



REVIEW ON ADVANCED DRUG DELIVERY SYSTEMS: INNOVATIONS IN FORMULATION AND DELIVERY TECHNOLOGIES

Sanket J Soni*¹, Ankitkumar N Patel²

*¹ Associate Director, Department of Project and Portfolio Management, Amneal Pharmaceuticals, New Jersey, USA.

² Director of Formulation, Department of Formulation R&D, Amneal Pharmaceuticals, New Jersey, USA.



Received: 19 June 2023 Revised: 14 July 2023 Accepted: 10 Aug 2024

Abstract

Advanced drug delivery systems (DDS) have transformed the pharmaceutical landscape, offering innovative solutions to enhance therapeutic outcomes and patient compliance. This review explores recent advancements in formulation technologies and delivery mechanisms, focusing on nanotechnology, polymeric systems, solid lipid nanoparticles (SLNs), and microparticle-based formulations. Nanotechnology has enabled the development of nanoparticles, liposomes, and nanocrystals that enhance drug solubility, stability, and targeted delivery. Polymeric drug delivery systems, including biodegradable polymers, offer sustained drug release, significantly improving chronic disease management and cancer therapy. SLNs and nanostructured lipid carriers (NLCs) provide stable matrices for drug encapsulation, particularly for lipophilic drugs, while microparticle-based formulations offer controlled and sustained drug release, reducing dosing frequency and enhancing patient compliance. Furthermore, novel delivery mechanisms such as transdermal systems, oral controlled release systems, targeted drug delivery, and inhalable therapies have expanded the possibilities for non-invasive, patient-friendly drug administration. Challenges in scaling up production, regulatory approval, and long-term safety remain significant, but emerging technologies like nanobots and bioengineered tissues hold promise for the future of personalized medicine. As these advanced delivery platforms continue to evolve, they are poised to revolutionize drug delivery, offering more precise, effective, and patient-centric treatments.

Keywords: Advanced drug delivery systems, Nanotechnology, Polymeric systems, Solid lipid nanoparticles, Microparticle formulations

This article is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License. Copyright © 2024 Author(s) retains the copyright of this article.



*Corresponding Author

Sanket J Soni

DOI: <https://doi.org/10.37022/tjmdr.v4i3.635>

Produced and Published by

South Asian Academic Publications

Introduction

Drug Delivery Systems (DDS) are technologies designed to transport therapeutic substances in the body to achieve a desired therapeutic effect. The primary goal of DDS is to deliver drugs in a controlled manner, ensuring that the active ingredients are released at the right place, at the right time, and in the right concentration. DDS plays a crucial role in modern medicine by enhancing the efficacy of treatments, reducing side effects, and improving patient compliance [1]. These systems are integral to the successful administration of a wide range of therapeutics, including small molecules, proteins, peptides, and nucleic

acids, across various routes, such as oral, intravenous, transdermal, and inhalational [2].

The evolution of drug delivery technologies has been driven by the need to improve the therapeutic outcomes of medications. Initially, drug delivery was limited to simple formulations like tablets and injections, with minimal control over drug release and distribution [3]. Over the decades, advancements in material science, chemistry, and biotechnology have led to the development of more sophisticated DDS, such as controlled-release formulations, transdermal patches, and targeted delivery systems [4]. These innovations have enhanced the effectiveness of drugs and opened new therapeutic possibilities, particularly in treating chronic and complex diseases. The progression from conventional delivery methods to advanced technologies marks a significant shift in how drugs are administered and how treatment outcomes are optimised [5].

Need for Advanced Drug Delivery Systems

Traditional drug delivery methods, while effective in many cases, often face significant limitations. These include poor bioavailability, rapid clearance from the body, lack of site-

specific targeting, and undesirable side effects. Oral delivery, for example, may suffer from degradation of the drug in the gastrointestinal tract, leading to reduced efficacy. Similarly, intravenous administration can result in systemic distribution, causing side effects in non-target tissues. These challenges underscore the need for more advanced drug delivery systems to overcome these limitations and provide more effective, safe, and patient-friendly treatment options [6]. Advanced Drug Delivery Systems (DDS) have been developed to address the shortcomings of traditional methods. These systems incorporate innovative technologies, such as nanoparticles, liposomes, and biodegradable polymers, to improve the delivery and efficacy of drugs. Advanced DDS can provide controlled and sustained release of drugs, target specific tissues or cells, and reduce the frequency of dosing. For example, targeted drug delivery systems can direct therapeutic agents specifically to diseased cells, minimizing exposure to healthy tissues and thereby reducing side effects [7]. Additionally, controlled-release formulations can maintain therapeutic drug levels over extended periods, improving patient adherence and treatment outcomes. These advancements are critical in managing diseases that require precise and sustained drug administration, such as cancer, diabetes, and neurological disorders [8].

2. Scope and Objectives

This review aims to provide an in-depth examination of the recent innovations in drug formulation and delivery technologies. As the field of drug delivery continues to evolve, it is essential to understand the latest advancements and how they are being applied to improve therapeutic outcomes. This review will explore the cutting-edge technologies shaping the future of drug delivery, including novel materials, new delivery mechanisms, and integrated systems that combine diagnosis and therapy.

3. Innovations in Formulation Technologies

Nanotechnology in Drug Formulation

Use of Nanoparticles, Liposomes, and Nanocrystals in Enhancing Drug Solubility and Stability

Nanotechnology has profoundly impacted drug formulation by enabling the creation of nanoparticles, liposomes, and nanocrystals that can significantly enhance the solubility and stability of drugs. Nanoparticles, typically ranging from 1 to 100 nanometers in size, offer a large surface area-to-volume ratio, which can increase the dissolution rate of poorly soluble drugs. Liposomes, spherical vesicles composed of lipid bilayers, encapsulate hydrophilic and hydrophobic drugs, protecting them from degradation and improving their bioavailability. Nanocrystals, which are crystalline drug particles reduced to the nanometer scale, can also enhance drug solubility and enable faster absorption. These Nano formulations are particularly valuable for drugs poorly soluble in water or prone to rapid degradation, as they improve the drug's

stability and bioavailability, enhancing its therapeutic efficacy[9].

Advantages of Nano Formulations in Targeted Delivery and Controlled Release

One of the critical advantages of Nano formulations is their ability to provide targeted drug delivery and controlled release. Nanoparticles can be engineered to target specific tissues or cells, reducing the impact on healthy tissues and minimizing side effects. This is especially important in the treatment of diseases like cancer, where targeted delivery can concentrate the therapeutic agent directly at the tumour site, improving treatment efficacy while reducing systemic toxicity. Additionally, Nano formulations can be designed to release their payload over an extended period, maintaining therapeutic drug levels in the body and reducing the frequency of dosing. This controlled release mechanism not only enhances patient compliance but also provides a more consistent therapeutic effect [10].

Polymeric Drug Delivery Systems

Role of Biodegradable Polymers in Sustained Drug Release

Biodegradable polymers play a crucial role in the development of sustained-release drug delivery systems. These polymers degrade naturally within the body, gradually releasing the drug over time. Common biodegradable polymers used in drug delivery include Polylactic acid (PLA), polyglycolic acid (PGA), and their copolymer, poly (lactic-co-glycolic acid) (PLGA). These polymers can be tailored to degrade at different rates, allowing for precise control of drug release. This sustained release is particularly beneficial in managing chronic diseases where maintaining consistent drug levels is critical. It reduces the need for frequent dosing, improves patient adherence, and minimizes the peaks and troughs in drug concentration that can lead to side effects or reduced efficacy [11].

Applications in Cancer Therapy, Vaccines, and Chronic Disease Management

Polymeric drug delivery systems have found wide application in various therapeutic areas, including cancer therapy, vaccines, and chronic disease management. In cancer therapy, biodegradable polymers are used to deliver chemotherapeutic agents directly to tumours, enhancing the concentration of the drug at the target site while minimizing systemic exposure. In vaccines, polymeric particles can be used as adjuvants to enhance the immune response or as carriers for sustained antigen release, improving the efficacy of the vaccine. For chronic diseases, such as diabetes or cardiovascular conditions, sustained-release formulations can help maintain therapeutic drug levels over extended periods, reducing the burden of frequent dosing and improving overall disease management [12].

Solid Lipid Nanoparticles (SLNs) and Nanostructured Lipid Carriers (NLCs)

Mechanisms and Benefits in Drug Formulation Solid Lipid Nanoparticles (SLNs) and Nanostructured Lipid Carriers (NLCs) represent advanced lipid-based delivery systems that offer several advantages in drug formulation.

SLNs comprise solid lipids that remain solid at room and body temperature, providing a stable matrix for drug encapsulation. [13] NLCs, on the other hand, are a newer generation of lipid carriers that combine solid and liquid lipids, creating a more flexible structure that can accommodate higher drug loading and reduce drug expulsion during storage. SLNs and NLCs protect the drug from degradation, enhance its bioavailability, and allow for controlled release. These systems are particularly useful for delivering lipophilic drugs and applications requiring prolonged drug release [14].

Examples of SLNs and NLCs in Commercial Drug Products SLNs and NLCs have been incorporated into several commercial drug products, demonstrating their effectiveness in various therapeutic applications. For example, SLNs are used in the formulation of topical products for skin delivery, where they provide a sustained release of active ingredients and improve skin hydration [16]. NLCs have been utilized in oral and injectable formulations to enhance the bioavailability of poorly soluble drugs. These lipid-based carriers have also been employed in cosmetic products, leveraging their ability to deliver active compounds effectively while enhancing the stability and shelf-life of the formulation [17].

Microparticle-Based Formulations

Development and Application of Microparticles in Controlled and Sustained Drug Release Microparticle-based formulations involve the use of particles ranging from 1 to 1000 micrometres in size to deliver drugs in a controlled and sustained manner. These microparticles are often made from biodegradable polymers that gradually break down in the body, releasing the drug over an extended period [18]. The development of microparticles involves techniques such as spray drying, solvent evaporation, and Coacervation, which allow for precise control over particle size, drug loading, and release kinetics. Microparticles are used in various applications, including injectable depots, providing a long-acting release of drugs such as hormones, peptides, or vaccines [19].

Benefits in Reducing Dosing Frequency and Improving Patient Compliance One of the significant benefits of microparticle-based formulations is their ability to reduce dosing frequency, which is particularly valuable for drugs that require long-term administration. By providing a sustained release of the drug, these formulations reduce the need for frequent injections or oral dosing, thereby improving patient compliance. This is especially important in chronic conditions, where consistent medication adherence is crucial for effective disease management [20]. Additionally, the controlled release provided by microparticles helps maintain stable drug levels in the bloodstream, reducing the risk of side effects associated with peak concentrations and ensuring a more consistent therapeutic effect [21].

Table 1: Summarising Innovations in Formulation Technologies

Category	Subcategory	Key Benefits
Nanotechnology in Drug Formulation	Use of Nanoparticles, Liposomes, and Nanocrystals	- Enhanced solubility and stability - Protection from degradation - Improved bioavailability
	Advantages of Nano formulations in Targeted Delivery and Controlled Release	- Targeted drug delivery to specific tissues or cells - Reduced systemic toxicity - Sustained and controlled drug release
Polymeric Drug Delivery Systems	Role of Biodegradable Polymers in Sustained Drug Release	- Reduced dosing frequency - Consistent therapeutic levels - Improved patient adherence
	Applications in Cancer Therapy, Vaccines, and Chronic Disease Management	- Enhanced drug concentration at the target site - Improved vaccine efficacy - Long-term management of chronic conditions
Solid Lipid Nanoparticles (SLNs) and Nanostructured Lipid Carriers (NLCs)	Mechanisms and Benefits in Drug Formulation	- Enhanced drug stability - Controlled and sustained release - Higher drug loading capacity (in NLCs)
	Examples of SLNs and NLCs in Commercial Drug Products	- Improved skin hydration (topical) - Enhanced bioavailability (oral and injectable) - Prolonged shelf-life
Microparticle-Based Formulations	Development and Application of Microparticles in Controlled and Sustained Drug Release	- Long-acting drug release - Precise control over release kinetics - Versatility in formulation (e.g., injectable, oral)
	Benefits in Reducing Dosing Frequency and Improving	- Reduced need for frequent dosing - Consistent therapeutic effect

	Patient Compliance	- Enhanced patient adherence, especially in chronic disease management
--	--------------------	--

3. Novel Drug Delivery Mechanisms

Transdermal Drug Delivery Systems

Advances in Patches, Microneedles, and Other Transdermal Technologies Transdermal drug delivery systems have seen significant advancements, particularly in the development of patches, microneedles, and other innovative technologies. Traditional transdermal patches deliver drugs through the skin by passive diffusion, but newer technologies enhance drug absorption and broaden the range of medicines that can be delivered transdermally [22]. Microneedles, for instance, create microscopic channels in the skin, allowing larger molecules or vaccines to be delivered painlessly and effectively. These technologies are particularly beneficial for administering drugs that require steady, controlled release, such as hormones or pain medications, and are expanding the possibilities for non-invasive drug administration [23].

Benefits of Non-Invasive Drug Administration and Improved Patient Comfort One of the primary benefits of transdermal drug delivery systems is their non-invasive nature, which significantly improves patient comfort and compliance. By avoiding the gastrointestinal tract and bypassing first-pass metabolism, transdermal systems can provide more consistent drug levels in the bloodstream [24]. This method also reduces the risk of gastrointestinal side effects and allows for easier administration, particularly in chronic conditions requiring long-term treatment. The convenience and comfort of transdermal systems make them an attractive option for patients and healthcare providers, leading to better adherence to treatment regimens [25].

Oral Controlled Release Systems

Innovations in Gastro retentive, Pulsatile, and Osmotic-Controlled Release Systems Oral controlled release systems have evolved to include a variety of innovative technologies that enhance drug bioavailability and optimize dosing schedules. Gastro retentive systems are designed to remain in the stomach for extended periods, ensuring that drugs with narrow absorption windows are fully absorbed. On the other hand, Pulsatile release systems are engineered to release the drug at specific times, mimicking the body's natural rhythms and improving therapeutic outcomes in diseases like asthma or arthritis. Osmotic-controlled release systems use osmotic pressure to deliver drugs at a constant rate, providing a steady release over an extended period. These innovations improve drug pharmacokinetic profiles and reduce dosing frequency, making treatment more convenient for patients [26].

Enhanced Bioavailability and Reduced Dosing Frequency, Controlled release systems, offer significant advantages in enhancing the bioavailability of drugs, particularly those that are poorly soluble or have short half-lives. By controlling the drug release rate, these systems ensure that a therapeutic dose is maintained in the bloodstream for extended periods, reducing the need for frequent dosing. This is particularly beneficial for chronic conditions where consistent drug levels are necessary to manage symptoms effectively. Additionally, controlled release systems reduce dosing frequency and improve patient adherence to treatment regimens, leading to better health outcomes [27].

Targeted Drug Delivery Systems

Active and Passive Targeting Mechanisms (e.g., Ligand-Receptor Targeting, pH-sensitive Systems) Targeted drug delivery systems represent a significant advancement in the precision of drug therapy. These systems can be designed with active targeting mechanisms, such as ligand-receptor interactions, where drugs are directed to specific cells or tissues by attaching ligands that bind to receptors expressed on the target cells. Like pH-sensitive systems, passive targeting mechanisms exploit the unique environment of diseased tissues (e.g., the acidic environment of tumours) to release the drug specifically at the site of action. These targeted systems are particularly useful in oncology, where minimizing damage to healthy tissues while maximising the drug's impact on cancer cells is critical [28].

Application in Oncology, Infectious Diseases, and Personalized Medicine The application of targeted drug delivery systems is widespread, with significant use in oncology, where precision in drug delivery can significantly impact treatment success. In infectious diseases, targeted systems can deliver antibiotics directly to the site of infection, reducing the risk of antibiotic resistance. Moreover, these systems are crucial in developing personalized medicine, where treatments are tailored to the individual patient's genetic makeup and the specific characteristics of their disease. By providing more accurate drug delivery, these systems improve the efficacy and safety of treatments, paving the way for more individualised therapeutic approaches [29].

Inhalable Drug Delivery Systems

Developments in Inhalation Therapies for Respiratory and Systemic Diseases Inhalable drug delivery systems have advanced significantly, offering new therapeutic options for respiratory and systemic diseases. These systems deliver drugs directly to the lungs, particularly beneficial for treating respiratory conditions like asthma, chronic obstructive pulmonary disease (COPD), and cystic fibrosis. Inhalable therapies can also be used for systemic delivery, where drugs are absorbed through the extensive surface area of the lungs into the bloodstream, providing a rapid onset of action. Innovations in this area include the development of dry powder inhalers, nebulisers, and

metered-dose inhalers that are optimized for delivering nanoparticles and microparticles [30].

Nanoparticles and Microparticles in Pulmonary Drug Delivery Nanoparticles and microparticles are increasingly being used in pulmonary drug delivery to enhance drug stability, improve absorption, and provide controlled release within the lungs. These particles can be engineered to reach specific regions of the lungs, allowing for targeted treatment of localized conditions or systemic diseases. For example, nanoparticles can be designed to penetrate deep into the alveoli, where they can release their payload in a controlled manner, improving the drug's efficacy while minimizing side effects. The use of nanoparticles and microparticles in inhalable drug delivery systems represents a significant advancement in treating respiratory and non-respiratory diseases [31-33].

Table 2: Marketed Products Using Novel Drug Delivery Mechanisms

Product Name	Delivery Mechanism	Indication	Manufacturer
Duragesic® (Fentanyl Patch)	Transdermal Patch	Chronic Pain	Janssen Pharmaceuticals
Exelon® Patch (Rivastigmine)	Transdermal Patch	Alzheimer's Disease	Novartis
Concerta®	Osmotic-Controlled Release Oral System	ADHD	Janssen Pharmaceuticals
OxyContin®	Oral Controlled Release	Chronic Pain	Purdue Pharma
Doxil®	Liposomal Targeted Delivery	Cancer (e.g., ovarian cancer)	Janssen Pharmaceuticals
Pulmicort® (Budesonide)	Inhalable Dry Powder	Asthma	AstraZeneca
Spiriva® (Tiotropium)	Inhalable Dry Powder	Chronic Obstructive Pulmonary Disease (COPD)	Boehringer Ingelheim
Advair® Diskus (Fluticasone/Salmeterol)	Inhalable Dry Powder	Asthma, COPD	GlaxoSmithKline
Herceptin® (Trastuzumab)	Targeted Drug Delivery (IV infusion)	HER2-positive Breast Cancer	Genentech

4. Advanced Delivery Platforms
Biodegradable Implants and Depots

Biodegradable implants and depots significantly advance localized and sustained drug delivery. These devices are made from biodegradable materials that gradually break down in the body, releasing the drug over a prolonged period. This controlled release ensures that a consistent therapeutic dose is delivered directly to the target site, reducing the need for frequent dosing and minimizing systemic side effects. Biodegradable implants are particularly beneficial in cancer treatment, where they can deliver chemotherapy directly to a tumour site, and in contraception, where hormone-releasing implants provide long-term birth control. In chronic pain management, these implants can continuously release pain-relief medication, improving patient comfort and adherence to treatment [34].

Hydrogels and Smart Polymers

Hydrogels and smart polymers are innovative materials designed to respond to specific stimuli, such as changes in pH, temperature, or the presence of certain enzymes, to release drugs on demand. These responsive hydrogels can be engineered to deliver therapeutic agents precisely when and where needed, making them ideal for applications in personalized medicine. In wound healing, hydrogels can release antimicrobial agents or growth factors to promote tissue regeneration and prevent infection. Drug-eluting stents, which release anti-inflammatory or antiproliferative drugs to prevent restenosis, also utilize these materials. Additionally, in tissue engineering, smart polymers are used as scaffolds that support the growth of new tissues while gradually releasing bioactive molecules to enhance healing [35].

Viral and Non-Viral Gene Delivery Systems

Gene therapy has seen significant advancements with the development of viral and non-viral gene delivery systems. Viral vectors, such as adenoviruses and lentiviruses, are highly efficient at delivering genetic material into cells, making them powerful tools for correcting genetic disorders. However, immune responses and potential safety concerns often limit their use. Non-viral systems, such as nanoparticles, offer a safer alternative using materials like liposomes or polymers to encapsulate and deliver genes without eliciting strong immune reactions. These non-viral vectors can be engineered for targeted delivery to specific tissues or cells, reducing off-target effects and improving therapeutic outcomes. Despite these advancements, challenges remain in optimising these delivery systems' efficiency, safety, and scalability for widespread clinical application [36].

Table 3: Summary of Advanced Delivery Platforms

Category	Applications	Advantages
Biodegradable Implants and Depots	<ul style="list-style-type: none"> - Cancer Treatment: Targeted chemotherapy delivery. - Contraception: Long-term birth control. - Chronic Pain: Sustained analgesic delivery. 	<ul style="list-style-type: none"> - Localized treatment minimizes systemic side effects. - Sustained release reduces dosing frequency. - Biodegradability removes need for surgery.
Hydrogels and Smart Polymers	<ul style="list-style-type: none"> - Wound Healing: Enhanced recovery with drug delivery. - Drug-Eluting Stents: Prevents artery restenosis. - Tissue Engineering: Supports cell growth and tissue regeneration. 	<ul style="list-style-type: none"> - Responsive release for tailored therapy. - Enhances healing while delivering drugs. - Versatile in various medical fields.
Viral and Non-Viral Gene Delivery	<ul style="list-style-type: none"> - Gene Therapy: Treats genetic disorders. - Cancer Treatment: Introduces therapeutic genes. - Vaccines: Non-viral delivery of mRNA vaccines. 	<ul style="list-style-type: none"> - Targeted gene delivery to specific cells. - Potential for one-time treatment. - Adaptable to various diseases.

5. Challenges and Future Directions

Regulatory and Manufacturing Challenges

Scaling up advanced drug delivery systems from the laboratory to commercial production presents significant challenges. The complexity of these systems, which often involve intricate materials and sophisticated mechanisms, makes manufacturing at a large scale difficult and expensive. Ensuring consistent quality across batches is critical, yet the variability in materials and processes can lead to issues in standardization and quality control. Moreover, regulatory approval for advanced drug delivery systems is often lengthy and complex. Regulatory agencies require comprehensive data on the safety, efficacy, and manufacturing consistency of these systems, and the novel nature of many advanced delivery technologies means that existing regulatory frameworks may not always be adequate, leading to delays in bringing new products to market [37].

Safety and Biocompatibility Concerns

The long-term safety and biocompatibility of novel drug delivery systems are paramount in their development and clinical use. While advanced systems like nanoparticles, biodegradable implants, and gene delivery vectors offer significant therapeutic advantages, they also introduce potential risks. For instance, nanoparticles may accumulate in tissues and organs, leading to toxicity, while viral gene delivery vectors can trigger immune responses that may compromise their efficacy or safety. Addressing these concerns requires extensive preclinical and clinical testing to evaluate potential adverse effects, including long-term toxicity, immune reactions, and unintended interactions with biological systems. Ensuring these systems are safe for long-term use is crucial for their acceptance in clinical practice [38-41].

Future Trends and Opportunities

The future of drug delivery is poised to be shaped by emerging technologies such as nanobots and bioengineered tissues, which offer unprecedented precision and control over therapeutic interventions. Nanobots, for example, could revolutionize drug delivery by navigating through the body to deliver drugs directly to diseased cells or tissues, offering highly targeted and minimally invasive treatments. Bioengineered tissues, combined with smart drug delivery systems, could enable the development of personalized treatments tailored to the individual patient's needs, particularly in regenerative medicine and complex diseases. The integration of these technologies with advanced drug delivery systems holds great promise for the future of personalized and precision medicine, where treatments are not only more effective but also safer and more patient-specific. As these technologies advance, they will open new opportunities for innovation in drug delivery, offering solutions to some of the most challenging medical conditions [42].

Conclusion

Advanced drug delivery systems represent a significant leap forward in the field of pharmaceutical sciences, offering novel approaches to overcoming the limitations of traditional drug delivery methods. Nanotechnology-based formulations, including nanoparticles, liposomes, and nanocrystals, have enhanced drug solubility, stability, and targeted delivery, significantly impacting cancer therapy and chronic disease management. Polymeric systems and SLNs/NLCs have provided sustained and controlled release options, improving patient adherence and therapeutic efficacy. Novel drug delivery mechanisms such as transdermal patches, oral controlled release systems, and inhalable therapies have made non-invasive and patient-friendly drug administration more feasible, enhancing patient comfort and compliance. However, the journey from laboratory innovation to market-ready products is fraught with challenges, particularly in scaling up production, ensuring consistent quality, and navigating the regulatory landscape. Long-term safety and

biocompatibility of these advanced systems also remain areas of active research. Looking ahead, the integration of emerging technologies such as nanobots and bioengineered tissues with advanced drug delivery systems holds immense potential for personalized and precision medicine. These innovations promise to deliver more targeted, effective, and patient-specific treatments, ultimately transforming the future of healthcare.

Funding

No

Acknowledgement

Nil

Conflict of Interest

No conflict of interest.

Informed Consent

Not applicable.

Ethical Statement

Not applicable.

Author Contribution

Sanket J Soni, Ankitkumar N Patel both are contributed equally.

References

1. Panyam J, Labhasetwar V. Biodegradable nanoparticles for drug and gene delivery to cells and tissue. *Adv Drug Deliv Rev*. 2003;55(3):329-47.
2. Ferrari M. Cancer nanotechnology: opportunities and challenges. *Nat Rev Cancer*. 2005;5(3):161-71.
3. Langer R, Tirrell DA. Designing materials for biology and medicine. *Nature*. 2004;428(6982):487-92.
4. Torchilin VP. Recent advances with liposomes as pharmaceutical carriers. *Nat Rev Drug Discov*. 2005;4(2):145-60.
5. Farokhzad OC, Langer R. Impact of nanotechnology on drug delivery. *ACS Nano*. 2009;3(1):16-20.
6. Duncan R. The dawning era of polymer therapeutics. *Nat Rev Drug Discov*. 2003;2(5):347-60.
7. Wang AZ, Langer R, Farokhzad OC. Nanoparticle delivery of cancer drugs. *Annu Rev Med*. 2012;63:185-98.
8. Jain RK. Delivery of molecular and cellular medicine to solid tumors. *Adv Drug Deliv Rev*. 2001;46(1-3):149-68.
9. Moghimi SM, Hunter AC, Murray JC. Long-circulating and target-specific nanoparticles: theory to practice. *Pharmacol Rev*. 2001;53(2):283-318.
10. Chou LY, Ming K, Chan WC. Strategies for the intracellular delivery of nanoparticles. *ChemSoc Rev*. 2011;40(1):233-45.
11. Davis ME, Chen ZG, Shin DM. Nanoparticle therapeutics: an emerging treatment modality for cancer. *Nat Rev Drug Discov*. 2008;7(9):771-82.
12. Allen TM, Cullis PR. Drug delivery systems: entering the mainstream. *Science*. 2004;303(5665):1818-22.
13. Riehemann K, Schneider SW, Luger TA, Godin B, Ferrari M, Fuchs H. Nanomedicine--challenge and perspectives. *AngewChem Int Ed Engl*. 2009;48(5):872-97.
14. Brigger I, Dubernet C, Couvreur P. Nanoparticles in cancer therapy and diagnosis. *Adv Drug Deliv Rev*. 2002;54(5):631-51.
15. 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.
16. 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.
17. Sailor MJ, Park JH. Hybrid nanoparticles for detection and treatment of cancer. *Adv Mater*. 2012;24(28):3779-802.
18. Grodzinski P, Silver M, Molnar LK. Nanotechnology for cancer diagnostics: promises and challenges. *Expert Rev Mol Diagn*. 2006;6(3):307-18.
19. Shi J, Kantoff PW, Wooster R, Farokhzad OC. Cancer nanomedicine: progress, challenges and opportunities. *Nat Rev Cancer*. 2017;17(1):20-37.
20. Parveen S, Misra R, Sahoo SK. Nanoparticles: a boon to drug delivery, therapeutics, diagnostics and imaging. *Nanomedicine*. 2012;8(2):147-66.
21. Xu Z, Chen L, Gu W, Gao Y, Lin L, Zhang Z, Guo R, Chen H. The performance of docetaxel-loaded solid lipid nanoparticles targeted to hepatocellular carcinoma. *Biomaterials*. 2009;30(2):226-32.
22. Sahoo SK, Parveen S, Panda JJ. The present and future of nanotechnology in human health care. *Nanomedicine*. 2007;3(1):20-31.
23. Hafner A, Lovrić J, Lakoš GP, Pepić I. Nanotherapeutics in the EU: an overview on current state and future directions. *Int J Nanomedicine*. 2014;9:1005-23.
24. Manda, P., Popescu, C., Juluri, A. et al. Micronized Zaleplon Delivery via Orodispersible Film and Orodispersible Tablets. *AAPS PharmSciTech* 19, 1358–1366 (2018).
25. Lakshmi Narasimha Rao, K., Praneeth Rao, K. Development and Validation of a Stability-Indicating LC Method for Determination of Bexarotene in Softgel Dosage Formulation. *Chromatographia* 80, 1211–1224 (2017).
26. Namballa M, Adimulapu A, Jesudasan RE. QbD Assisted Optimization of Microwave-assisted Synthesis of Polyacrylamide Grafted Tragacanth: Characterization and Instrumental Analysis. *Current Microwave Chemistry*. 2024 Apr 1;11(1):16-29.
27. Kakullamarri PR, Rao KLN (2017) Enhanced Bioavailability and Anticancer Activity of Vitamin Analogs. *J BioequivAvailab* 9: 439-441.
28. He Q, Shi J. Mesoporous silica nanoparticle based nano drug delivery systems: synthesis, controlled drug release and delivery, pharmacokinetics and biological effects. *Nanoscale*. 2011;3(3):1167-85.

29. Zhang L, Gu FX, Chan JM, Wang AZ, Langer RS, Farokhzad OC. Nanoparticles in medicine: therapeutic applications and developments. *Clin Pharmacol Ther.* 2008;83(5):761-9.
30. Prow TW, Grice JE, Lin LL, Faye R, Butler M, Becker W, Wurm EM, Yoong C, Robertson TA, Soyer HP, Roberts MS. Nanoparticles and microparticles for skin drug delivery. *Adv Drug Deliv Rev.* 2011;63(6):470-91.
31. Ravello S, Angel M, Subramanian H, Thangavel N, Namballa M, Lokesh D, Mishra AK, Nagaraju GV. Navigating the Future of Cancer Diagnosis: A Comprehensive Review of Novel Approaches for Community-Based Treatment. *future.*;1:6.
32. Wang F, Yu M, Yan X, Liu X, Zhao Y. Dendrimer-based nanoparticles for cancer diagnosis and therapy. *J Control Release.* 2017;259:136-48.
33. Wickline SA, Lanza GM. Nanotechnology for molecular imaging and targeted therapy. *Circulation.* 2003;107(8):1092-5.
34. Ramezani M, Coombes AG, Won R, Pocock G, Davies MC, Duncan R, Illum L, Davis SS. Microglia as a target for drug delivery in multiple sclerosis. *J Drug Target.* 1997;4(1):65-78.
35. Koo OM, Rubinstein I, Onyuksel H. Role of nanotechnology in targeted drug delivery and imaging: a concise review. *Nanomedicine.* 2005;1(3):193-212.
36. Owens DE, Peppas NA. Opsonization, biodistribution, and pharmacokinetics of polymeric nanoparticles. *Int J Pharm.* 2006;307(1):93-102.
37. LaVan DA, McGuire T, Langer R. Small-scale systems for in vivo drug delivery. *Nat Biotechnol.* 2003;21(10):1184-91.
38. Allen TM. Liposomal drug formulations: rationale for development and what we can expect for the future. *Drugs.* 1998;56(5):747-56.
39. Ulbrich K, Hekmatara T, Herbert E, Kreuter J. Transferrin- and transferrin-receptor-antibody-modified nanoparticles enable drug delivery across the blood-brain barrier (BBB). *Eur J Pharm Biopharm.* 2009;71(2):251-6.
40. Petros RA, DeSimone JM. Strategies in the design of nanoparticles for therapeutic applications. *Nat Rev Drug Discov.* 2010;9(8):615-27.
41. Sahoo SK, Labhasetwar V. Nanotech approaches to delivery and imaging drug. *Drug Discov Today.* 2003;8(24):1112-20.
42. Anderson JM, Rodriguez A, Chang DT. Foreign body reaction to biomaterials. *Semin Immunol.* 2008;20(2):86-100.