Int. J. Pharm. Investigation, 2026; 16(2):536-540.
https://www.jpionline.org

Review Article

The Impact of Nanoparticulate Drug Delivery Systems on Cancer Therapy and the Role of Artificial Intelligence

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ABSTRACT

Cancer remains a leading cause of global mortality. Conventional treatments such as chemotherapy, radiation, and surgery often lead to severe side effects and limited effectiveness. Nanoparticulate Drug Delivery Systems (NDDS) offer novel strategies to enhance drug targeting, solubility, and treatment outcomes. This review discusses the types, mechanisms, advantages, challenges, and future directions of NDDS in cancer therapy. The role of Artificial Intelligence (AI) in optimizing drug formulations, targeting strategies, and real-time monitoring is also explored. NDDS improve drug solubility, circulation time, and targeted delivery while minimizing side effects. Mechanisms such as the Enhanced Permeability and Retention (EPR) effect, active targeting, and controlled release enhance therapeutic efficacy. AI assists in drug design, nanoparticle characterization, personalized therapy, and resistance prediction. NDDS, supported by AI-driven approaches, have significant potential to revolutionize cancer treatment. Addressing biocompatibility, scalability, regulatory hurdles, and tumor heterogeneity remains essential for wider clinical adoption.

Keywords: Cancer, Nanoparticulate Drug Delivery System, Artificial intelligence.

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Received: 02-09-2025;
Revised: 22-10-2025;
Accepted: 18-12-2025.

INTRODUCTION

The intricate nature of cancer biology and the diversity of tumors present major obstacles to successful treatment, even with advancements in early detection and therapy, numerous tumors continue to be diagnosed at later stages, resulting in unfavorable outcomes. Although chemotherapy and radiation therapy have shown some success, they often result in the indiscriminate spread of drugs, which can harm healthy cells and diminish the effectiveness of the treatment (Hanahan and Weinberg, 2011). Nanoparticle-based drug delivery methods have come to the forefront as an effective way to overcome these challenges. Therapeutic drugs, such as immune-modulating agents, gene therapies, or chemotherapeutics, can be encapsulated in these systems as nanoparticles that can be designed for targeted release and selective accumulation at tumor locations (Barenholz, 2007). The integration of Artificial Intelligence (AI) in the creation, enhancement, and usage of nano-particulate drug delivery systems within clinical environments is significantly transforming this field (Liu *et al.*, 2016). Nano-particulate drug delivery systems offer significant therapeutic advantages including enhanced targeting, controlled release, and reduced side effects; while facing challenges such as toxicity, formulation complexity, and scalability. The integration of AI into these systems is accelerating advances by enabling precision targeting, optimization of nanoparticle design, and real-time control of drug release. This review examines the therapeutic benefits, design challenges, and potential applications of nano-particulate drug delivery systems. It also explores how AI is advancing these technologies.

DOI: 10.5530/ijpi.20260109

Nanoparticulate Drug Delivery Systems: Overview and Classification

Structure and Functionality

Nanoparticulate drug delivery systems consist of nanoparticles engineered for targeted therapeutic outcomes. These nanoparticles include liposomes, micelles, dendrimers, polymeric nanoparticles, and inorganic nanoparticles, each possessing distinct characteristics. Factors such as size, surface charge, and functionalization play crucial roles in influencing their interactions with biological systems and the efficacy of drug delivery (Panyam and Labhasetwar, 2003; Prabhu *et al.*, 2021).

Types of Nanoparticulate Systems in Cancer Therapy

Liposomes

These are spherical structures formed from phospholipid layers that can encapsulate both water-soluble and fat-soluble medications. Liposomes can enhance the stability of drugs, prolong their duration in the body, and reduce adverse effects. Customized liposomal formulations can be modified with ligands or antibodies to specifically target and deliver drugs to cancer cells (Allen and Cullis, 2013; Gabizon and Barenholz, 1993).

Polymeric Nanoparticles

Nanoparticles that encapsulate drugs are composed of biodegradable polymers such as Poly (Lactic-Co-Glycolic Acid) (PLGA). These devices can aim at tumor areas by utilizing the Enhanced Permeability and Retention (EPR) effect, allowing for controlled release and extended circulation times. In summary, PLGA-based nanoparticles leverage the EPR effect for targeted tu mor drug delivery, enabling sustained, regulated release and prolonged circulation, making them a leading platform for cancer therapy and other biomedical applications (Desai, 2012; Nair and Dhandapani, 2019).

Dendrimers

These macromolecules possess a unique structure and exhibit a highly branched, tree-like appearance. Their versatility allows for the attachment of various medications, targeting ligands, and imaging agents, which enhances drug solubility, targeting ability, and effectiveness (Duncan and Izzo, 2005; Shcharbin *et al*., 2019).

Inorganic Nanoparticles

These nanoparticles, such as gold nanoparticles and silica nanoparticles, are used for drug delivery and imaging. Their surfaces can be modified to enhance drug binding, and they provide extra advantages in diagnostic applications due to their optical characteristics (Jiang *et al*., 2016; Jain *et al*., 2008).

Mechanisms of Action in Cancer Therapy

The effectiveness of NDDS in cancer treatment comes from their ability to leverage the physiological properties of tumors, enhancing drug delivery. These mechanisms include:

Enhanced Permeability and Retention (EPR) Effect

Tumors show dysfunctional blood vessels and inadequate lymphatic drainage, leading to the preferential accumulation of nanoparticles within the tumor microenvironment. This occurrence is referred to as the EPR effect and constitutes a key principle that facilitates targeted drug delivery using nanoparticles (Jain, 1987).

Passive Targeting

Nanoparticles have the ability to passively gather at tumor locations as a result of the Enhanced Permeability and Retention (EPR) effect, enabling them to evade quick elimination from the bloodstream, which enhances their therapeutic effectiveness (Maeda *et al*., 2000).

Active Targeting

Nanoparticles can be modified with particular ligands, antibodies, or peptides that identify receptors or antigens that are overexpressed on cancer cells. This improves the precision and selectivity of drug delivery, minimizing harm to healthy tissues (Allen and Cullis, 2013).

Controlled Release

Nanoparticles can be designed to deliver drugs in reaction to certain triggers like pH levels, temperature variations, or specific enzymes. This targeted release enhances the drug's pharmacokinetics, keeping therapeutic levels at the tumor location for longer durations (Gaumet *et al*., 2008).

Combination Therapy

Nanoparticles are capable of co-delivering various therapeutic agents, including chemotherapeutics, immunotherapeutics, and gene therapies, which allows for combination therapies that improve treatment effectiveness and address resistance mechanisms (Jain, 2000).

Therapeutic Benefits of Nanoparticulate Drug Delivery Systems

Improved Drug Solubility and Bioavailability

Numerous anticancer medications exhibit low solubility, which restricts their therapeutic effectiveness. Utilizing nanoparticles can enhance the solubility and stability of these medications, thereby improving their bioavailability and therapeutic efficacy (Sahoo *et al*., 2007).

Reduced Toxicity

By targeting drug delivery directly to the tumor, NDDS decreases the contact of healthy tissues with harmful chemotherapy drugs, consequently lessening side effects like nausea, immune system suppression, and loss of hair (Moghimi *et al*., 2005).

Targeted Drug Delivery

Nanoparticles can effectively transport medications directly to cancer cells, resulting in increased drug levels at the tumor location, which enhances the chances of successful treatment while protecting healthy cells (Bartlett and Davis, 2006).

Longer Circulation Time

Nanoparticles can be designed to avoid detection by the immune system, resulting in longer circulation periods and enhanced drug concentration at the tumor location. This is especially advantageous for medications that have a brief half-life (Allen and Martin, 2018).

Theranostic Applications

Nanoparticles present the opportunity for integrated therapy and diagnostics (theranostics), allowing for simultaneous administration of medication and imaging. This capability can be especially valuable for tracking treatment responses and tumor development in real-time (Mitragotri *et al*., 2014).

The Role of Artificial Intelligence in NDDS

Artificial intelligence is increasingly essential for the creation and improvement of nanoparticulate drug delivery systems aimed at cancer treatment shown in Figure 1. The incorporation of AI in this area improves drug formulation, design, and targeting methods. Key functions of AI encompass:

Drug Design and Optimization

Machine learning algorithms are capable of forecasting the ideal ratio of drugs to carriers, as well as the size and surface properties of nanoparticles. AI models can also replicate how nanoparticles interact with biological systems, allowing for predictions about the pharmacokinetics and pharmacodynamics of the nanoparticles loaded with drugs (Wani and Ahsan, 2020).

Nanoparticle Synthesis and Characterization

The use of AI for automating the creation and characterization of nanoparticles is on the rise. By examining extensive datasets derived from nanoparticle attributes (such as dimensions, morphology, and surface charge), AI can discern patterns and enhance synthesis methods to ensure uniform quality (Chaudhary *et al*., 2020).

Personalized Cancer Therapy

Artificial intelligence algorithms can examine individual patient data, such as genomic profiles, to create customized nanoparticle

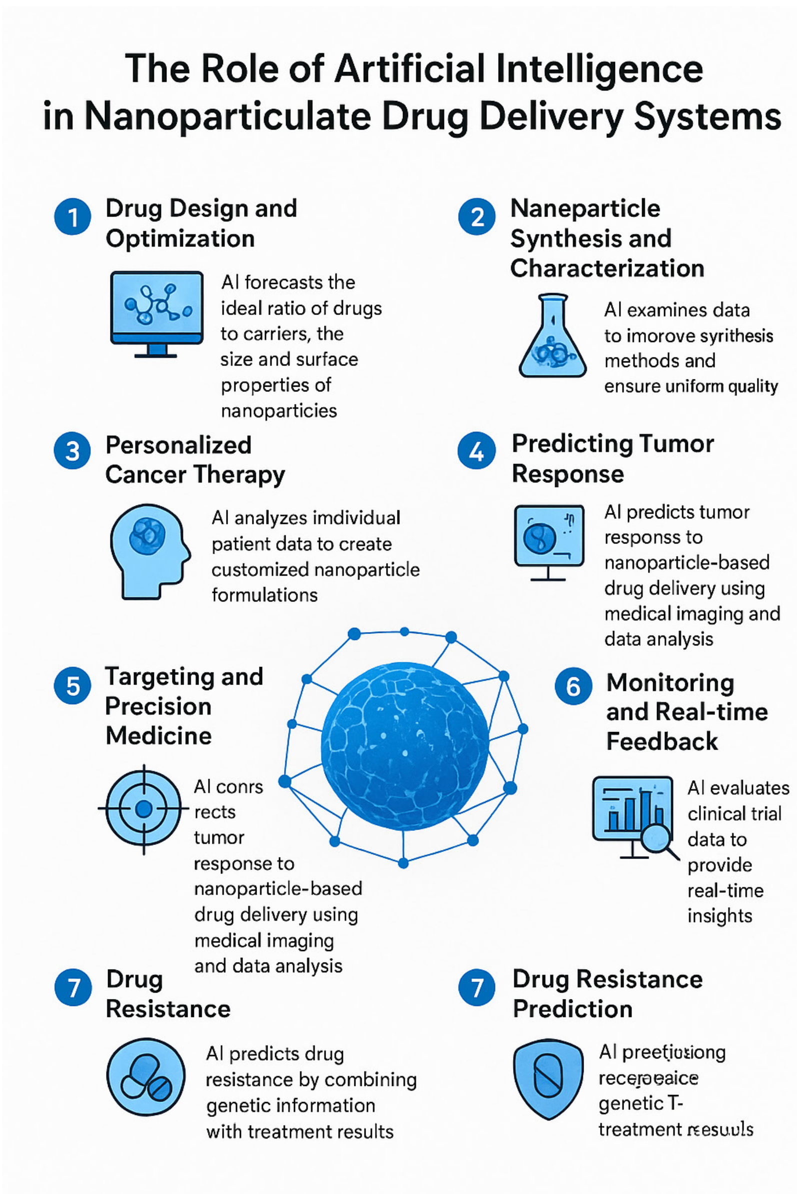

Figure 1: The role of artificial intelligence in NDDS, illustrating drug design, synthesis, targeting, monitoring, and personalized therapy applications.

formulations suited to the distinct features of the patient's tumor. This approach can enhance treatment results by ensuring that the drug delivery system is specifically crafted to target the unique biomarkers or genetic mutations of the tumor (Chaudhary *et al*., 2020).

Predicting Tumor Response

Artificial intelligence can be utilized in medical imaging and data analysis to anticipate the response of tumors to nanoparticle-based drug delivery. By examining the diversity within tumors and patterns of drug distribution, AI can project the effectiveness of treatments, enabling healthcare providers to modify treatment strategies in real-time (Yang *et al*., 2021).

Targeting and Precision Medicine

Computational models driven by AI can discern particular receptors or antigens that are overexpressed in specific types of cancer, which aids in the functionalization of nanoparticles for better targeting. This enhances the accuracy of therapies using nanoparticles, reducing off-target effects and improving the chances of successfully eliminating tumors (Lee *et al*., 2021).

Monitoring and Real-time Feedback

By utilizing AI to evaluate extensive datasets from clinical trials or patient treatment records, real-time insights can be generated regarding the effectiveness and safety of NDDS. This facilitates ongoing refinement of treatment plans and prompts identification of possible adverse effects (Khosravi *et al*., 2021).

Drug Resistance Prediction

Artificial intelligence can help to elucidate the processes contributing to drug resistance in cancer. By combining genetic information with treatment results, AI models can forecast the chances of resistance to a particular medication, enabling researchers to create nanoparticles that evade resistance mechanisms or simultaneously deliver agents that counteract resistance (Sun *et al*., 2020).

Challenges and Limitations

Although there are significant benefits, numerous obstacles persist in the creation and clinical use of nanoparticle-based drug delivery systems:

Biocompatibility and Toxicity

The long-term safety of nanoparticles is still a topic of concern. Nanoparticles have the potential to trigger immune responses or accumulate in essential organs, which can result in toxicity (Lai *et al*., 2020).

Scalability and Manufacturing

Producing nanoparticles in large quantities while ensuring uniformity and quality control poses significant challenges. It is crucial to standardize production methods for successful clinical application (Zang *et al*., 2020).

Regulatory Challenges

Because of their unique characteristics, the regulatory approval process for nanoparticulate systems is more intricate than that for traditional medications. Demonstrating their safety and effectiveness through thorough preclinical and clinical trials poses a considerable challenge (Mei *et al*., 2020).

Tumor Heterogeneity

Tumors exhibit significant heterogeneity, and the EPR effect might not be consistent among all tumor types. Such differences can result in less effective drug delivery in some instances (Huang *et al*., 2019).

Cost

The production and creation of nanoparticles can be expensive, posing a major challenge for the advancement of cost-effective treatments (Sur *et al*., 2015).

Future Perspectives

Nanoparticulate drug delivery systems, when paired with AI technology, possess significant potential to transform cancer treatment. Upcoming advancements are expected to concentrate on:

Personalized Nanomedicine

Customizing nanoparticles according to a specific patient's cancer characteristics may improve the effectiveness of the treatment (Gajbhiye *et al*., 2020).

AI-driven Nanoparticle Optimization:

AI will continue to play a key role in optimizing nanoparticle formulations, improving targeting strategies, and predicting treatment outcomes with greater precision (Vagner *et al*., 2018).

Smart Nanoparticles

Nanoparticles that respond to specific biological stimuli (e.g., changes in pH, temperature, or enzymes) for controlled and localized drug release are being developed, and AI models will help identify the best conditions for these systems (Wang *et al*., 2021).

CONCLUSION

Nanoparticulate drug delivery systems present a promising approach to address many limitations found in traditional cancer treatments. By enhancing drug solubility, targeting accuracy, and minimizing side effects, NDDS represents a groundbreaking method for tailored cancer care. The incorporation of AI further expedites the advancement of these systems, allowing for more efficient, individualized, and accurate treatments. Nevertheless, obstacles such as biocompatibility, scalability, and regulatory challenges need to be resolved before these systems can be broadly implemented in clinical environments. Ongoing research and innovation in nanomedicine and AI will be crucial for realizing the complete potential of nanoparticulate systems in cancer therapy.

ACKNOWLEDGEMENT

The authors express gratitude to the faculty, staff, and research collaborators at The Pharmaceutical College, Barpali, for their guidance and support in the development of this review.

ABBREVIATIONS

AI: Artificial Intelligence; **PLGA:** Poly (lactic-co-glycolic acid); **EPR:** Enhanced Permeability and Retention; **NDDS:** Nanoparticulate Drug Delivery Systems.

CONFLICTS OF INTEREST

Authors declare that they have no conflict of interest.

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Cite this article: Dash SK, Padhan A, Khan AS, Behera TK, Mohapatra S, Parta S, *et al*. The Impact of Nanoparticulate Drug Delivery Systems on Cancer Therapy and the Role of Artificial Intelligence. Int. J. Pharm. Investigation. 2026;16(2):536-40.