration, cellular uptake, and intracellular release	Improved delivery efficiency across multiple biological barriers
Microenvironment-responsive targeting	Uses disease-associated characteristics such as altered pH, enzyme activity, or redox status	Selective drug release within pathological microenvironments

This table outlines the principal targeting approaches used to improve the localization, cellular uptake, and controlled release of nanomedicines at disease-relevant sites.

Table 3. Disease-Specific Applications and Precision Opportunities of Nanobiotechnology

Disease area	Major therapeutic challenges	Nanobiotechnology applications	Precision opportunity
Cancer	Tumour heterogeneity, poor penetration, systemic toxicity, drug resistance	Chemotherapy, immunotherapy, nucleic-acid delivery, phototherapy, combination therapy, theranostics	Biomarker- and receptor-guided targeting; tumour-microenvironment-responsive delivery
Neurological diseases	Blood–brain barrier and limited drug penetration into the central nervous system	Brain-targeted drug and nucleic-acid delivery	Receptor-mediated transport and brain-region-specific targeting
Cardiovascular diseases	Poor tissue specificity and systemic adverse effects	Targeted delivery of cardiovascular therapeutics and anti-inflammatory agents	Vascular and tissue-specific targeting
Diabetes and metabolic diseases	Poor oral bioavailability and degradation of biological therapeutics	Oral and controlled delivery of insulin and other antidiabetic agents	Improved protection, absorption, and controlled release
Infectious diseases	Pathogen localization, intracellular infection, resistance, and systemic toxicity	Antimicrobial and antiviral drug delivery; vaccine and nucleic-acid delivery	Pathogen- or cell-specific targeting and intracellular delivery
Inflammatory diseases	Chronic inflammation and nonspecific drug distribution	Targeted delivery of anti-inflammatory therapeutics	Inflammation-responsive and tissue-specific delivery
Genetic diseases	Efficient and safe delivery of nucleic acids	mRNA, siRNA, DNA, and other nucleic-acid delivery systems	Molecularly guided delivery based on genetic or cellular targets
Other complex diseases	Biological barriers, heterogeneous pathology, and limited therapeutic selectivity	Multifunctional nanocarriers and combination approaches	Integration of biomarkers, patient characteristics, and disease microenvironment

This table summarizes major disease areas in which nanobiotechnology-based delivery systems are being investigated and highlights the corresponding precision-delivery opportunities.

Table 4. Precision Nanomedicine: Design Variables, Biological Rationale, and Expected Impact

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Design variable	Biological relevance	Potential impact on therapy
Particle size	Influences biodistribution, tissue penetration, cellular uptake, and clearance	Can improve tissue accumulation and optimize circulation characteristics
Particle shape	Affects cellular interactions, circulation, and tissue penetration	May influence targeting efficiency and biological behaviour
Surface charge	Determines interactions with cell membranes, proteins, and biological fluids	Influences cellular uptake, protein-corona formation, and toxicity
Surface chemistry	Controls interactions with proteins, cells, and tissues	Enables improved stability, immune evasion, and targeting
Targeting ligands	Recognize specific receptors or biomarkers	Enhances selective cellular or tissue uptake
Drug-loading capacity	Determines the amount and type of therapeutic cargo that can be incorporated	Supports efficient delivery and combination therapy
Release characteristics	Control the rate and location of therapeutic release	Enables sustained or stimuli-responsive drug delivery
Biodegradability	Determines persistence and elimination of the nanocarrier	Can improve safety and reduce long-term accumulation
Protein-corona interactions	Adsorbed proteins can alter nanoparticle identity and biological behaviour	Influences biodistribution, targeting, immune recognition, and clearance
Disease biomarkers	Reflect molecular or cellular characteristics of specific diseases	Enable patient- and disease-specific targeting
Tissue microenvironment	Includes pH, enzymes, redox conditions, and other pathological features	Provides opportunities for site-specific and responsive drug release

This table presents the major physicochemical and biological parameters that can be engineered to improve the precision and therapeutic performance of nanomedicines.

CONCLUSION

The field of nanobiotechnology is rapidly changing the paradigm for drug delivery from general systemic use to precise, directed, and potentially patient-specific medicine. Through the use of liposomes, lipid nanoparticles, polymeric nanoparticles, micelles, dendrimers, nanogels, inorganic nanoparticles, biomimetic systems, and hybrids, scientists are exploring multiple routes by which to improve solubility of medicines, improve stability, modify pharmacokinetics, alter tissue distribution, modify cellular uptake and release a specific amount of medicine at a specific time.

The best evidence, clinical trials, and most development is currently taking place in oncology and nucleic-acid therapy, while developments in neurology, cardiovascular therapies, metabolic disease, infection, inflammation, and genetics are occurring at a rapid pace. Furthermore nanoparticle engineering is continually evolving to incorporate the features of molecular targeting, stimuli-responsive release, biomimetic surfaces, theranostics, and artificial intelligence.

Despite the impressive advancement, nanobiotechnology cannot overcome all hurdles. Biology's intrinsic variability, protein–corona formation of nanoparticles in plasma, clearance mechanisms of nanoparticles, toxicity issues of certain nanoparticle materials, manufacturability, reproducibility, regulatory concerns and the discrepancy between experimental models and human subjects represent significant ongoing challenges. To facilitate progress of precision nanomedicine requires the interplay of engineers, chemists, pharmacists, clinicians, molecular biologists, computational scientists, regulatory bodies, and public-health professionals.

For nanocarrier technology to proceed beyond its experimental stage to global, patient-specific therapies will require not only technological development but also successful clinical trials, standardization, long-term toxicity studies, cost-effective manufacturing, and attention to equity in access to treatment. When these scientific, clinical, regulatory and social issues can be tackled synergistically, nanobiotechnology promises to be a driving force for the medicine of the 21st century. [1-5,22].

DECLARATIONS

Ethics approval

Ethics approval was not applicable because this article is a narrative review based on published literature and did not involve human participants, patient records, or identifiable personal data.

Consent for publication

Not applicable.

Competing interests

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Author contributions

All authors contributed to the conception, literature review, drafting, critical revision, and approval of the final manuscript.

Data availability

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