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SynBioNanoDesign strategies for next-generation targeted drug delivery systems

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ABSTRACT

The convergence of synthetic biology and nanotechnology-termed SynBioNanoDesign-has opened new frontiers in the development of next-generation targeted drug delivery systems (TDDS). By integrating the programmability of synthetic biology with the precision and versatility of engineered nanomaterials, SynBioNanoDesign enables the creation of highly specialized drug carriers capable of dynamic, stimuli-responsive, and site-specific therapeutic delivery. These hybrid systems offer several advantages over conventional drug delivery methods, including improved bioavailability, reduced systemic toxicity, enhanced cellular uptake, and the potential for personalized medicine. Synthetic biology facilitates the design of genetic circuits and biomolecular components that can be embedded into nanomaterials to achieve autonomous sensing, decision-making, and therapeutic release. In parallel, advances in nanotechnology provide customizable platforms-such as liposomes, nanoparticles, and dendrimers-for efficient encapsulation and transport of therapeutic agents. Despite these advancements, challenges remain in ensuring the biocompatibility, stability, and clinical scalability of SynBioNanoDesign-based systems. This highlights current strategies, key applications, and the potential of SynBioNanoDesign to transform drug delivery science, while also addressing critical limitations and future research directions necessary for its clinical translation.

KEYWORDS

Synthetic biology; Nanomaterials; Targeted drug delivery; SynBioNanoDesign; Precision medicine; Bioengineering; Smart nanocarriers.

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Introduction

Synthetic biology and nanotechnology have converged to establish a transformative framework for the rational design and fabrication of targeted drug delivery (TDD) platforms. Synthetic biology, by integrating engineering principles with biological systems, enables the design of novel biological components and the reprogramming of existing cellular mechanisms. This interdisciplinary approach not only expands the frontier of biomedical innovation but also offers unprecedented opportunities in therapeutic delivery.

Recent advances in synthetic biology have led to the creation of genetic circuits capable of sophisticated decision-making, revolutionizing areas such as diagnosis, therapy, and biosensing. Concurrently, the field has extended its influence into materials science, driving the development of next-generation nanomaterials with customized morphologies and functions [1]. These biologically engineered materials-referred to collectively as SynBioNanoDesign-embody the fusion of biological programmability with nanoscale engineering.

SynBioNanoDesign reimagines biological systems as responsive, programmable platforms for constructing functional nanomaterials. These materials, distinguished by their nanoscale dimensions and emergent properties, offer enhanced biocompatibility, controlled release, and site-specific targeting, thereby improving the safety and efficacy of drug delivery systems. Compared to their bulk counterparts, engineered nanomaterials developed through synthetic biology exhibit superior functional diversity and adaptability.

The integration of synthetic biology with nanomaterial science has produced a versatile toolbox of nanoscale devices and carriers, such as nanoparticles, dendrimers, nanocapsules, and liposomes. These structures serve as efficient delivery vehicles, signal transducers, and therapeutic enhancers. Importantly, synthetic biology contributes precise molecular control, enabling reversible and programmable biological interactions. The resulting nanomaterials are not only effective in targeted delivery but also exhibit key advantages such as low toxicity, environmental sustainability, biological specificity, and cost-efficiency [2].

Importance of Targeted Drug Delivery in Precision Medicine

Targeted drug delivery systems (TDDS) have emerged as a pivotal innovation in modern medicine, particularly in the treatment of complex diseases such as cancer. By enabling the controlled and site-specific delivery of therapeutic agents, TDDS significantly enhance treatment efficacy while minimizing systemic side effects and toxicity. Unlike conventional therapies, which often suffer from non-specific distribution and harmful off-target effects, TDDS concentrate therapeutic agents at the disease site, reducing required dosages, improving patient outcomes, and enabling cost-effective treatments. This targeted approach is especially valuable in oncology, where it helps mitigate the severe side effects associated with traditional chemotherapy and addresses issues such as drug resistance and limited drug bioavailability. Furthermore, TDDS facilitate the co-delivery of multiple drugs,

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improving therapeutic synergy and opening avenues for personalized medicine tailored to individual patient profiles. Beyond cancer, targeted delivery systems offer substantial benefits in managing chronic conditions like diabetes and cardiovascular diseases by enhancing long-term treatment adherence and therapeutic precision. However, traditional TDDS face limitations such as instability, structural heterogeneity, and poor solubility [3]. To overcome these challenges, nanomaterials-based drug delivery platforms have been developed, offering improved stability, solubility, and controlled drug release. As a result, TDDS, particularly those incorporating nanotechnology, are at the forefront of precision medicine, revolutionizing therapeutic strategies across various fields of healthcare.

Role of Nanomaterials in Modern Drug Delivery Systems

Nanomaterials-defined by at least one dimension within the 1-100 nm range-have gained significant attention in the development of targeted drug delivery systems due to their unique physical, chemical, and biological properties. These nanoscale carriers are capable of encapsulating therapeutic agents and facilitating their cellular uptake through mechanisms such as endocytosis, thereby enhancing drug delivery and treatment efficacy [4]. One of the key advantages of nanomaterials lies in their high surface-to-volume ratio, which increases their loading capacity and allows for the attachment of multiple therapeutic agents and targeting ligands. This facilitates targeted delivery to specific tissues, enhancing drug bioavailability, refining pharmacokinetic profiles, and reducing unintended effects on healthy cells.

Nanomaterials also exhibit quantum effects that can be exploited for stimuli-responsive drug release, triggered by external factors such as light, electric fields, or magnetic fields. Additionally, surface modifications can impart multifunctionality, enabling nanomaterials to serve dual roles in diagnosis and therapy, advancing the potential for personalized medicine. These properties collectively contribute to improved therapeutic efficacy, reduced systemic toxicity, simplified drug administration, and better patient compliance [5].

Both organic and inorganic nanomaterials-including nanoparticles, liposomes, dendrimers, and polymeric micelles-are being actively explored as drug delivery vehicles. For instance, a novel nanocarrier combining paeonol and polymet liposomes has demonstrated promising results in ischemic stroke therapy by targeting damaged neuronal cells, reducing neuroinflammation, scavenging reactive oxygen species, and modulating microglial activity [6]. Similarly, manganese phosphate nanomaterials coated with phospholipids have been developed for tumor immunotherapy, showing enhanced tumor-targeting capabilities and increased cytotoxic T cell activity.

Synthetic Biology: A Tool for Material Engineering

Synthetic biology has emerged as a transformative discipline that redefines how we design and manipulate biological systems for practical applications. In the context of material science and drug delivery, synthetic biology offers a powerful platform for engineering living and non-living systems with unprecedented precision. By applying engineering principles-such as modularity, standardization, and hierarchical design-synthetic biology enables the construction of biological circuits, programmable biomolecules, and functional organisms tailored for therapeutic purposes.

One of the key applications of synthetic biology in material engineering is the creation of genetically encoded systems that can guide the assembly and functionality of nanomaterials. This includes engineered proteins, peptides, nucleic acids, and metabolic pathways that can serve as templates, scaffolds, or regulatory elements for nanostructure fabrication. For instance, DNA origami and peptide-based self-assembly techniques allow precise spatial arrangement of functional groups on nanocarriers, improving their targeting capabilities and drug release profiles [7].

Additionally, synthetic organisms such as engineered bacteria or mammalian cells can be programmed to produce bio-compatible nanomaterials or to serve as “smart” drug delivery systems themselves. These living therapeutics can sense disease biomarkers in real time and respond accordingly by releasing therapeutic agents or modulating the local microenvironment.

Furthermore, synthetic biology enables dynamic control of nanomaterials through environmental responsiveness-incorporating mechanisms that respond to pH, temperature, enzymes, light, or redox conditions. Such responsiveness is especially valuable in cancer therapy, where the tumor microenvironment often differs significantly from healthy tissue. Genetic circuits embedded in delivery vehicles can initiate controlled therapeutic release only in the presence of specific stimuli, minimizing off-target effects [8].

SynBioNanoDesign: Convergence of Synthetic Biology and Nanotechnology

SynBioNanoDesign represents the strategic fusion of synthetic biology and nanotechnology to create next-generation drug delivery systems with enhanced specificity, responsiveness, and efficiency. This interdisciplinary framework combines the programmable and modular nature of synthetic biology with the physicochemical versatility of nanomaterials, resulting in hybrid platforms capable of performing complex therapeutic functions within biological environments [9].

At the core of SynBioNanoDesign is the concept of programmability, where genetic circuits or synthetic bioswitches are integrated into nanomaterial systems to enable logic-based or stimulus-triggered drug release. These systems can detect specific intracellular or extracellular signals-such as pH shifts, enzymatic activity, or disease biomarkers-and respond with precision-timed therapeutic action [10]. For example, nanocarriers functionalized with genetic constructs can release drugs only in the hypoxic environment of a tumor or in response to elevated levels of a pathogenic enzyme, minimizing harm to healthy tissue.

Stimuli-responsive nanomaterials are also central to SynBioNanoDesign strategies. These include smart materials that react to light, temperature, magnetic fields, or redox conditions. When coupled with synthetic biology, such responsiveness becomes more finely tuned and programmable.

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For instance, synthetic light-switchable proteins can be incorporated into nanocarriers to control drug release spatially and temporally using external light sources [11].

Another hallmark of SynBioNanoDesign is the development of bio-hybrid systems, where engineered cells or biomolecular components work in concert with synthetic nanomaterials. Engineered bacteria, for instance, can be harnessed to localize to tumor sites, secrete therapeutic molecules, or transport drug-loaded nanoparticles to disease-specific environments. Likewise, extracellular vesicles or exosomes engineered via synthetic biology offer biocompatible delivery options with inherent targeting capabilities.

Moreover, the modular design principles from synthetic biology allow nanomaterials to be customized with various functional domains-such as targeting ligands, imaging agents, and multiple drug payloads-enabling multi-functional delivery platforms. These multifunctional systems not only deliver drugs but also perform real-time diagnostics (theranostics), track therapeutic progress, and adjust treatment parameters dynamically [12].

Applications in Targeted Drug Delivery

The integration of SynBioNanoDesign into targeted drug delivery is swiftly revolutionizing the field of modern therapeutics. By merging synthetic biology's ability to program biological responses with the advanced functionalization of nanomaterials, diverse and complex medical conditions can now be addressed with improved precision, safety, and therapeutic efficiency. The following sub-sections highlight key application areas where SynBioNanoDesign is making a significant impact.

Cancer therapy

Cancer remains one of the primary targets for SynBioNanoDesign-based systems. These hybrid platforms are engineered to recognize tumor-specific markers such as overexpressed receptors, acidic microenvironments, or hypoxic conditions. For instance, synthetic gene circuits embedded in nanoparticles can detect these tumor-specific cues and initiate the release of chemotherapeutic agents only at the tumor site, minimizing systemic toxicity [13]. In addition, bio-hybrid systems-like engineered bacteria or mammalian cells-can be programmed to selectively home to tumor sites and deliver therapeutic payloads or immunomodulators in a controlled manner.

Neurological disorders

Treating brain diseases poses a major challenge due to the blood-brain barrier (BBB), which restricts most therapeutics from entering the central nervous system. SynBioNanoDesign offers innovative solutions such as ligand-modified nanocarriers that can cross the BBB, guided by synthetic biology-driven targeting strategies. These systems have been utilized for the delivery of neuroprotective agents, anti-inflammatory drugs, and gene therapies in conditions like Alzheimer's disease, Parkinson's disease, and ischemic stroke [14].

Infectious diseases

SynBioNanoDesign is proving valuable in combating bacterial, viral, and parasitic infections. Engineered nanomaterials can be designed to detect pathogen-specific signals-such as toxins or enzymes-and respond by releasing antimicrobial agents. For example, synthetic biology can be used to produce bacteriophage-inspired particles or CRISPR-based antimicrobial systems encapsulated within nanocarriers, offering a new mode of action against antibiotic-resistant pathogens [15].

Autoimmune and inflammatory diseases

Targeted delivery of anti-inflammatory drugs or immune modulators is essential in managing chronic inflammatory diseases such as rheumatoid arthritis and inflammatory bowel disease. SynBioNanoDesign platforms can be engineered to detect inflammation biomarkers and deliver therapeutics locally, reducing systemic side effects. Synthetic biology tools allow for feedback-controlled drug release based on cytokine levels or tissue damage signals [16].

Metabolic and cardiovascular disorders

In metabolic diseases such as diabetes, SynBioNanoDesign enables glucose-responsive insulin delivery using engineered cells or responsive nanogels. Similarly, in cardiovascular diseases, targeted delivery of thrombolytics, anti-inflammatory agents, or gene therapies using synthetic biological cues and nanocarrier systems can improve outcomes by reducing drug dosage and minimizing side effects [17].

Personalized medicine and theranostics

One of the most promising applications of SynBioNanoDesign is in personalized medicine. By integrating patient-specific data, synthetic circuits can be customized to respond to individual disease signatures. Moreover, multifunctional nanocarriers can combine diagnostic and therapeutic capabilities (theranostics), allowing for real-time monitoring of disease progression and dynamic adjustment of treatment regimens [18].

Advantages of SynBioNanoDesign-Based Systems

The integration of synthetic biology with nanotechnology in the SynBioNanoDesign framework offers a variety of unique advantages over conventional and standalone drug delivery approaches. These benefits position SynBioNanoDesign as a promising avenue for the development of intelligent, responsive, and highly efficient therapeutic platforms.

High precision and specificity

One of the most notable advantages of SynBioNanoDesign systems is their ability to deliver therapeutic agents with exceptional precision. Engineered gene circuits and synthetic receptors can sense disease-specific biomarkers or environmental cues, ensuring that drug release occurs only in targeted tissues or cells. This specificity minimizes off-target effects and maximizes therapeutic impact, particularly important in sensitive applications such as cancer treatment or gene therapy [19].

Controlled and responsive drug release

SynBioNanoDesign enables dynamic control of drug release through the incorporation of stimuli-responsive elements. These may include pH-sensitive nanocarriers, enzyme-cleavable linkers, or synthetic biology modules that respond to endogenous (e.g., redox state, metabolite concentration) or

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exogenous (e.g., light, magnetic field) signals. This level of responsiveness allows for spatiotemporal regulation of therapy, reducing toxicity and enhancing drug efficacy.

Multifunctionality

By leveraging the modularity of synthetic biology and the structural versatility of nanomaterials, SynBioNanoDesign platforms can integrate multiple functions into a single system. These multifunctional systems can perform simultaneous tasks such as targeting, imaging, therapeutic delivery, and monitoring. This is particularly beneficial for theranostics and personalized medicine, where diagnostics and treatment are combined in real time [20].

Enhanced biocompatibility and reduced toxicity

The use of biologically derived or biocompatible synthetic components in SynBioNanoDesign systems reduces the risk of immunogenic responses and systemic toxicity. Furthermore, synthetic biology allows for the fine-tuning of biomolecular interfaces, optimizing interaction with host tissues and minimizing adverse effects during long-term treatments.

Reconfigurability and adaptability

SynBioNanoDesign systems can be reprogrammed or adapted to address evolving therapeutic needs. For instance, synthetic circuits can be updated with new input-output logic to respond to drug resistance mutations or shifting disease biomarkers. This adaptability makes the platform suitable for chronic diseases and complex conditions that require long-term or adjustable treatment strategies [21].

Environmental sustainability and cost-effectiveness

Synthetic biology offers scalable and environmentally friendly production processes using engineered microbes, reducing the need for harsh chemicals or complex synthesis routes. Combined with nanotechnology's potential for mass production, SynBioNanoDesign holds promise for economically viable, sustainable therapeutic solutions.

Challenges and Limitations

Despite the transformative potential of SynBioNanoDesign in targeted drug delivery, several critical challenges and limitations must be addressed before these technologies can be widely adopted in clinical settings (Figure 1).

Biological complexity and predictability

Synthetic biology components often operate in complex and variable biological environments, where factors such as immune responses, metabolic activity, and gene expression noise can disrupt the predictability and reliability of engineered systems. Achieving robust performance in vivo remains a significant challenge, especially when transferring in vitro successes to clinical applications.

Safety and immunogenicity

Introducing synthetic biological circuits or engineered nanomaterials into the human body raises concerns regarding biocompatibility and immune activation. Unintended immune responses may lead to inflammation, toxicity, or the rapid clearance of therapeutic agents. Ensuring long-term safety and minimizing off-target effects are crucial for clinical translation [22].

Regulatory and ethical hurdles

The convergence of synthetic biology and nanotechnology blurs traditional boundaries in biomedical innovation, making regulatory approval complex and time-consuming. Regulatory agencies often lack standardized frameworks for evaluating these hybrid systems, and ethical concerns-particularly surrounding gene editing, cell programming, and long-term biological integration-remain active topics of debate.

Scalability and manufacturing

Producing SynBioNanoDesign systems at industrial scales poses significant manufacturing challenges. Maintaining reproducibility, structural integrity, and functional consistency in engineered biological-nanomaterial hybrids is difficult, especially for personalized or multi-component systems. Cost-effective and scalable synthesis methods are still under development [23].

Stability and storage

Synthetic biological components and nanomaterials can be sensitive to environmental factors such as temperature, pH, and mechanical stress. Ensuring the stability of these systems during storage, transport, and administration is essential to preserve therapeutic efficacy.

Delivery efficiency

Achieving targeted delivery with high precision remains difficult, especially in heterogeneous tumor microenvironments or poorly vascularized tissues. Physical and biological barriers-such as the blood-brain barrier or dense extracellular matrices-limit the accessibility and distribution of therapeutic agents, reducing overall efficacy.

Limited clinical validation

Most SynBioNanoDesign strategies are still in preclinical or early-stage research phases. There is limited clinical data demonstrating their long-term efficacy, safety, and superiority over existing therapies. More in vivo studies and human clinical trials are necessary to validate their performance and therapeutic potential.

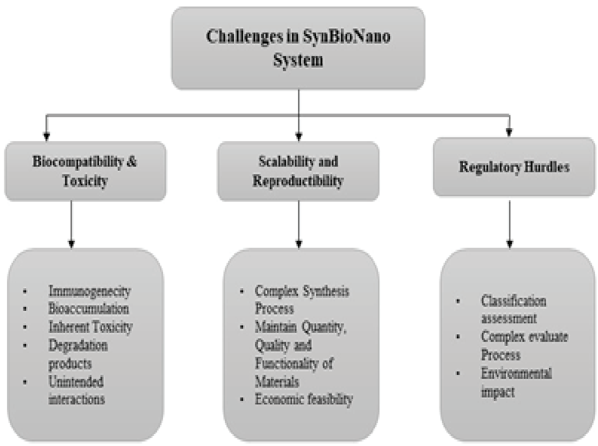

Figure 1. Overview of current challenges in SynBioNano for drug delivery.

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Future Perspectives and Research Directions

The integration of synthetic biology and nanotechnology-termed SynBioNanoDesign-represents a powerful interdisciplinary frontier poised to reshape the future of targeted drug delivery systems. While remarkable progress has been made, several transformative directions must be pursued to unlock the full potential of this field.

- **Designing smarter biological circuits:** Future efforts will focus on engineering synthetic gene circuits with enhanced precision, programmability, and minimal off-target effects. These circuits could enable dynamic responses to specific biological signals, allowing drug release to be tightly controlled in time and space.
- **Next-generation biocompatible nanomaterials:** The development of novel nanomaterials that are fully biocompatible, biodegradable, and non-immunogenic will be critical. These materials must also support functional customization to meet the unique demands of diverse therapeutic targets [24].
- **Clinical translation and scalable manufacturing:** Bridging laboratory innovation with clinical applications requires standardization of protocols, scalable production methods, and streamlined regulatory pathways. Emphasis must be placed on improving reproducibility, safety assessments, and quality control measures.
- **Artificial intelligence and machine learning integration:** AI-driven modeling and machine learning tools will revolutionize the design of synthetic biological systems and nanocarriers. Predictive algorithms can optimize delivery kinetics, target specificity, and biocompatibility, accelerating the development pipeline.
- **Personalized medicine and theranostics:** SynBioNano systems offer promising platforms for personalized medicine by integrating diagnostic and therapeutic functions into a single nanodevice (theranostics). Tailored therapies based on patient-specific biomarkers could lead to significantly improved outcomes [25].
- **Ethical, regulatory, and environmental considerations:** As the field advances, addressing ethical concerns, biosafety, environmental impact, and public perception will be crucial. Developing robust international frameworks and guidelines for SynBioNano applications will ensure responsible innovation.

Conclusion

The fusion of synthetic biology and nanotechnology has opened a new era in targeted drug delivery, offering unprecedented precision, functionality, and adaptability. Through the SynBioNanoDesign approach, it is now possible to construct dynamic, programmable drug delivery systems that respond to specific biological cues, maximize therapeutic efficacy, and minimize side effects.

This review highlights the core principles, current applications, and emerging advantages of SynBioNano systems, while also recognizing the significant challenges that remain-ranging from biocompatibility and delivery efficiency to scalability and regulatory complexity. Despite these hurdles, rapid advancements in genetic circuit design, nanomaterial engineering, and systems biology continue to expand the capabilities of this multidisciplinary field.

Looking ahead, SynBioNanoDesign stands at the forefront of next-generation biomedical innovation. With ongoing research and cross-sector collaboration, it holds the potential to transform conventional drug delivery paradigms, enabling smarter, safer, and more personalized therapeutics for complex diseases such as cancer, neurological disorders, and chronic conditions.

Ultimately, SynBioNanoDesign offers not just a technological advance but a conceptual shift in how we engineer medicine-bringing together the logic of biology with the precision of materials science to realize truly intelligent therapeutic solutions.

Disclosure Statement

No potential conflict of interest was reported by the author.

References

1. Xia PF, Ling H, Foo JL, Chang MW. Synthetic genetic circuits for programmable biological functionalities. Biotechnol Adv. 2019; 37(6):107393. https://doi.org/10.1016/j.biotechadv.2019.04.015
2. Lombardo D, Kiselev MA, Caccamo MT. Smart nanoparticles for drug delivery application: development of versatile nanocarrier platforms in biotechnology and nanomedicine. J Nanomater. 2019;2019(1):3702518. https://doi.org/10.1155/2019/3702518
3. Singh AP, Biswas A, Shukla A, Maiti P. Targeted therapy in chronic diseases using nanomaterial-based drug delivery vehicles. Signal Transduct Target Ther. 2019;4(1):33. https://doi.org/10.1038/s41392-019-0068-3
4. Chenthamara D, Subramaniam S, Ramakrishnan SG, Krishnaswamy S, Essa MM, Lin FH, et al. Therapeutic efficacy of nanoparticles and routes of administration. Biomater Res. 2019;23(1):20. https://doi.org/10.1186/s40824-019-0166-x
5. Srinivasan M, Rajabi M, Mousa SA. Multifunctional nanomaterials and their applications in drug delivery and cancer therapy. Nanomater. 2015;5(4):1690-1703. https://doi.org/10.3390/nano5041690
6. Zhu L, Zhong W, Meng X, Yang X, Zhang W, Tian Y, et al. Polymeric nanocarriers delivery systems in ischemic stroke for targeted therapeutic strategies. J Nanobiotechnol. 2024;22(1):424. https://doi.org/10.1186/s12951-024-02673-4
7. Iranmanesh H, Subhash B, Glover DJ, Bedford NM. Proteins and peptides for functional nanomaterials: Current efforts and new opportunities. MRS Bull. 2020;45(12):1005-1016. https://doi.org/10.1557/mrs.2020.299
8. Qiao Y, Wan J, Zhou L, Ma W, Yang Y, Luo W, et al. Stimuli-responsive nanotherapeutics for precision drug delivery and cancer therapy. Wiley Interdiscip Rev Nanomed Nanobiotechnol. 2019;11(1):e1527. https://doi.org/10.1002/wnan.1527
9. Lussier F, Staufer O, Platzman I, Spatz JP. Can bottom-up synthetic biology generate advanced drug-delivery systems?. Trends Biotechnol. 2021;39(5):445-459. https://doi.org/10.1016/j.tibtech.2020.08.002
10. Gulfam M, Sahle FF, Lowe TL. Design strategies for chemical-stimuli-responsive programmable nanotherapeutics. Drug Discov Today. 2019;24(1):129-147. https://doi.org/10.1016/j.drudis.2018.09.019
11. Sahle FF, Gulfam M, Lowe TL. Design strategies for physical-stimuli-responsive programmable nanotherapeutics. Drug Discov Today. 2018;23(5):992-1006. https://doi.org/10.1016/j.drudis.2018.04.003
12. Sao R, Vaish R, Sinha N. Multifunctional drug delivery systems

https://doi.org/10.61577/jnd.2025.100004

using inorganic nanomaterials: a review. J Nanosci Nanotechnol. 2015;15(3):1960-1972. https://doi.org/10.1166/JNN.2015.9761
13. Uthaman S, Huh KM, Park IK. Tumor microenvironment-responsive nanoparticles for cancer theragnostic applications. Biomater Res. 2018;22(1):22. https://doi.org/10.1186/s40824-018-0132-z
14. Han L, Jiang C. Evolution of blood–brain barrier in brain diseases and related systemic nanoscale brain-targeting drug delivery strategies. Acta Pharm Sin B. 2021;11(8):2306-2325. https://doi.org/10.1016/j.apsb.2020.11.023
15. Gupta A, Mumtaz S, Li CH, Hussain I, Rotello VM. Combatting antibiotic-resistant bacteria using nanomaterials. Chem Soc Rev. 2019;48(2):415-427. https://doi.org/10.1039/c7cs00748e
16. Dou Y, Li C, Li L, Guo J, Zhang J. Bioresponsive drug delivery systems for the treatment of inflammatory diseases. J Contr Release. 2020;327:641-666. https://doi.org/10.1016/j.jconrel.2020.09.008
17. Li C, Liu X, Liu Y, Huang F, Wu G, Liu Y, et al. Glucose and H2O2 dual-sensitive nanogels for enhanced glucose-responsive insulin delivery. Nanoscale. 2019;11(18):9163-9175. https://doi.org/10.1039/c9nr01554j
18. Zhang RX, Li J, Zhang T, Amini MA, He C, Lu B, et al. Importance of integrating nanotechnology with pharmacology and physiology for innovative drug delivery and therapy–an illustration with firsthand examples. Acta Pharm Sin. 2018;39(5):825-844. https://doi.org/10.1038/aps.2018.33
19. Kitada T, DiAndreth B, Teague B, Weiss R. Programming gene and engineered-cell therapies with synthetic biology. Science. 2018;359(6376):eaad1067. https://doi.org/10.1126/science.aad1067
20. Jo SD, Ku SH, Won YY, Kim SH, Kwon IC. Targeted nanotheranostics for future personalized medicine: recent progress in cancer therapy. Theranostics. 2016;6(9):1362. https://doi.org/10.7150/thno.15335
21. Ozdemir T, Fedorec AJ, Danino T, Barnes CP. Synthetic biology and engineered live biotherapeutics: toward increasing system complexity. Cell Syst. 2018;7(1):5-16. https://doi.org/10.1016/j.cels.2018.06.008
22. Kyriakides TR, Raj A, Tseng TH, Xiao H, Nguyen R, Mohammed FS, et al. Biocompatibility of nanomaterials and their immunological properties. Biomed Mater. 2021;16(4):042005. https://doi.org/10.1088/1748-605X/abe5fa
23. Chubukov V, Mukhopadhyay A, Petzold CJ, Keasling JD, Martín HG. Synthetic and systems biology for microbial production of commodity chemicals. NPJ Syst Biol Appl. 2016;2(1):1-11. https://doi.org/10.1038/npjsba.2016.9
24. Huang H, Lovell JF. Advanced functional nanomaterials for theranostics. Adv Funct Mater. 2017;27(2):1603524. https://doi.org/10.1002/adfm.201603524
25. Kojima R, Aubel D, Fussenegger M. Novel theranostic agents for next-generation personalized medicine: small molecules, nanoparticles, and engineered mammalian cells. Curr Opin Chem Biol. 2015;28:29-38. https://doi.org/10.1016/j.cbpa.2015.05.021

https://doi.org/10.61577/jnd.2025.100004