

Review Article

The Advancements of Nanobiotechnology in Novel Drug Delivery System: Current Trends and Future Directions

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Abstract

Nanobiotechnology has revolutionized drug delivery systems by enabling precise, controlled, and targeted therapeutic interventions that significantly enhance treatment efficacy while minimizing systemic toxicity. This review comprehensively examines current trends in nanocarrier design, including liposomes, polymeric nanoparticles, dendrimers, quantum dots, and carbon nanotubes and their applications in overcoming biological barriers and improving drug bioavailability. Emphasis is placed on smart, stimuli-responsive delivery platforms and multifunctional nanomedicines that combine therapy with real-time imaging for theranostics. The article also addresses critical challenges such as nanoparticle toxicity, manufacturing scalability, and regulatory hurdles that impede clinical translation. Looking forward, emerging technologies like nanorobotics, artificial intelligence integration, and sustainable manufacturing promise to drive the next generation of personalized, precision nanomedicine. Interdisciplinary collaboration will be essential to unlock the full clinical potential of nanobiotechnology, ultimately transforming global healthcare outcomes.

Keywords

Nanobiotechnology, Targeted Drug Delivery, Nanoparticles, Controlled Release, Nanorobotics

1. Introduction

The evolution of drug delivery systems (DDS) began in the mid-1900s with the introduction of the Spansule sustained-release capsule in 1952 for 12-hour delivery of drugs [1, 2]. Modifications like PEGylation and the use of lipid nanoparticles have of course made drug delivery more effective and safer over the years by allowing more controlled, targeted and sustained release of therapeutic agents [3]. The development of DDS, however is less rapid than for some other disciplines such as computing because, safety and efficacy must be thoroughly proven before any clinical use. Advancement does exist, as seen by the development of nanotechnology carriers, smart delivery systems, and per-

sonalized medicine, all aimed at overcoming the drawbacks of conventional systems and maximizing therapy effectiveness in a targeted manner [4, 5].

Nanobiotechnology has the potential to change the drug delivery paradigm by allowing the engineering of nanosized drug delivery vehicles providing increased therapeutic efficacy and safety when compared to conventional drugs [6]. Nanoparticles including liposomes, polymeric nanoparticles and dendrimers, may entrap drugs, thus safeguarding the compounds from degradation, enhancing solubility and bio-availability, thereby overcoming the problems related to absorption that are characteristic of conventional formulations

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[7, 8]. Surface modifications with ligands or antibodies toward certain pathological cells allow for disease-targeted delivery, reducing toxicities caused by off-target effects. Their small size, remove 'plus' or replace it with a more formal conjunction such as 'additionally' (if additional emphasis is needed), permits them to traverse biological barriers, e.g., the blood-brain barrier and thus treat conditions that were previously hard to treat [8, 9]. Nanoparticles can also be designed for controlled/sustained drug delivery, allowing therapeutic drug concentrations to be maintained for long periods of time and decreasing the frequency of dosing, therefore improving patient compliance [10]. In addition, nanobiotechnology enables the use of more sophisticated biological therapies, including the use of siRNAs, monoclonal antibodies and gene therapies [11]. Certain nanoparticles have the ability to co-deliver multiple therapeutic agents, enabling combination therapy and integration with physical modalities such as radiotherapy, particularly for cancer [12]. Nanobiotechnology is still facing many issues regarding clinical application and biocompatibility, but is a paradigm shift in that it overcomes problems associated with traditional drug delivery such as poor bioavailability, systemic toxicity, non-targeted delivery, and non-controlled release, leading to a vast improvement in a drug's efficacy and safety profile [13, 14].

Current Trends and Future Directions aims to present a global overview of the new developments related to drug delivery system based on nanobiotechnology and the impact of these developments in the field of treatment. This article will be specifically concerned with recent progress in diverse nanocarriers such as liposomes, polymeric nanoparticles, dendrimers and metallic nanoparticles that improve drug stability and bioavailability, allow for targeted drug delivery, and minimize systemic toxicity. In this regard, it will discuss advances such as microfluidics for the production of nanoparticles at scale, micro-robotics for controlled on-spot-drug delivery and stimulus responsive nanocarriers that release drugs in a controlled manner and in a sustained fashion. Nanotechnology's convergence with other cutting-edge fields such as personalized medicine and gene therapy will also be addressed, as these will allow for even more accurate, efficient and patient- friendly therapeutic strategies [15, 16]. It will also discuss some of the challenges in transferring to the clinic, such as biocompatibility, regulatory considerations, and scaling production, to have a balanced view on the future prospects. Finally, it will highlight next steps, with an emphasis on breakthroughs that will increase the already known possibilities of nanobiotechnology to revolutionize the way drugs are delivered and make a positive impact in people's lives globally.

2. Current Trends in Nanobiotechnology for Drug Delivery

Nanobiotechnology in drug delivery is currently employed

rapidly and its platforms are used widely to improve drug capability, deliverability, targeting, and patient compliance [17]. Drug delivery systems employing nanotechnology, which include liposomes, polymeric nanoparticles, dendrimers or lipid nanoparticles, are being increasingly used for more precision in targeting the drug directly at the tissue or cells of interest, minimizing side effects and systemic toxicity [7, 18, 19].

2.1. Nanocarrier Platforms

Nanocarrier platforms have revolutionized novel drug delivery technology by enabling targeted, controlled, and efficient therapeutic delivery, particularly in cancer treatment [20]. Among these, liposomes are highly valued for their excellent biocompatibility, biodegradability, and low immunogenicity, mimicking cell membranes which facilitates their interaction with biological systems [21, 22]. Liposomes have been widely applied in cancer therapy, notably for delivering chemotherapeutic agents like doxorubicin. Their ability to encapsulate both hydrophilic and hydrophobic drugs protects the payload from rapid metabolism and clearance, allowing controlled drug release and reduced systemic toxicity [23]. Furthermore, liposomes can be surface-modified with targeting ligands such as epidermal growth factor (EGF) to enhance specificity toward cancer cells overexpressing receptors like EGFR, thereby improving therapeutic efficacy and minimizing damage to healthy cells [24, 25]. Advanced liposomal formulations also show promise in overcoming tumor resistance, crossing the blood-brain barrier, and combining with immunotherapy or phototherapy for synergistic effects [26].

2.1.1. Polymeric Nanoparticles

Polymeric nanoparticles, especially those made from biodegradable polymers like poly (lactic-co-glycolic acid) (PLGA), provide a versatile platform for controlled and sustained drug release [27, 28]. These nanoparticles protect drugs from degradation and allow precise tuning of release kinetics by altering polymer composition and molecular weight. PLGA-based nanoparticles have been extensively studied for cancer therapy due to their biocompatibility and ability to deliver drugs in a controlled manner, reducing dosing frequency and side effects [29, 30].

2.1.2. Dendrimers

Dendrimers are highly branched, tree-like polymers that offer unique advantages for multidrug delivery and functionalization [31]. Their well-defined structure allows for the attachment of multiple drug molecules and targeting moieties on their surface, enabling simultaneous delivery of different therapeutics and enhanced targeting to specific cells or tissues [32, 33]. This multifunctionality makes dendrimers attractive for personalized medicine approaches where combination therapies are required.

2.1.3. Metallic Nanoparticles

Metallic nanoparticles, such as gold and silver nanoparticles, are increasingly explored for their dual role in cancer therapy and imaging [8, 34]. Gold nanoparticles can be used in photothermal therapy, where they convert light energy into heat to selectively destroy tumor cells [35]. Additionally, their optical properties enable enhanced imaging contrast, facilitating tumor detection and monitoring [36]. Silver nanoparticles exhibit cytotoxic effects against cancer cells but require careful design to reduce toxicity to normal cells. Combining metallic nanoparticles with liposomal carriers, such as EGF-labeled silver nanoparticle-loaded liposomes, has shown improved targeting and reduced off-target toxicity, highlighting the potential of hybrid nanocarriers in cancer theranostics [37, 38].

2.2. Targeted Drug Delivery

Current trends in nanobiotechnology for targeted drug delivery emphasize the development of ligand-functionalized nanoparticles and hyaluronic acid (HA)-based systems to enhance tumor-specific uptake and cancer therapy [39]. Ligand-functionalized nanoparticles are engineered to bind selectively to receptors overexpressed on tumor cells, enabling receptor-mediated endocytosis and precise drug delivery that improves therapeutic efficacy while reducing systemic toxicity [40, 41]. Concurrently, HA-based delivery platforms exploit HA's natural affinity for CD44 receptors, commonly upregulated in cancer cells, to facilitate targeted drug accumulation and controlled release within tumor microenvironments [42]. These nanocarriers often incorporate stimuli-responsive features, such as pH sensitivity to trigger drug release specifically in acidic tumor tissues, further enhancing treatment specificity [42]. Advances in scalable manufacturing techniques, like microfluidic mixing, support large-scale production of these sophisticated nanomedicines. Collectively, these innovations are driving the rapid growth of targeted drug delivery, particularly in oncology, by improving drug bioavailability, minimizing off-target effects, and enabling personalized therapeutic strategies [43, 44].

2.3. Stimuli-responsive Systems

Current research in nanobiotechnology focuses heavily on developing *smart* stimuli-responsive systems [45]. These advanced nanomaterials specifically leverage unique features of tumor microenvironments, particularly differences in pH and temperature to achieve highly targeted drug delivery and controlled release [19, 30, 46]. pH-sensitive nanocarriers, for example, are designed to stay stable at the body's normal pH but break down in the slightly acidic conditions typical of tumors. This allows them to release therapeutic agents precisely where needed, improving targeting precision while minimizing side effects throughout the body [46]. Temperature-sensitive polymers can add another layer of control: They

respond to the naturally warmer environment of tumor tissues or externally applied heat, triggering drug release at the exact treatment site [47]. What makes these systems especially promising are recent advances in multifunctional nanoplat-forms. These integrate responsiveness to *multiple* stimuli, like pH, temperature, redox signals, and reactive oxygen species to enhance treatment effectiveness and tackle challenges such as drug resistance [19]. Many also feature biomimetic designs and synergistic theranostic capabilities, meaning they don't just deliver drugs [26, 48]. They can simultaneously provide diagnostic imaging and even support tissue regeneration. By combining nanostructured materials with stimuli-responsive polymers, researchers are enhancing drug-loading capacity, sensitivity to biological triggers, and stability within the body [49]. This progress is paving the way for smarter biomaterials in precision medicine, especially for complex diseases like cancer [49].

2.4. Biologics Delivery

Current advances in nanobiotechnology for delivering biologics spotlight lipid nanoparticles (LNPs) a breakthrough system that revolutionized mRNA vaccine delivery, as seen in COVID-19 vaccines from Pfizer/BioNTech and Moderna [50-53]. LNPs shield fragile mRNA from degradation and help cells absorb it efficiently by fusing with immune cells' lipid membranes, which sparks strong immune responses [54].

Because of their strong safety profile, high tolerability, and scalable production, LNPs have accelerated new vaccines and gene therapies for diseases like cancer and cardiovascular disorders [55]. Today, dozens of LNP-based RNA therapeutics are advancing through clinical trials [50].

Beyond LNPs, the field is embracing gene editing tools and siRNA delivery systems, where nanocarriers boost targeted delivery while minimizing whole body side effects [56]. Together, these nanotechnology platforms are transforming biologic drug delivery: Improving treatment precision and effectiveness, enhancing patient compliance, driving regulatory updates (FDA/EMA guidelines) to safely integrate these therapies into mainstream medicine [57].

3. Technological Innovations

In 2025, nanobiotechnology is transforming drug delivery through four key innovations: Includes Smart nano-systems, Hybrid nanoplat-forms, Nanorobotics, and Advanced materials (biodegradable polymers, novel nanostructures) [39]. Together, these technologies tackle chronic drug delivery challenges: poor solubility, whole-body toxicity, and imprecise targeting. New manufacturing methods like microfluidics allow scalable, consistent production of these complex systems are accelerating the shift toward personalized precision medicine [58, 59].

3.1. Smart Nano-systems

Smart nano-systems are redefining precision drug delivery in nanobiotechnology [60]. By enabling tightly controlled, targeted therapeutic release, these systems maximize treatment impact while minimizing side effects. A key breakthrough is the rise of metal-biomolecule networks (MBNs), which are coordination structures built *only* from non-toxic metals (like calcium or iron) and biomolecules such as DNA [61]. Unlike conventional carriers, MBNs offer inherent metabolic stability plus broad therapeutic activity (antiviral, antibacterial, anticancer, etc.), eliminating the need for complex drug-loading chemistry [62, 63].

These systems activate only at disease sites and responding to biological triggers like pH shifts or enzymes to release drugs precisely [64, 65]. This targeting slashes systemic toxicity while boosting efficacy. Other nanocarriers (liposomes, polymeric/dendritic nanoparticles, metallic particles) further enhance drug stability, bioavailability, and controlled release, helping therapeutics bypass natural barriers like the blood-brain barrier [66]. Organized, they enable personalized medicine and combination strategies, even merging treatment with diagnostics (*theranostics*) on a single platform [57, 67-69]. Though scaling and clinical translation remain hurdles, smart nano-systems, particularly MBNs are poised to transform outcomes in cancer, infections and beyond [70, 71].

3.2. Hybrid Nanoplatfoms

Polymer-lipid hybrid nanoplatfoms merge the best of both worlds: the robustness of polymeric nanoparticles and the biocompatibility of liposomes [72]. This fusion creates "core-shell" nanoparticles where a biodegradable polymer core (PLGA) provides sturdy scaffolding for high drug loading and controlled release, while a lipid outer layer boosts biocompatibility, aids cell interactions, and prevents particle clumping [73, 74].

Critically, the lipid shell acts as a molecular fence trapping drugs inside the polymer core until they reach their target. This drastically cuts premature leakage while maximizing drug encapsulation. Advanced designs now enable: Spatio-temporal targeting (delivering drugs to specific sites at specific times), multi-stage cascade delivery (releasing therapeutics in sequence) and Organelle specific targeting (hijacking cells' own lipid transport systems) [75].

These hybrids outperform purely polymeric or lipid-based carriers in *in vivo* studies, efficiently delivering: Small-molecule drugs, Proteins & peptides, Genetic therapies (DNA/RNA) and Vaccines [76, 77]. With tunable properties, longer-lasting release, and unmatched serum stability, polymer-lipid hybrids are emerging as next-generation carriers for overcoming traditional nanocarrier limitations and moving us closer to truly personalized therapies [74, 78].

3.3. Nanorobotics

Magnetic soft nanorobots are redefining precision drug

delivery. These untethered, flexible microrobots navigate the body's complex terrain, like the winding colon or delicate neural tissues using external magnetic fields to perform rolling, crawling, or tumbling motions [79]. Their miniature size and high dexterity let them reach confined disease sites other systems can't. Nanorobotics are sophisticated drug control method and used to Deliver up to four different drugs in precise sequences, Adjust dosages on demand for personalized therapies and Release liquid drugs via integrated microfluidic modules [80-82].

Magnetic steering ensures exact localization, letting robots "park" at targets to maximize drug exposure while minimizing systemic side effects [83]. This spatiotemporal precision helps them overcome stubborn biological barriers, a game-changer for diseases needing multi-drug treatments (cancer, neurological disorders) [84]. By merging minimally invasive navigation with reprogrammable dosing, these nanorobots promise safer, more effective treatments for complex conditions [85, 86].

3.4. Advanced Materials

Carbon quantum dots (CQDs) and carbon nanotubes (CNTs) are pushing boundaries in precision drug delivery [87]. These advanced nanomaterials tackle delivery challenges in complementary ways: CQDs shine (literally) with their tunable glow (photoluminescence) for real-time treatment tracking, High surface area for efficient drug loading Biocompatibility that minimizes immune reactions [47, 88]. They are ideal for *theranostics* by combining targeted therapy with live imaging feedback. CNTs act as nano-cargo ships, due to their hollow tubes store drugs like dexamethasone (anti-inflammatory) or chemo agents, Surface functionalization enables "smart" release triggered by tumor pH/heat multi-walled designs improve drug solubility and sustain release [89].

Together, they enable unprecedented control: Targeted delivery to diseased cells, Reduced side effects, multi-functional treatment monitoring. But caution remains: While functionalization improves CNT safety, potential toxicity and environmental impact need further study before widespread clinical use [90, 91].

4. Clinical Applications

Nanobiotechnology is actively treating patients today, with targeted nanoparticles delivering drugs precisely to diseased cells, like tumors slashing side effects while boosting effectiveness [92-94]. Already in clinics, FDA/EMA approved nanomedicines (including liposomal drugs, polymeric micelles like Genexol-PM/NK105 for breast/ovarian/pancreatic/lung cancers, and protein-based nanoparticles) allow higher IV or oral drug doses with fewer complications by improving solubility, controlled release, and bioavailability [95, 96]. Beyond oncology, these advances enable macromolecule delivery for infections and heart disease, real-time treatment imaging, and multi-drug combos [71, 93, 97]. Smart implants with adaptive

drug release and antibacterial nano-coatings, further prevent hospital infections, collectively transforming care across autoimmune disorders, regenerative medicine, and more through safer, more precise therapies [81, 98, 99].

5. Challenges and Limitations

Despite their promise, nanobiotechnology drug delivery systems still face tough hurdles: Truly precise targeting remains elusive, as biological barriers like the blood-brain barrier, uneven tumor landscapes, and fluid pressure buildup often block drug access [18, 100, 101]. Safety worries persist too, some nanoparticles trigger immune reactions or toxicity, while delivering water-repelling drugs without harsh solvents remains tricky (though albumin-bound paclitaxel shows progress) [102]. Manufacturing is another headache: complex multi-component designs make consistent, large-scale production difficult, complicating quality control and FDA/EMA approval [100, 103]. Even smart surface tweaks (like PEG coatings or targeting tags) trade better performance for added design complexity [104]. Underpinning all this is our incomplete grasp of how nanoparticles interact with the body and which patients benefit most highlighting the urgent need for deeper research and personalized approaches before these advanced systems can fully deliver on the promise of precision medicine.

6. Future Directions

Future directions of nanobiotechnology in novel drug delivery systems focus on enhancing precision, scalability, and multifunctionality through several emerging trends [105]. Advances in nanotechnology can enabled carriers such as liposomes, micelles, and polymeric nanoparticles are being scaled up via innovative manufacturing techniques like microfluidic mixing, enabling high-volume, reproducible production without compromising quality [106-108]. The integration of smart drug delivery systems that respond to stimuli (pH, temperature, enzymes) allows for controlled, site-specific release, improving therapeutic outcomes and minimizing side effects [3, 109]. The rise of biologics and large-molecule drugs is driving development of advanced delivery devices, including wearable pumps for subcutaneous administration, enhancing patient compliance. Cutting-edge innovations like micro-robotics and nanorobots promise targeted, programmable drug release within the body, overcoming biological barriers and enabling personalized dosing regimens [19]. Additionally, real-time imaging and artificial intelligence are expected to tailor nanomedicine therapies dynamically [110]. Sustainability and eco-friendly design are gaining attention, with greener inhalers and reusable components emerging. Generally, future nanobiotechnology drug delivery aims to combine precision, adaptability, and scalability to meet complex clinical needs and improve patient

outcomes globally.

7. Conclusion

Nanobiotechnology is fundamentally changing how we deliver medicines, creating targeted, controlled, and do all treatments that work better with fewer side effects. Breakthroughs like nanoparticle carriers, smart systems that release drugs only when triggered (pH, temperature, etc.), and real-time tracking tech are rewriting the rulebook for treating cancer, infections, and more. But to fully unlock this potential, scientists, engineers, doctors, and regulators must team up to tackling stubborn technical hurdles, ensuring safety, and smoothing the path to approval. The real excitement lies ahead: blending these tiny tech wonders with AI, personalized medicine, and planet-friendly manufacturing. This fusion promises a new era of precision therapies, custom-fit to each patient's needs, ultimately transforming global healthcare and putting patients everywhere at the heart of medical progress.

Abbreviations

AI	Artificial Intelligence
CD44	Cluster of Differentiation 44
CNTs	Carbon Nanotubes
CQDs	Carbon Quantum Dots
DDS	Drug Delivery Systems
DNA	Deoxyribonucleic Acid
EGF	Epidermal Growth Factor
EGFR	Epidermal Growth Factor Receptor
EMA	European Medicines Agency
FDA	Food and Drug Administration
HA	Hyaluronic Acid
LNPs	Lipid Nanoparticles
MBNs	Metal-biomolecule Networks
mRNA	Messenger RNA
PEG	Peg
PLGA	Poly Lactic-co-glycolic Acid
RNA	Ribonucleic Acid
siRNA	Small Interfering RNA

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Conflicts of Interest

The author declares no conflicts of interest.

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