INTERNATIONAL JOURNAL OF MEDICAL AND PHARMACEUTICAL RESEARCH

Vol.01-03-2026 E ISSN:XXXX-XXXX P ISSN:XXXX-XXXX

NANOTECHNOLOGY BASED DRUG DELIVERY SYSTEMS FOR EFFECTIVE CANCER TREATMENT

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ABSTRACT

Cancer remains one of the most significant challenges in modern medical science, creating a continuous need for safer, more effective, and targeted treatment approaches. Conventional cancer treatments, including chemotherapy and radiotherapy, are widely used but may cause serious side effects because therapeutic drugs can also affect healthy cells and tissues. Nanotechnology-based drug delivery systems have emerged as an advanced approach to improving cancer treatment by transporting therapeutic agents through specially designed nanoscale carriers. These systems include liposomes, polymeric nanoparticles, dendrimers, lipid-based nanoparticles, metallic nanoparticles, and other advanced nanocarriers. They can improve drug solubility, stability, circulation time, and targeted delivery while supporting controlled drug release at specific tumor sites. Nanotechnology also provides opportunities for combining chemotherapy, gene therapy, immunotherapy, and diagnostic procedures within advanced therapeutic platforms. Recent research highlights the potential of smart nanocarriers that respond to biological conditions such as temperature, pH, and enzyme activity. However, challenges related to toxicity, biocompatibility, manufacturing costs, tumor penetration, and clinical approval remain important concerns. This research examines the applications, advantages, limitations, and future possibilities of nanotechnology-based drug delivery systems in cancer treatment. The study emphasizes that continued scientific research, clinical evaluation, and technological development are essential for improving the safety and effectiveness of nanomedicine and supporting more personalized cancer treatment approaches.

KEYWORDS

Nanotechnology, Drug Delivery Systems, Cancer Treatment, Nanoparticles, Nanomedicine, Targeted Drug Delivery, Liposomes, Polymeric Nanoparticles, Controlled Drug Release, Cancer Therapy.

INTRODUCTION

Cancer is one of the leading causes of illness and mortality worldwide and remains a major challenge for modern healthcare systems. The disease develops when abnormal cells grow uncontrollably, invade surrounding tissues, and may spread to other parts of the body. Although medical science has made significant progress in cancer diagnosis and treatment, many patients continue to experience difficulties associated with treatment effectiveness, drug resistance, and adverse effects. Conventional treatment methods, including chemotherapy, radiotherapy, surgery, and immunotherapy, have improved survival outcomes in several types of cancer. However, chemotherapy drugs may also damage healthy cells, resulting in complications such as fatigue, nausea, hair loss, reduced immunity, and organ toxicity. These limitations have encouraged researchers to explore advanced pharmaceutical technologies that can improve drug

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delivery and increase treatment effectiveness. Fahim et al. (2026) explain that nanotechnology offers important opportunities for improving targeted drug delivery, controlling therapeutic release, and developing advanced treatment strategies in modern oncology.Nanotechnology has introduced new possibilities in pharmaceutical research through the development of materials and delivery systems at the nanoscaleDifferent nanocarriers, including liposomes, polymeric nanoparticles, dendrimers, solid lipid nanoparticles, and metallic nanoparticles, are being investigated for their potential applications in cancer treatment. Jabbar et al. (2026) discuss how different nanotechnology-based delivery platforms can improve pharmacokinetic properties and reduce selected treatment-related toxicities in cancer patients.One of the most important advantages of nanotechnology-based drug delivery systems is their potential to improve targeted treatment. Conventional chemotherapy drugs circulate throughout the body and may affect both cancerous and healthy cells, increasing the possibility of unwanted side effects. Nanocarriers can be designed with particular surface properties or targeting molecules that help them interact with specific biological structures associated with cancer cells. This approach may increase the concentration of therapeutic agents near tumor tissues and reduce unnecessary exposure of healthy tissues. Targeting can involve passive mechanisms associated with tumor blood vessel characteristics or active mechanisms using specific molecules that recognize receptors on cancer cells. However, the effectiveness of these mechanisms varies according to tumor biology and individual patient characteristics. Firouzpour et al. (2026) highlight the importance of nanoparticle design, surface functionalization, and tumor-targeting mechanisms in improving the potential effectiveness of cancer nanomedicine.

Different types of nanocarriers have been developed to improve the delivery of anticancer medicines. Solid lipid nanoparticles and nanostructured lipid carriers can also improve the stability and delivery of certain pharmaceutical compounds. Metallic and magnetic nanoparticles are being investigated for their potential applications in targeted treatment, imaging, and other advanced therapeutic approaches. Jayaraj et al. (2026) explain that different nanocarrier platforms possess specific physicochemical properties that influence their drug-loading capacity, biological interactions, circulation behavior, and therapeutic applications.Another important development in cancer nanomedicine is the introduction of smart drug delivery systems. These systems are designed to release therapeutic agents in response to particular biological or external conditions. For example, some nanoparticles respond to changes in pH, temperature, enzyme activity, or chemical conditions within the tumor microenvironment. Such characteristics may allow drugs to remain relatively stable during circulation and release their therapeutic contents when suitable conditions are present. Researchers are also investigating delivery systems that respond to external stimulation, including light, magnetic fields, heat, and ultrasound. These technologies may improve treatment precision and support the development of advanced therapeutic combinations. The 2026 review on emerging smart nanocarriers highlights the

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potential of stimuli-responsive nanoparticles for controlled drug release and tumor-specific treatment (Alam, 2026).

Nanotechnology-based drug delivery systems also provide opportunities for combining different cancer treatment approaches within a single therapeutic platform. Researchers are investigating nanocarriers capable of delivering chemotherapy medicines, genetic materials, immunotherapeutic agents, and other therapeutic substances. Such combinations may help address different biological processes involved in cancer development and treatment resistance. Nanotechnology can also support theranostic applications, in which diagnostic and therapeutic functions are integrated into a single system. These approaches may assist in monitoring treatment responses and developing more individualized therapeutic strategies. Lionadi and Payam (2026) explain that nanoparticles have significant potential in cancer treatment through targeted drug delivery, improved pharmacokinetics, molecular imaging, and personalized therapeutic applications. Nevertheless, their successful use depends on understanding tumor biology and evaluating the safety of each formulation.Despite its potential advantages, nanotechnology-based cancer treatment faces several scientific, technical, and clinical challenges. Nanoparticles may interact differently with biological tissues depending on their size, shape, surface charge, composition, and chemical properties. Some delivery systems may accumulate in organs such as the liver and spleen, while others may experience limited penetration into solid tumors. Additional concerns include unexpected immune responses, long-term toxicity, manufacturing consistency, production costs, and regulatory requirements. A formulation that demonstrates promising results in laboratory experiments may not produce similar outcomes in human patients because of differences in biological conditions and tumor characteristics. Liu et al. (2025) emphasize that clinical translation of cancer nanomedicines remains challenging because of biological barriers, variable tumor accumulation, safety considerations, and manufacturing limitations. Therefore, this research examines the role of nanotechnology-based drug delivery systems in effective cancer treatment, focusing on their major applications, therapeutic advantages, existing challenges, and future development opportunities.

RESEARCH OBJECTIVES

1. To examine the major types and applications of nanotechnology-based drug delivery systems in cancer treatment.
2. To evaluate the effectiveness of nanocarriers in improving targeted drug delivery and reducing treatment-related side effects.
3. To identify the major challenges and future opportunities associated with nanotechnology-based cancer therapies.

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RESEARCH QUESTIONS

1. What are the major types and applications of nanotechnology-based drug delivery systems in cancer treatment?
2. How can nanocarriers improve targeted drug delivery and reduce treatment-related side effects?
3. What are the major challenges and future opportunities associated with nanotechnology-based cancer therapies?

LITERATURE REVIEW

Nanotechnology-based drug delivery has become an important area of pharmaceutical and medical research because of its potential to improve the effectiveness of cancer treatment. Fahim et al. (2026) examined the integration of nanotechnology into oncology through advanced nanoparticle-based strategies for targeted cancer diagnosis and treatment. Their research discussed different nanoparticle synthesis methods, physicochemical characterization techniques, and tumor-targeting mechanisms. Their findings highlight the importance of nanoparticle size, surface properties, composition, and biological interactions in determining therapeutic performance. The study also identifies clinical translation, manufacturing consistency, and long-term safety as important challenges that must be addressed before advanced nanomedicines can achieve wider clinical application.Jabbar et al. (2026) conducted a review of nanotechnology in drug delivery systems for cancer therapy. Their research examined clinically validated drug delivery platforms and different types of nanocarriers, including lipid-based carriers, polymeric nanoparticles, and dendrimers. The study explained that nanotechnology can improve the pharmacokinetic properties of therapeutic medicines and reduce selected toxicities in specific cancer indications. It also discussed targeted drug delivery, controlled release, and the importance of selecting suitable pharmaceutical materials for cancer treatment. The researchers used academic databases, including Google Scholar, PubMed, and ScienceDirect, to identify relevant scientific publications. Their findings demonstrate that nanotechnology has significant potential in pharmaceutical development, although safety evaluation, formulation quality, and clinical validation remain essential for successful implementation.

Firouzpour et al. (2026) examined nanoparticle-based drug delivery systems for effective cancer treatment, focusing on their mechanisms and biomedical applications. Their research discussed different organic and inorganic nanoparticle platforms and their potential contributions to improving drug solubility, stability, pharmacokinetics, and tumor-specific targeting. The study also highlighted the importance of smart nanoparticles and hybrid nanostructures in modern cancer therapy. Particular attention was given to clinically established formulations, including liposomal and albumin-bound anticancer medicines, to demonstrate how nanotechnology-based

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pharmaceutical products can progress from research into clinical applications. Their review also identified toxicity, regulatory approval, and manufacturing scale-up as important barriers. These findings suggest that successful nanomedicine development requires a balance between technological innovation, therapeutic effectiveness, and clinical safety.Jayaraj et al. (2026) investigated nanocarrier-based strategies for advanced cancer drug delivery and therapeutics. Their research examined different delivery platforms, including liposomes, polymeric nanoparticles, dendrimers, micelles, solid lipid nanoparticles, and inorganic systems. The study discussed the biological interactions of these carriers and their ability to improve drug solubility, circulation time, and controlled release. It also explained how the physicochemical characteristics of nanocarriers influence their therapeutic performance and interaction with tumor tissues. Their findings indicate that advanced nanocarriers can support targeted drug delivery and improve the pharmaceutical performance of anticancer medicines. However, the study also emphasizes the need for additional research into biological compatibility, safety, and clinical effectiveness before complex nanocarrier systems can be widely adopted.

Alam (2026) examined emerging smart nanocarrier-based drug delivery systems for cancer therapeutics. The research focused on stimuli-responsive nanocarriers that can release therapeutic agents in response to internal biological conditions or external physical stimulation. Internal triggers include pH changes, enzyme activity, and temperature variations, while external triggers may include light, heat, magnetic fields, and ultrasound. The study explained how smart drug delivery systems can improve treatment precision by controlling the release of therapeutic substances at particular sites. The findings suggest that smart nanocarriers offer promising opportunities for developing more controlled and targeted cancer therapies, although their clinical translation requires further investigation into safety, manufacturing, and biological performance.Liu et al. (2025) reviewed recent advances in the bench-to-bedside translation of cancer nanomedicines. Their research examined the development of nanotechnology-based treatments and the difficulties associated with transferring experimental findings into clinical practice. The study discussed applications of nanomedicines in chemotherapy, phototherapy, sonodynamic therapy, nucleic acid therapy, and immunotherapy. It also highlighted the importance of overcoming biological barriers, improving tumor accumulation, reducing unwanted toxicity, and developing reliable manufacturing processes. The researchers explained that nanoparticles may interact differently with biological systems, which can influence their distribution, effectiveness, and safety. Their findings demonstrate that promising laboratory results must be supported by appropriate clinical evidence before nanotechnology-based treatments can be considered reliable options for cancer patients.

Lionadi and Payam (2026) investigated the role of nanotechnology in cancer therapy and its potential contribution to personalized treatment. Their research discussed the use of nanoparticles for targeted drug delivery, improved pharmacokinetics, reduced systemic toxicity,

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and molecular imaging. The study examined different nanoparticle platforms, including liposomal, polymeric, inorganic, and hybrid systems, and discussed their therapeutic applications in oncology. The authors also highlighted the importance of understanding tumor heterogeneity, biological barriers, and individual patient characteristics when designing nanotechnology-based treatments. Their findings indicate that advanced nanoparticles may contribute to more precise cancer therapies and support the integration of diagnostic and therapeutic technologies. However, they emphasize that successful clinical translation requires reproducible manufacturing, appropriate safety evaluation, and patient-specific treatment strategies. Collectively, these studies demonstrate that nanotechnology-based drug delivery systems have considerable potential in cancer treatment, while further research is required to overcome their biological, technical, and clinical limitations.

METHODOLOGY

This research adopts a qualitative research methodology to examine nanotechnology-based drug delivery systems and their applications in effective cancer treatment. The study is based on secondary information collected from previously published academic research articles, scientific reviews, pharmaceutical journals, and medical research publications. Relevant literature published between 2025 and 2026 has been considered to understand recent developments in nanomedicine and advanced pharmaceutical technologies. Academic information is identified through Google Scholar, PubMed, ScienceDirect, and other recognized scholarly databases. The selected publications focus on different types of nanocarriers, targeted drug delivery, controlled drug release, cancer treatment effectiveness, and the safety of nanotechnology-based pharmaceutical formulations.The research methodology involves reviewing existing scientific literature to identify the major types and applications of nanotechnology-based drug delivery systems. Particular attention is given to liposomes, polymeric nanoparticles, dendrimers, solid lipid nanoparticles, metallic nanoparticles, and smart nanocarriers. The study examines their structural characteristics, drug-loading capabilities, targeting mechanisms, and potential advantages in cancer treatment. Published research is also reviewed to understand how nanocarriers may improve drug solubility, protect therapeutic agents from degradation, increase drug accumulation near tumor tissues, and support controlled release. Information from different studies is compared to identify common findings and important developments in pharmaceutical nanotechnology.The methodology also examines the limitations and challenges associated with nanotechnology-based cancer treatment. These include nanoparticle toxicity, biological compatibility, immune responses, limited tumor penetration, manufacturing difficulties, and regulatory requirements. The study considers published evidence concerning the clinical development of nanomedicines and the differences between experimental findings and actual medical applications. Particular importance is given to the safety and effectiveness of nanoparticle formulations because their biological behavior can influence treatment outcomes.

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Through this approach, the research evaluates both the therapeutic potential and the practical limitations of nanotechnology-based drug delivery systems.Finally, the collected information is analyzed according to the research objectives and questions. The study examines the potential contribution of nanocarriers to improving targeted drug delivery, reducing unwanted exposure of healthy tissues, and supporting advanced cancer treatment approaches. It also reviews future research opportunities related to smart nanocarriers, personalized medicine, combination therapy, and improved pharmaceutical manufacturing. The methodology provides a comprehensive understanding of the current scientific developments and identifies areas requiring further clinical investigation.

RESEARCH DESIGN

The present study follows a descriptive and analytical research design based on secondary academic literature. This design is appropriate because the research aims to examine existing scientific knowledge about nanotechnology-based drug delivery systems and their role in cancer treatment. The descriptive component explains the major types of nanoparticles, their pharmaceutical properties, and their applications in oncology. The analytical component examines their potential therapeutic advantages, limitations, and contribution to improving drug delivery. This research design provides a structured framework for understanding the development and application of nanomedicine in modern pharmaceutical sciences.The research design focuses on different categories of nanocarriers used in cancer treatment, including liposomes, polymeric nanoparticles, dendrimers, lipid-based nanoparticles, and inorganic nanostructures. Each category is examined according to its composition, drug-loading capacity, stability, targeting potential, and controlled-release characteristics. The study also considers smart nanocarriers that respond to particular biological or external conditions. These systems are examined to understand how their properties may support more precise drug delivery and improve the therapeutic performance of anticancer medicines. The comparison of different nanocarrier systems helps identify their major advantages and limitations.

A comparative approach is also incorporated to examine conventional drug delivery methods and nanotechnology-based pharmaceutical systems. The comparison focuses on drug distribution, targeting ability, drug stability, therapeutic effectiveness, and possible side effects. Particular attention is given to the differences between experimental results and clinical applications because successful laboratory performance does not necessarily guarantee improved patient outcomes. The study also considers the importance of biocompatibility, toxicity evaluation, and manufacturing consistency when assessing advanced nanomedicines. This approach helps establish a balanced understanding of the benefits and limitations of nanotechnology in cancer treatment.The research design further examines future developments in nanomedicine and their possible contribution to modern oncology. These developments include stimuli-responsive drug

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delivery, multifunctional nanoparticles, combination therapy, and personalized treatment approaches. The study also considers the importance of clinical research, pharmaceutical quality control, and regulatory approval in the development of advanced drug delivery systems. By examining existing academic evidence and comparing different research findings, the design provides an organized understanding of the opportunities and challenges associated with nanotechnology-based cancer treatment.

DATA ANALYSIS

The data analysis is based on a qualitative examination of information collected from selected academic publications, scientific reviews, and pharmaceutical research studies. The collected information is organized into major themes, including nanoparticle classification, targeted drug delivery, controlled drug release, cancer treatment effectiveness, and pharmaceutical safety. These themes are examined to identify common research findings and important developments in nanotechnology-based cancer treatment. Particular attention is given to the studies conducted by Fahim et al. (2026), Jabbar et al. (2026), and Firouzpour et al. (2026), which discuss nanoparticle structures, drug delivery mechanisms, and clinical applications of nanomedicine.The analysis also examines the therapeutic advantages and limitations of different nanocarrier systems. Their potential contributions are evaluated in terms of improved drug solubility, drug stability, targeted delivery, circulation time, and reduced systemic toxicity. At the same time, the research considers challenges such as biological barriers, nanoparticle accumulation in healthy organs, immune responses, manufacturing consistency, and long-term safety. Studies by Liu et al. (2025) and Lionadi and Payam (2026) provide important evidence for understanding the differences between promising experimental developments and successful clinical implementation.Finally, the findings from different publications are compared and interpreted according to the research objectives and questions. The analysis identifies the most important applications of nanotechnology-based drug delivery systems and examines their potential contribution to improving cancer treatment. Particular attention is given to smart nanocarriers, personalized medicine, and combination therapeutic approaches. The overall analysis provides a balanced understanding of the current scientific progress, existing limitations, and future possibilities of nanotechnology in pharmaceutical research.

FINDINGS

The findings of this research indicate that nanotechnology-based drug delivery systems offer important opportunities for improving cancer treatment. The reviewed literature demonstrates that different nanocarriers, including liposomes, polymeric nanoparticles, dendrimers, and lipid-based nanoparticles, can support the transportation of therapeutic agents and improve their pharmaceutical properties. These systems may increase drug stability, improve solubility, and

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support controlled drug release. Research by Fahim et al. (2026) and Jabbar et al. (2026) highlights the importance of nanoparticle design and targeting mechanisms in developing advanced cancer therapies. The findings suggest that nanotechnology can contribute to more efficient drug delivery when formulations are appropriately designed and clinically evaluated.The research further indicates that targeted and smart drug delivery systems have significant potential in reducing unwanted drug exposure and improving treatment precision. Nanocarriers can be modified to interact with particular biological structures or respond to conditions within the tumor microenvironment. Smart delivery systems may release therapeutic substances in response to pH changes, temperature, enzyme activity, or external stimulation. These characteristics can support controlled drug release and provide opportunities for combining different treatment approaches. The reviewed literature suggests that nanotechnology may also contribute to personalized cancer treatment through the development of delivery platforms designed according to individual tumor characteristics.Another important finding is that the clinical application of nanotechnology-based drug delivery systems continues to face several challenges. The reviewed studies identify toxicity, limited tumor penetration, biological variability, immune responses, manufacturing difficulties, and regulatory requirements as major concerns. Experimental effectiveness does not always guarantee similar results in clinical settings, making careful evaluation essential before widespread medical application. The findings also demonstrate the importance of continued research into biocompatibility, long-term safety, and manufacturing quality. Therefore, the successful development of nanomedicine requires cooperation between pharmaceutical researchers, medical professionals, biotechnology experts, and regulatory institutions.

CONCLUSION

Nanotechnology-based drug delivery systems represent an important development in modern pharmaceutical research and cancer treatment. The findings of this research demonstrate that advanced nanocarriers, including liposomes, polymeric nanoparticles, dendrimers, and lipid-based systems, offer promising opportunities for improving the delivery of anticancer medicines. These technologies can improve drug stability, solubility, circulation, and controlled release while supporting targeted treatment approaches. Their potential applications in chemotherapy, gene therapy, immunotherapy, and combination treatments demonstrate the growing importance of nanotechnology in modern oncology. These developments provide opportunities to improve pharmaceutical formulations and support more effective cancer treatment strategies.The research also concludes that nanotechnology may help address some limitations of conventional cancer treatment by improving drug delivery precision and reducing unnecessary exposure of healthy tissues. Smart nanocarriers and stimuli-responsive delivery systems offer additional possibilities for controlling the release of therapeutic agents according to specific biological conditions. Furthermore, advanced nanomedicine may support personalized treatment approaches by

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considering the characteristics of individual tumors and patients. However, the effectiveness of these technologies depends on appropriate nanoparticle design, biological compatibility, drug-loading capacity, and reliable clinical evidence. Therefore, nanotechnology-based drug delivery systems should undergo careful scientific evaluation before being widely adopted in medical practice.In conclusion, the future development of nanotechnology-based cancer treatment requires continuous scientific research, clinical testing, and improvements in pharmaceutical manufacturing. Researchers should focus on reducing nanoparticle toxicity, improving tumor penetration, developing more reliable targeting mechanisms, and establishing consistent production standards. Healthcare professionals and pharmaceutical institutions should also consider patient safety, treatment effectiveness, and regulatory requirements during the development of advanced nanomedicines. With further technological progress and responsible clinical implementation, nanotechnology-based drug delivery systems may contribute significantly to safer, more precise, and more effective cancer treatment in the future.

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