STM JOURNALS

Research & Reviews: A Journal of
Drug Design & Discovery

ISSN: 2349-9036
Volume 12, Issue 2, 2025
May–August
DOI (Journal): 10.37591/RRJoDDD

https://journals.stmjournals.com/rrjoddd

Research RRJoDDD

Clone-Specific Drug Delivery Systems: Targeted Approaches and Future Clinical Applications

Suryakant Kumar[1], Kamalesh Mistry[2,*], Md. Zulphakar Ali[2], Md. Aftab Alam[3], Noorul Huda[2], Neha Nahid[3]

Abstract

Clone-specific drug delivery systems represent a transformative frontier in personalized medicine, addressing the longstanding challenge of clonal heterogeneity within diseases such as cancer, infectious diseases, and autoimmune disorders. Traditional drug delivery platforms often fail to discriminate between pathogenic and healthy cells, leading to systemic toxicity and reduced therapeutic efficacy. In contrast, clone-specific systems aim to selectively target and eliminate disease-driving cellular clones based on unique molecular signatures, thereby improving treatment outcomes and minimizing adverse effects. These approaches leverage advanced technologies such as single-cell RNA sequencing, multi-omics profiling, CRISPR-based gene modulation, and ligand-directed nanocarriers to identify and selectively engage pathogenic clones. Innovations in polymeric nanoparticles, exosome-based delivery platforms, and bioengineered liposomes have enabled the design of smart, responsive delivery systems that release therapeutic payloads in a spatially and temporally controlled manner. Clone-specific targeting holds promise in oncology, where subclonal tumor evolution contributes to therapeutic resistance and disease relapse. Similarly, persistent clonal populations in infectious diseases and autoreactive immune cells in autoimmune disorders present critical targets for these next-generation therapies. The integration of artificial intelligence and big data analytics further enhances the identification and mapping of disease-relevant clones, allowing for real-time therapeutic modulation. Despite these advancements, several challenges remain, including off-target effects, scalability, regulatory approval, and ethical concerns. Nevertheless, ongoing preclinical and clinical studies underscore the translational potential of clone-specific drug delivery systems as a cornerstone of precision medicine.

Keywords: Clone-specific drug delivery, targeted therapy, clonal heterogeneity, nanoparticles, single-cell sequencing, CRISPR, precision medicine, smart drug delivery, personalized therapeutics, exosome-based therapy

***Author for Correspondence**
Kamalesh Mistry
E-mail: drkamaleshmistry@gmail.com

[1]Research Scholar, Department of Pharmacy, Faculty of Pharmaceutical Science, Mewar University, Gangrar, Chittorgarh, Rajasthan, India
[2]Assistant Professor, Department of Pharmacy, Faculty of Pharmaceutical Science, Mewar University, Gangrar, Chittorgarh, Rajasthan, India
[3]Lecturer, Department of Pharmacy, Faculty of Pharmaceutical Science, Mewar University, Gangrar, Chittorgarh, Rajasthan, India

Received Date: April 10, 2025
Accepted Date: April 16, 2025
Published Date: July 12, 2025

Citation: Suryakant Kumar, Kamalesh Mistry, Md. Zulphakar Ali, Md. Aftab Alam, Noorul Huda, Neha Nahid. Clone-Specific Drug Delivery Systems: Targeted Approaches and Future Clinical Applications. Research & Reviews: A Journal of Drug Design & Discovery. 2025; 12(2): 21–29p.

INTRODUCTION

Clone-specific drug delivery systems have emerged as a novel and highly specialized approach in the era of precision medicine, particularly for addressing clonal heterogeneity in complex diseases [1]. Clonal heterogeneity refers to the existence of multiple genetically distinct subpopulations of cells within the same disease, which is particularly common in cancers, infectious diseases, and autoimmune disorders [2]. Traditional therapeutic interventions, while effective for some patients, often fail to eradicate all disease-relevant clones, leading to relapses, resistance, and poor long-term outcomes [3]. This limitation has driven the development of clone-specific strategies that aim to selectively target and eliminate pathogenic

cellular clones based on their unique molecular, genetic, or epigenetic profiles [4]. The conceptual framework of clone-specific drug delivery integrates cutting-edge technologies including single-cell omics, clonal barcoding, lineage tracing, and spatial transcriptomics to identify and characterize pathogenic clones. Once identified, targeted therapeutic systems are engineered to deliver drugs specifically to these clones using ligands, antibodies, or nucleic acid-based recognition systems [5]. Smart delivery vehicles such as stimuli-responsive nanoparticles, engineered liposomes, exosomes, and polymeric micelles further enhance the specificity, bioavailability, and pharmacokinetics of these agents. This approach is particularly transformative in the context of tumor evolution and treatment resistance, where dynamic clonal expansion can render standard therapies ineffective [6]. Clone-specific strategies offer a tailored intervention that evolves alongside disease progression, potentially preventing resistance and relapse. Furthermore, these systems hold promise in infectious diseases where latent or persistent clones evade immune detection, and in autoimmune diseases were autoreactive clones drive pathology [7]. As these technologies move toward clinical translation, challenges such as regulatory approval, safety, and large-scale manufacturing must be addressed. Nonetheless, clone-specific drug delivery represents a powerful convergence of molecular diagnostics, nanotechnology, and therapeutic engineering, redefining how complex diseases are treated at the cellular level [8].

MECHANISMS AND TECHNOLOGIES FOR CLONE-SPECIFIC TARGETING

Molecular Recognition and Clonal Identification Technologies

Clone-specific targeting begins with the ability to recognize and distinguish pathological cellular clones from healthy counterparts. Molecular recognition systems, including monoclonal antibodies, aptamers, and ligand-receptor interactions, are fundamental tools in this process. Monoclonal antibodies are particularly well-established, engineered to selectively bind to antigens uniquely expressed by target clones. Their high specificity and clinical applicability have made them central to targeted drug delivery in oncology and immunology [9]. Aptamers, short strands of nucleic acids with the ability to fold into specific 3D structures, serve as alternative recognition molecules. They offer several benefits, including chemical stability, low immunogenicity, and synthetic accessibility. Ligand-receptor binding systems also play a critical role, leveraging overexpressed receptors on the surface of pathogenic cells to direct therapies precisely to disease-associated clones. Advancements in single cell sequencing and multi-omics platforms have transformed our ability to profile and track clonal populations. These techniques enable high-resolution characterization of individual cells, uncovering genomic, transcriptomic, and epigenomic signatures that define distinct clones. Such profiling not only identifies therapeutic targets but also informs prognosis, therapeutic resistance, and relapse mechanisms. Moreover, CRISPR-Cas systems now allow for precise clonal tagging and functional genomic screens, enabling researchers to directly manipulate specific clones for therapeutic or investigational purposes (Figure 1) [10].

Nanotechnology-Enabled Targeted Delivery

Once pathogenic clones have been identified, precision drug delivery becomes essential for therapeutic success. Nanotechnology offers a suite of carrier platforms capable of being engineered for clone-specific targeting. Lipid nanoparticles (LNPs), polymeric nanoparticles, dendrimers, micelles, and extracellular vesicles such as exosomes are among the most prominent systems. These carriers can be modified on their surfaces with ligands, antibodies, or aptamers specific to clonal biomarkers, enhancing specificity and minimizing systemic toxicity [11].

Lipid nanoparticles have gained significant attention in recent years, especially with the rise of RNA-based therapies. Their ability to encapsulate nucleic acids and be functionalized with clone-specific ligands makes them valuable for gene silencing and mRNA delivery. Polymeric nanoparticles, known for their controlled-release properties and biocompatibility, can also be adapted for clonal targeting through chemical surface modifications. Dendrimers, with their branched architecture, provide a versatile platform for multifunctional drug delivery, though challenges in synthesis and toxicity remain. The growing use of exosomes as natural delivery vehicles is another emerging trend. Derived from cells, these vesicles exhibit innate biocompatibility and the ability to transfer therapeutic molecules directly to target clones. Table 1 provides a comparative overview of key technologies utilized in clone-specific targeting, summarizing their mechanisms, applications, strengths, and limitations [12].

Table 1. Technologies and mechanisms are used for clone-specific targeting.

Mechanism/ Technology	Function	Application Area	Advantages	Limitations	Reference
Monoclonal Antibodies	Target clone-specific surface antigens	Oncology, Autoimmune Disorders	High specificity, clinically validated	Immunogenicity, costly production	[13]
Aptamers	Nucleic acid-based recognition of target clones	Viral Infections, Hematologic Cancers	Stable, low immunogenicity	Lower in vivo stability than antibodies	[14]
Ligand-Receptor Interactions	Targeting based on overexpressed cell surface receptors	Targeted Drug Delivery, Cell Sorting	Versatile, adaptable to various carriers	Requires prior identification of unique receptors	[15]
Single-Cell Sequencing	Clonal identification via transcriptomics/genomics	Personalized Medicine, Diagnostics	High resolution, reveals heterogeneity	Costly, complex data interpretation	[16]
CRISPR/Cas Systems	Clonal tagging and gene editing	Functional Genomics, Therapeutics	Precision, dual diagnostic-therapeutic function	Off-target effects, ethical concerns	[17]
Lipid Nanoparticles (LNPs)	Delivery of drugs or RNA with clone-specific ligands	mRNA Therapy, Gene Silencing	Efficient encapsulation, scalable	Stability issues, hepatic accumulation	[18]
Polymeric Nanoparticles	Controlled release and targeted delivery	Cancer, Autoimmune Therapies	Biodegradable, surface modifiable	Complex synthesis	[19]
Exosomes and Extracellular Vesicles	Natural carriers for intercellular communication	Biomarker Delivery, Cell Therapy	Biocompatible, natural targeting ability	Low yield, heterogeneity	[20]
Dendrimers	Highly branched nanostructures for multi-functionalization	Gene Therapy, Targeted Chemotherapy	High loading capacity, tunable structure	Potential toxicity, synthesis challenges	[21]

ADVANCED DRUG DELIVERY SYSTEMS FOR CLONE TARGETING

Advanced drug delivery systems (DDS) have redefined the landscape of precision medicine by enabling high specificity targeting of pathological clones, particularly in heterogeneous diseases like cancer, chronic infections, and autoimmune disorders. Among the most explored platforms are liposomal and polymeric nanoparticles, which can be functionalized with targeting ligands such as antibodies, aptamers, or peptides. These surface modifications facilitate precise homing to clone-specific receptors or antigens, ensuring that therapeutic payloads are delivered exclusively to the cells of interest, thereby minimizing off-target toxicity and improving therapeutic indices [22]. Such modifications are highly customizable and support a variety of cargo, including small molecules, proteins, and nucleic acids. Exosome-based delivery systems have also garnered significant attention due to their endogenous origin, biocompatibility, and natural tropism toward specific tissues and cell types. These nanovesicles, secreted by nearly all cell types, can be engineered to carry therapeutic agents and direct them toward clonal populations using surface-displayed targeting moieties. In several preclinical studies, exosome-based delivery has demonstrated efficient internalization by target cells and enhanced bioavailability of therapeutics, especially for neurological and immunological conditions. Smart DDS technologies, including pH-responsive, enzyme-sensitive, and stimuli-responsive carriers, represent a new frontier in clone-specific drug delivery. These systems are designed to release their therapeutic payload in response to internal triggers such as the acidic microenvironment of tumors or the presence of clone-specific enzymes, ensuring precise spatiotemporal control over drug release. For instance, pH-responsive liposomes disassemble in the acidic pH typical of tumor environments, while enzyme-sensitive hydrogels degrade in the presence of proteases secreted by specific clones. Comparative studies have consistently shown that targeted DDS outperform their non-targeted counterparts in terms of pharmacokinetics, biodistribution, therapeutic efficacy, and toxicity profiles [23]. Table 2 outlines a detailed comparison of various delivery systems used in clone-specific targeting, highlighting their relative strengths and limitations across key pharmacological parameters.

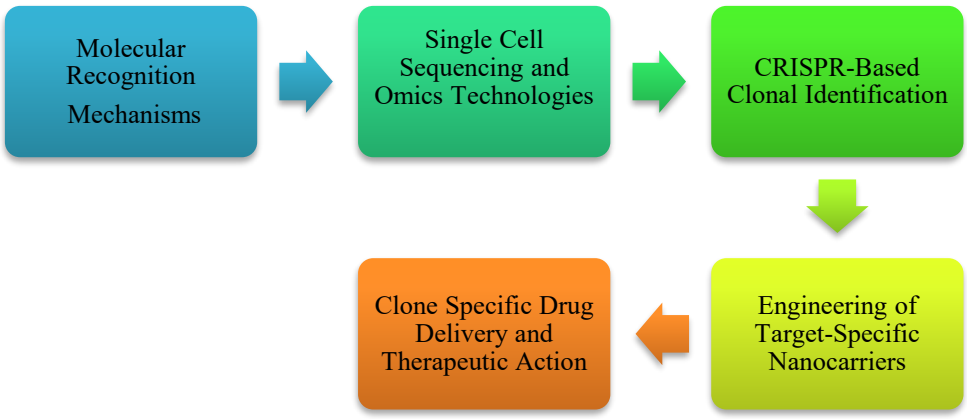

Figure 1. Mechanisms and technologies for clone-specific targeting.

Table 2. Comparative analysis of drug delivery systems for clone-specific targeting.

Delivery System	Targeting Strategy	Payload Types	Trigger/Stimulus	Pharmacokinetic Benefits	Clinical Relevance	Reference
Liposomal Nanoparticles	Surface-modified with antibodies/peptides	Small molecules, RNA, proteins	pH-sensitive, passive accumulation	Enhanced circulation time, reduced clearance	Approved and in late-stage clinical trials	[24]
Polymeric Nanoparticles	Ligand-mediated or stealth-coated	DNA, siRNA, chemotherapeutics	Enzyme-sensitive, heat-responsive	Sustained release, low immunogenicity	Multiple preclinical and early-phase trials	[25]
Exosomes	Engineered with clone-specific surface ligands	miRNA, siRNA, proteins	Cell-specific uptake	High bioavailability, immune evasion	Early clinical stage, promising in oncology	[26]
Stimuli-Responsive Hydrogels	Degradable in response to tumor enzymes or pH	Proteins, peptides	Enzyme-triggered degradation	Localized release, reduced systemic exposure	Preclinical and early clinical development	[27]
Dendrimers	Multivalent ligand attachment for enhanced binding	Nucleic acids, peptides	pH or redox sensitivity	Rapid internalization, targeted payload delivery	Preclinical studies in inflammatory diseases	[28]
Solid Lipid Nanoparticles	Passive or active targeting via surface engineering	Anti-inflammatory drugs, siRNA	Heat/light-responsive release	Stable formulation, good tissue penetration	Clinical evaluation of chronic lung disease	[29]
Viral Vectors (AAV, lentivirus)	Gene-specific clone targeting via receptor tropism	Gene editing constructs	Transcriptional control	Long-term expression, clonal integration	Approved in gene therapies (e.g., SMA)	[30]

CLINICAL APPLICATIONS AND TRANSLATIONAL RESEARCH

Clone-specific drug delivery systems (DDS) have begun to demonstrate transformative potential in clinical settings across multiple disease domains, including oncology, infectious diseases, and immune-mediated disorders. One of the most compelling applications is in oncology, where the complexity of tumor heterogeneity often leads to the emergence of drug-resistant subclones during therapy [31]. These resistant subclones can evade traditional chemotherapeutics, leading to treatment failure and relapse. Clone-specific DDS, designed to target these subpopulations precisely, have shown promise in

overcoming resistance by ensuring therapeutic agents are directed to even the most elusive malignant cell populations. This strategy is increasingly being incorporated in personalized cancer therapy frameworks, supported by genomic profiling and molecular diagnostics. In the context of infectious diseases, chronic and recurrent infections such as tuberculosis, hepatitis B, and HIV present a major clinical challenge due to the persistence of specific microbial clones that are resistant to conventional antimicrobials. Clone-specific approaches enable the targeted delivery of antivirals or antibiotics directly to infected host cells or microbial reservoirs, improving therapeutic efficacy while reducing systemic toxicity and resistance development [32]. Nanocarrier systems conjugated with ligands for microbial surface antigens or host receptors have been explored in clinical and preclinical trials with encouraging results. Similarly, in autoimmune and genetic disorders, the identification of pathogenic immune clones has facilitated the design of targeted delivery systems that selectively eliminate autoreactive T or B cells, sparing normal immune function. This approach is particularly relevant in diseases like systemic lupus erythematosus, multiple sclerosis, and type 1 diabetes, where immune dysregulation is driven by specific cell populations. Moreover, gene therapy and RNA-based delivery tools have enhanced the precision of such interventions. Numerous clinical trials are underway to evaluate the safety, efficacy, and translational viability of clone-specific DDS across different disease models. Real-world case studies have also highlighted their potential to improve outcomes in refractory and rare diseases [33]. Table 3 summarizes various clinical applications and ongoing investigations in this domain.

Table 3. Clinical applications of clone-specific drug delivery systems.

Disease Area	Target Clone Type	Therapeutic Strategy	Delivery Platform	Clinical Status	Advantage	Reference
Oncology	Drug-resistant tumor subclones	Monoclonal antibody-drug conjugates (ADCs), RNA delivery	Lipid nanoparticles, ADCs	Multiple Phase II/III trials	Overcomes chemoresistance, personalized targeting	[34]
Hematologic Cancers	Leukemic or lymphoma-specific clones	siRNA or CAR-T cell targeting	Viral vectors, exosomes	FDA-approved and investigational stages	High clonal specificity, long-term remission potential	[33]
Tuberculosis	Persistent Mycobacterium tuberculosis clones	Nanoparticle-encapsulated antibiotics	Polymeric nanoparticles	Early-phase clinical trials	Reduces drug dosage, enhances efficacy	[35]
HIV/AIDS	Latent viral clones in CD4+ T cells	CRISPR-mediated excision, targeted antivirals	Lipid-based carriers, aptamer systems	Preclinical and animal model studies	Curative potential, minimal off-target effects	[36]
Hepatitis B	Hepatocyte-resident viral clones	mRNA therapy, RNA interference	LNPs with liver-specific ligands	Phase I/II clinical trials	Suppresses viral replication, minimal hepatotoxicity	[37]
Autoimmune Disorders	Autoreactive B/T cell clones	Clone-specific immunosuppressants, RNA therapeutics	Dendrimers, antibody-conjugates	Ongoing Phase I trials	Preserves normal immune function	[38]
Genetic Disorders	Mutant gene-expressing clones (e.g., CF, SMA)	Gene correction using CRISPR or mRNA	AAV vectors, exosomes	Approved and experimental therapies	Durable expression, single-dose treatment possibility	[39]
Neurodegenerative Diseases	Misfolded protein-expressing neuronal clones	siRNA, antisense oligonucleotides	Liposomes, hydrogels	Clinical tria for AL Huntington's	Delays progression, clone-specific gene silencing	[40]
Rare Metabolic Disorders	Enzyme-deficient cell clones	Gene therapy, enzyme replacement via clone-targeted carriers	Viral vectors, synthetic carriers	Expanded access and clinical trials	Sustained enzyme delivery, reduced immune response	[41]

FUTURE PERSPECTIVES

The landscape of clone-specific drug delivery systems is evolving rapidly, driven by the convergence of technological innovation, precision medicine, and systems biology. Looking ahead, one of the most transformative advancements anticipated is the integration of artificial intelligence (AI) and machine learning into the design and implementation of these therapies [42]. By harnessing real-time data from single-cell sequencing, spatial transcriptomics, and multi-omics platforms, AI can facilitate high-resolution clonal mapping and enable predictive modeling of therapeutic response. This would allow the development of personalized treatment regimens that adapt dynamically to changes in clonal heterogeneity, especially in diseases like cancer, where resistant subclones often lead to relapse. Despite these advancements, several key challenges remain [43]. One significant barrier is the scalability of clone-specific therapies. The manufacturing processes for such targeted systems are often complex, requiring precise surface modifications, ligand attachments, and stringent quality control to maintain therapeutic specificity. These systems must also be produced at scale without compromising reproducibility or safety, which is a formidable task in current pharmaceutical manufacturing pipelines. Furthermore, the regulatory frameworks for these emerging therapies are still developing. Regulatory bodies such as the FDA and EMA are working to adapt to novel platforms that combine drug delivery with gene editing, RNA modulation, or immunotherapy. This includes evaluating potential risks such as off-target effects, immune reactions, and long-term genetic alterations [44].

Ethical considerations also pose a major challenge in the future deployment of clone-specific drug delivery systems. The ability to target specific clonal populations, particularly in the immune system or in germline cells, raises complex questions about therapeutic boundaries, equity in access, and unintended consequences. The ethical implications of manipulating clonal behavior, especially in early-stage or pre-symptomatic individuals, require careful consideration by medical ethicists, policymakers, and the broader public [45]. In addition, future innovation is likely to include hybrid systems that combine clone-targeting capabilities with gene editing or RNA interference technologies, thereby enhancing therapeutic potency and precision. These systems hold promises for more comprehensive disease control, but their complexity adds further hurdles in terms of design, regulation, and implementation. Ultimately, multidisciplinary collaboration between biomedical researchers, clinical practitioners, regulatory experts, and ethical committees will be crucial in navigating the path forward. Only through such integrative approaches can clone-specific drug delivery systems fulfill their potential to transform therapeutic paradigms across a range of diseases [46].

CONCLUSIONS

Clone-specific drug delivery systems represent a significant advancement in the field of precision medicine, offering an unprecedented level of therapeutic selectivity by targeting disease-associated clonal populations. Through the integration of technologies such as single-cell sequencing, ligand-directed targeting, and smart drug carriers, these systems are capable of distinguishing between pathological and non-pathological cell clones with high specificity. This capability not only enhances the efficacy of treatment but also significantly reduces off-target effects and systemic toxicity, a major limitation in conventional therapies. The emergence of novel nanocarriers, exosome-based platforms, and stimuli-responsive delivery systems further enhances the ability to deliver therapeutic agents precisely where they are needed within the complex biological environment. Clinical applications are already taking shape, particularly in oncology, where resistant subclones often lead to treatment failure. The selective eradication of such clones could improve long-term patient outcomes and limit disease recurrence. Similar strategies are being explored in chronic infections, autoimmune diseases, and genetic disorders where clonal cell populations play a central role. While the promise of clone-specific systems is compelling, several challenges persist, including issues related to scalability, regulatory approval, cost-effectiveness, and ethical implications. Despite these hurdles, the future of clone-specific drug delivery is promising. The convergence of artificial intelligence, bioinformatics, and systems biology is expected to accelerate the identification of clonal targets and streamline the design of delivery systems. Continued interdisciplinary collaboration and innovation will be key in translating these cutting-edge approaches from bench to bedside. As research in this field advances, clone-specific drug

delivery systems have the potential to reshape therapeutic strategies and open new frontiers in individualized patient care.

REFERENCES

1. Peer D, Karp JM, Hong S, Farokhzad OC, Margalit R, Langer R. Nanocarriers as an emerging platform for cancer therapy. Nat Nanotechnol. 2007;2(12):751–60.
2. Bae YH, Park K. Targeted drug delivery to tumors: Myths, reality and possibility. J Control Release. 2011;153(3):198–205.
3. Blanco E, Shen H, Ferrari M. Principles of nanoparticle design for overcoming biological barriers to drug delivery. Nat Biotechnol. 2015;33(9):941–51.
4. Wang AZ, Langer R, Farokhzad OC. Nanoparticle delivery of cancer drugs. Annu Rev Med. 2012;63:185–98.
5. Rosenblum D, Joshi N, Tao W, Karp JM, Peer D. Progress and challenges towards targeted delivery of cancer therapeutics. Nat Commun. 2018;9(1):1410.
6. Barenholz Y. Doxil® the first FDA-approved nano-drug: Lessons learned. J Control Release. 2012;160(2):117–34.
7. Zhang Y, Zhang RX, Wang Y, Fu CY, Chen J. Ligand-based targeted therapy: Molecular basis, design strategies and recent progress. J Drug Target. 2020;28(4):283–301.
8. Yu B, Tai HC, Xue W, Lee LJ, Lee RJ. Receptor-targeted nanocarriers for therapeutic delivery to cancer. Mol Membr Biol. 2010;27(7):286–98.
9. Allen TM, Cullis PR. Liposomal drug delivery systems: From concept to clinical applications. Adv Drug Deliv Rev. 2013;65(1):36–48.
10. Ramasamy T, Ruttala HB, Chitrapriya N, Poudel BK, Youn YS, Kim JO. Engineered nanocarriers for improved drug delivery. J Control Release. 2017;263:153–70.
11. Wang J, Wang Y, Xiong H, Li M, Li J. Aptamer-conjugated nanocarriers for targeted cancer therapy. Curr Med Chem. 2011;18(25):4165–74.
12. Torchilin VP. Passive and active drug targeting: Drug delivery to tumors as an example. Handb Exp Pharmacol. 2010;(197):3–53.
13. Wang Y, Xie Y, Kilchrist KV, Li J, Duvall CL. Nanocarriers for precision delivery of drugs and nucleic acids. J Control Release. 2019;313:147–59.
14. Zhang Y, Chan HF, Leong KW. Advanced materials and processing for drug delivery: The past and the future. Adv Drug Deliv Rev. 2013;65(1):104–20.
15. Min Y, Caster JM, Eblan MJ, Wang AZ. Clinical translation of nanomedicine. Chem Rev. 2015;115(19):11147–90.
16. Choi KY, Liu G, Lee S, Chen X. Theranostic nanoplatforms for simultaneous cancer imaging and therapy: current approaches and future perspectives. Nanoscale. 2012;4(2):330–42.
17. Kamaly N, Yameen B, Wu J, Farokhzad OC. Degradable controlled-release polymers and polymeric nanoparticles: Mechanisms of controlling drug release. Chem Rev. 2016;116(4):2602–63.
18. He C, Lu JM, Lin WY, Jiang Z, Xia Y, Li D, et al. Nanomedicine applications of protein–polymer conjugates. J Control Release. 2016;240:67–81.
19. He H, Liu L, Morin EE, Liu M, Schwendeman A. Mechanisms of injectable PLGA drug delivery systems for cancer therapy. Adv Drug Deliv Rev. 2020;159:264–83.
20. Zhong Y, Goltsche K, Cheng L, Xie F, Meng F, Deng C, et al. Long-circulating, biodegradable polymeric nanoparticles for targeted drug delivery in cancer therapy. Chem Commun. 2014;50(85):12873–6.
21. Mullard A. FDA approves landmark CAR-T therapy. Nat Rev Drug Discov. 2017;16(10):669.
22. Ledford H. CRISPR treatment inserted directly into the body for first time. Nature. 2020;579(7797):185.
23. Hynes RO. The extracellular matrix: Not just pretty fibrils. Science. 2009;326(5957):1216–9.
24. Liu Z, Zhang L, Chen Y, Wang Q. Overcoming barriers for nanocarrier-based tumor targeting. Chem Soc Rev. 2020;49(2):227–48.

25. Wang M, Thanou M. Targeting nanoparticles to cancer. Pharmacol Res. 2010;62(2):90–9.
26. Riehle RD, Cornea V, Sullenger BA. Harnessing aptamers to image and treat cancer. Pharmacol Ther. 2018;181:126–38.
27. Dostalek M, Gardner I, Gurbaxani BM, Rose RH, Chetty M. Pharmacokinetics, pharmacodynamics and physiologically-based pharmacokinetic modelling in monoclonal antibody drug development. Clin Pharmacokinet. 2017;56(6):591–609.
28. Ravi K, Kumar VR, Rathi S, Singh S, Patel B, Singh S, et al. A Comprehensive Review on Ulcer and Their Treatment. Zhongguo Ying Yong Sheng Li Xue Za Zhi. 2023 Dec 21;39:e20230006. doi: 10.62958/j.cjap.2023.006. PMID: 38755116.
29. Singh V, Arora S, Akram W, Alam S, Kumari L, Kumar N, et al. Involvement of molecular mechanism and biological activities of Pemirolast: A therapeutic review. New Emirates Med J. 2024;5:e02506882308410. https://doi.org/10.2174/0102506882308410240607053814
30. Rajput DS, Gupta N, Singh S, Sharma B. A comprehensive review: personalized medicine for rare disease cancer treatment. Zhongguo Ying Yong Sheng Li Xue Za Zhi. 2023 Dec 23;39:e20230008. doi: 10.62958/j.cjap.2023.008. PMID: 38830754.
31. Singh S, Chaurasia A, Rajput DS, Gupta N. Mucoadhesive drug delivery system and there future prospective: are a promising approach for effective treatment? Zhongguo Ying Yong Sheng Li Xue Za Zhi. 2023 Dec 20;39:e20230005. doi: 10.62958/j.cjap.2023.005. PMID: 38751344.
32. Kumar S, Saha S, Sharma B, Singh S, Shukla P, Mukherjee S, et al. The role of resveratrol in Alzheimer's disease: A comprehensive review of current research. Curr Funct Foods. 2023;2(2):e121223224364. https://doi.org/10.2174/0126668629269244231127071411
33. Patel S, Ismail Y, Singh S, Rathi S, Shakya S, Patil SS, et al. Recent innovations and future perspectives in transferosomes for transdermal drug delivery in therapeutic and pharmacological applications. Zhongguo Ying Yong Sheng Li Xue Za Zhi. 2024 Oct 24;40:e20240031. doi: 10.62958/j.cjap.2024.031. PMID: 39442957.
34. Vaghela MC, Rathi S, Shirole RL, Verma J, Shaheen, Panigrahi S, et al. Leveraging AI and machine learning in six-sigma documentation for pharmaceutical quality assurance. Zhongguo Ying Yong Sheng Li Xue Za Zhi. 2024 Jul 18;40:e20240005. doi: 10.62958/j.cjap.2024.005. PMID: 39019923.
35. Singh S, Chaurasia A, Rajput DS, Gupta N. An overview on mucoadhesive buccal drug delivery systems & approaches: A comprehensive review. Afr J Biol Sci (South Afr). 2024;6(5):522–41. https://doi.org/10.33472/AFJBS.6.5.2024.522-541
36. Ravikkumar VR, Patel BD, Rathi S, Parthiban S, Upadhye MC, Shah AM, Rehan SSA, Samanta S, Singh S. Formulation and Evaluation of Drumstick Leaves Tablet as An Immunomodulator. Zhongguo Ying Yong Sheng Li Xue Za Zhi. 2024 Jun 21;40:e20240004. doi: 10.62958/j.cjap.2024.004. PMID: 38902996.
37. Dewangan HK, Singh S, Mishra R, Dubey RK. A review on application of nanoadjuvant as delivery system. Int J Appl Pharm. 2020;12(4):24–33.
38. Singh S, Chaurasia A, Gupta N, Rajput DS. Effect of formulation parameters on enalapril maleate mucoadhesive buccal tablet using quality by design (QbD) approach. Zhongguo Ying Yong Sheng Li Xue Za Zhi. 2024 Jun 27;40:e20240003. doi: 10.62958/j.cjap.2024.003. PMID: 38925868.
39. Patel SK, Prathyusha S, Kasturi M, Godse KC, Singh R, Rathi S, et al. Optimizing irbesartan fast dissolving tablets using natural polysaccharides for enhanced drug delivery and patient compliance. Int Res J Multidiscip Scope (IRJMS). 2025;6(1):1181–90. https://doi.org/10.47857/irjms.2025.v06i01.02542
40. Koo H, Huh MS, Ryu JH, Lee DE, Sun IC, Choi K, et al. Nanoprobes for biomedical imaging in cancer. Chem Soc Rev. 2011;40(7):2653–74.
41. Batrakova EV, Kim MS. Using exosomes, naturally-equipped nanocarriers, for drug delivery. J Control Release. 2015;219:396–405.
42. Gill S, June CH. Going viral: Chimeric antigen receptor T-cell therapy for hematological malignancies. Immunol Rev. 2015;263(1):68–89.
43. Doudna JA, Charpentier E. The new frontier of genome engineering with CRISPR-Cas9. Science. 2014;346(6213):1258096.

44. Cox DBT, Platt RJ, Zhang F. Therapeutic genome editing: Prospects and challenges. Nat Med. 2015;21(2):121–31.
45. Shen Y, Jin E, Zhang B, Liu L, Zhang Q. Smart stimuli-responsive nanocarriers for drug delivery. Curr Pharm Des. 2019;25(7):752–65.
46. Wang F, Chen L, Zhang R, Chen Z. A review on nanocarriers for the delivery of small molecule drugs in cancer therapy. Chin Chem Lett. 2020;31(3):641–8.

