World Journal of Pharmaceutical Science and Research
www.wjpsronline.com
Review Article
ISSN: 2583-6579
SJIF Impact Factor: 6.916
Year - 2026
Volume: 5; Issue: 5
Page: 204-213

ROLE OF NANOPARTICLES IN CANCER DIAGNOSIS AND THERAPY

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Article Received: 10 March 2026 || Article Revised: 1 April 2026 || Article Accepted: 21 April 2026

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How to cite this Article: Rohan Kailas Kathale, Dipak anil Kathale, Ritesh Santosh Pachade, Aishwarya Suryakant Kharat, Nikita Kailas kale, Prof. Ajay L. Lahane, Dr. Nandu Kayande (2026) ROLE OF NANOPARTICLES IN CANCER DIAGNOSIS AND THERAPY. World Journal of Pharmaceutical Science and Research, 5(5), 204-213.

ABSTRACT

Nanoparticles have emerged as powerful tools in the field of oncology, offering significant advancements in both cancer diagnosis and therapy. Due to their unique physicochemical properties, such as small size, large surface area, and the ability to be functionalized with targeting ligands, nanoparticles enable improved detection and treatment of tumors. In cancer diagnosis, nanoparticles enhance imaging techniques by acting as contrast agents in modalities like magnetic resonance imaging, computed tomography, and fluorescence imaging, allowing for early and accurate tumor detection. Their ability to selectively accumulate in tumor tissues through the enhanced permeability and retention effect further improves diagnostic precision.In therapeutic applications, nanoparticles serve as efficient drug delivery systems, enabling targeted delivery of chemotherapeutic agents directly to cancer cells while minimizing damage to healthy tissues. Additionally, nanoparticles are being explored in advanced therapies such as photothermal and photodynamic therapy, where they facilitate localized destruction of cancer cells upon external stimulation. Some nanoparticle systems also support combined diagnostic and therapeutic functions, known as theranostics, which allow simultaneous monitoring and treatment of cancer.Despite these promising benefits, challenges such as potential toxicity, long-term safety, and large-scale production remain concerns that need to be addressed. Overall, nanoparticles represent a transformative approach in cancer management, with the potential to significantly improve early diagnosis, targeted therapy, and patient outcomes.

KEYWORDS: Nanoparticle-mediated drug delivery, cancer imaging techniques, targeted cancer therapy, tumor-specific accumulation, nanotheranostics, controlled drug release, biomedical nanotechnology.

INTRODUCTION

Cancer remains one of the leading causes of mortality worldwide, posing a significant challenge to global healthcare systems despite decades of intensive research and therapeutic advancements. The complexity of cancer arises from its multifactorial nature, involving genetic mutations, abnormal cell signaling, and interactions with the surrounding microenvironment. Conventional approaches to cancer diagnosis and treatment, including imaging techniques, surgery, chemotherapy, and radiotherapy, have contributed substantially to patient care. However, these methods often face limitations such as lack of specificity, delayed detection, systemic toxicity, and the development of drug resistance. These challenges highlight the urgent need for innovative strategies that can improve early diagnosis and provide more effective and targeted treatment options.

In recent years, nanotechnology has emerged as a transformative field with the potential to revolutionize cancer management. Nanoparticles, typically ranging in size from 1 to 100 nanometers, possess unique physicochemical properties that distinguish them from bulk materials. Their small size allows them to interact at the cellular and molecular levels, while their large surface area enables the attachment of various functional molecules, including drugs, targeting ligands, and imaging agents. These characteristics make nanoparticles highly suitable for biomedical applications, particularly in oncology, where precision and specificity are crucial.

Early detection of cancer significantly increases the chances of successful treatment, yet many traditional diagnostic methods struggle to identify tumors at initial stages. Nanoparticles can be engineered to act as contrast agents in various imaging modalities such as magnetic resonance imaging (MRI), computed tomography (CT), positron emission tomography (PET), and optical imaging. By improving signal intensity and specificity, nanoparticles enable clearer visualization of tumor tissues, facilitating earlier and more reliable diagnosis. Furthermore, nanoparticles can be functionalized with targeting molecules such as antibodies, peptides, or small ligands that recognize specific biomarkers expressed on cancer cells, thereby enhancing selective accumulation at tumor sites.

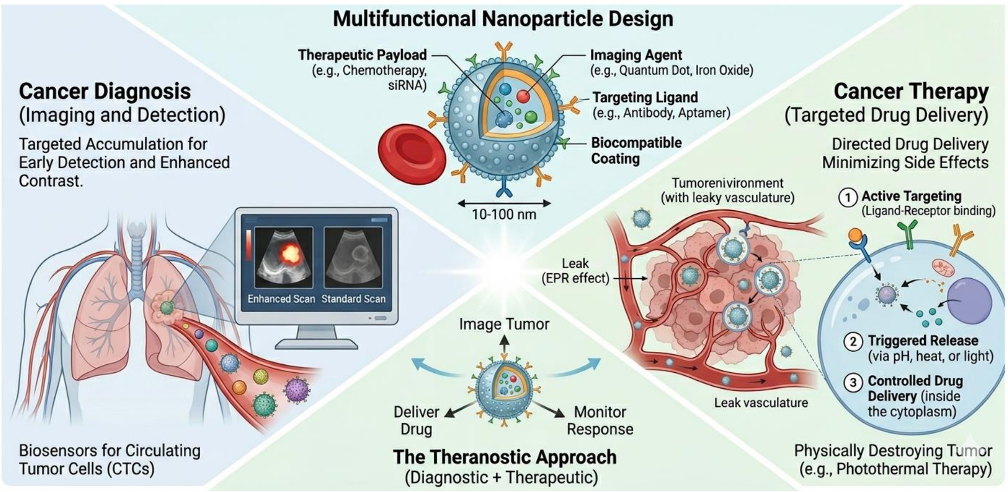
In addition to diagnosis, nanoparticles have shown remarkable potential in cancer therapy. Conventional chemotherapy often affects both cancerous and healthy cells, leading to severe side effects and reduced patient quality of life. Nanoparticles can be designed to carry anticancer drugs directly to tumor tissues, minimizing exposure to normal cells and thereby reducing toxicity. This targeted delivery is often achieved through both passive and active mechanisms. Passive targeting takes advantage of the enhanced permeability and retention (EPR) effect, a phenomenon in which nanoparticles accumulate preferentially in tumor tissues due to leaky vasculature and poor lymphatic drainage. Active targeting, on the other hand, involves the attachment of specific ligands to the nanoparticle surface, enabling precise binding to cancer cell receptors.

Moreover, nanoparticles allow for controlled and sustained drug release, which helps maintain optimal therapeutic concentrations over extended periods. This feature not only improves treatment efficacy but also reduces the frequency of drug administration. Various types of nanoparticles, including liposomes, polymeric nanoparticles, dendrimers, metallic nanoparticles, and lipid-based systems, have been extensively studied for their drug delivery capabilities. Each type offers distinct advantages depending on the application, such as biocompatibility, stability, and ease of functionalization.

Beyond drug delivery, nanoparticles are also being explored in innovative therapeutic approaches such as photothermal therapy and photodynamic therapy. In photothermal therapy, certain nanoparticles can absorb light energy and convert it into heat, leading to localized destruction of cancer cells. Similarly, in photodynamic therapy, nanoparticles are used to deliver photosensitizing agents that generate reactive oxygen species upon light activation, causing targeted cell damage. These techniques offer minimally invasive alternatives to traditional treatments and can be combined with other therapies to enhance overall effectiveness.

Another promising area is the development of theranostic nanoparticles, which integrate diagnostic and therapeutic functions into a single platform. These multifunctional systems enable simultaneous imaging and treatment, allowing real-time monitoring of therapeutic responses and facilitating personalized medicine. By providing immediate feedback on treatment efficacy, theranostics can help clinicians adjust therapeutic strategies more effectively, improving patient outcomes.

Despite the numerous advantages, the application of nanoparticles in cancer diagnosis and therapy is not without challenges. Issues related to toxicity, biocompatibility, and long-term safety remain major concerns. The behavior of nanoparticles in biological systems is complex and influenced by factors such as size, shape, surface charge, and composition. Unintended accumulation in vital organs and potential immune responses must be carefully evaluated. Additionally, large-scale production, standardization, and regulatory approval pose significant hurdles that need to be addressed before widespread clinical implementation can be achieved.



Ethical and environmental considerations also play a role in the development and use of nanotechnology in medicine. The long-term impact of nanoparticle exposure on both human health and the environment requires thorough investigation. Regulatory frameworks must evolve to ensure the safe and responsible use of nanomaterials, balancing innovation with risk management.

In conclusion, nanoparticles represent a promising frontier in the fight against cancer, offering innovative solutions for both diagnosis and therapy. Their unique properties enable improved imaging, targeted drug delivery, and the development of advanced therapeutic techniques. While significant progress has been made, ongoing research is essential to overcome existing challenges and fully realize the potential of nanoparticles in clinical oncology. As interdisciplinary collaboration continues to advance this field, nanoparticles are expected to play an increasingly important role in achieving more precise, effective, and personalized cancer care.

MATERIALS AND METHODS

In cancer diagnosis, early and accurate detection is essential for improving patient survival rates. Traditional diagnostic techniques often face challenges such as low sensitivity and limited specificity, particularly in detecting tumors at an early stage. Nanoparticles can significantly enhance diagnostic efficiency by acting as contrast agents in imaging techniques such as magnetic resonance imaging, computed tomography, and optical imaging. Due to their tunable optical and magnetic properties, nanoparticles improve image clarity and enable better visualization of tumor tissues. Furthermore, they can be modified with targeting ligands that bind specifically to cancer cell markers, allowing selective accumulation at tumor sites and reducing the likelihood of false-positive results.

Another important advantage of nanoparticles in diagnosis is their ability to exploit the enhanced permeability and retention effect. Tumor tissues often have leaky blood vessels and poor lymphatic drainage, which allows nanoparticles to accumulate more readily than in normal tissues. This passive targeting mechanism improves the detection of tumors and supports more precise imaging. In addition, active targeting strategies involve attaching molecules such as antibodies or peptides to the nanoparticle surface, enabling them to recognize and bind specifically to cancer cells. These approaches collectively enhance the accuracy and reliability of cancer diagnosis.

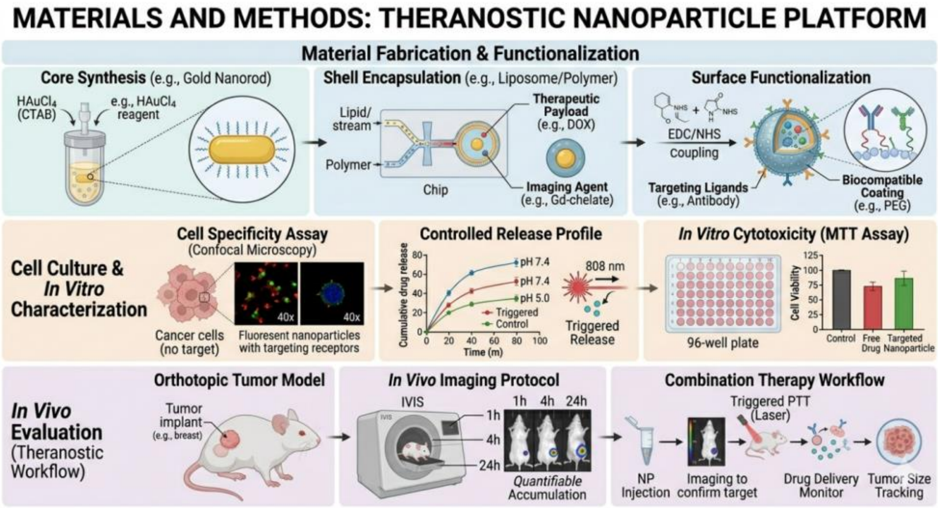
In the therapeutic domain, nanoparticles play a crucial role in improving the delivery of anticancer drugs. Conventional chemotherapy is often associated with severe side effects due to the non-specific distribution of drugs throughout the body. Nanoparticles can be used as carriers to deliver drugs directly to tumor tissues, thereby minimizing damage to healthy cells. This targeted drug delivery approach increases the effectiveness of treatment while reducing toxicity. Nanoparticles can encapsulate a wide range of therapeutic agents, protect them from degradation, and release them in a controlled manner, ensuring sustained therapeutic action.

Various types of nanoparticles have been explored for cancer therapy, including liposomes, polymeric nanoparticles, dendrimers, metallic nanoparticles, and solid lipid nanoparticles. Each type offers specific advantages depending on the application. For example, liposomes are highly biocompatible and widely used in drug delivery, while metallic nanoparticles such as gold nanoparticles are useful in imaging and thermal therapies. Polymeric nanoparticles provide controlled drug release, and dendrimers offer precise structural control for targeted delivery.

Beyond conventional drug delivery, nanoparticles are also used in advanced therapeutic techniques such as photothermal and photodynamic therapy. In photothermal therapy, certain nanoparticles absorb light energy and convert it into heat, which can destroy cancer cells in a localized manner. Photodynamic therapy involves the use of light-activated compounds that generate reactive oxygen species to kill cancer cells. These approaches are minimally invasive and can be combined with other treatments to enhance overall therapeutic outcomes.

A significant advancement in this field is the development of theranostic nanoparticles, which combine diagnostic and therapeutic functions in a single system. These multifunctional nanoparticles allow simultaneous imaging and treatment, enabling real-time monitoring of therapeutic responses. This integrated approach supports personalized medicine, where treatments can be tailored according to the specific characteristics of a patient’s tumor.

Despite their promising potential, the use of nanoparticles in cancer diagnosis and therapy faces several challenges. Issues related to toxicity, long-term safety, and biocompatibility remain major concerns. The interaction of nanoparticles with biological systems is complex, and unintended accumulation in vital organs may lead to adverse effects. Additionally, large-scale production, standardization, and regulatory approval pose significant barriers to clinical translation.



Classification of Nanoparticles

For the purpose of this review, nanoparticles were categorized based on their composition and functional properties. Major categories included metallic nanoparticles (such as gold and silver nanoparticles), polymeric nanoparticles, liposomes, dendrimers, and solid lipid nanoparticles. Each category was analyzed in terms of its structural characteristics, preparation methods, and suitability for specific diagnostic or therapeutic applications. This classification helped in identifying the strengths and limitations of different nanoparticle systems.

Evaluation of Diagnostic Applications

The role of nanoparticles in cancer diagnosis was assessed by reviewing studies that utilized nanoparticles as contrast agents or imaging probes. Various imaging techniques such as magnetic resonance imaging (MRI), computed tomography (CT), positron emission tomography (PET), and optical imaging were considered. Parameters such as sensitivity, specificity, signal enhancement, and targeting ability were evaluated. Special attention was given to studies demonstrating early detection of tumors and improved imaging accuracy through nanoparticle-based systems.

Evaluation of Therapeutic Applications

Therapeutic applications of nanoparticles were analyzed by examining their use in drug delivery, photothermal therapy, photodynamic therapy, and combination treatments. The effectiveness of nanoparticle-mediated drug delivery systems was evaluated based on factors such as drug loading capacity, release kinetics, targeting efficiency, and reduction of systemic toxicity. Studies demonstrating enhanced therapeutic outcomes compared to conventional treatments were highlighted. Additionally, the concept of theranostics, which integrates diagnosis and therapy, was reviewed in detail.

Analysis of Targeting Mechanisms

Both passive and active targeting mechanisms were examined. Passive targeting through the enhanced permeability and retention (EPR) effect was discussed in relation to nanoparticle accumulation in tumor tissues. Active targeting strategies involving surface modification with ligands such as antibodies, peptides, and small molecules were also analyzed. The efficiency of these targeting approaches in improving specificity and reducing off-target effects was evaluated based on available literature.

Safety and Toxicity Assessment

Safety is a critical aspect of nanoparticle application in medicine. Therefore, studies addressing the toxicity, biocompatibility, and biodegradability of nanoparticles were included in the review. Data related to cytotoxicity, immunogenic responses, and long-term accumulation in organs were carefully examined. Regulatory considerations and challenges associated with clinical translation were also discussed to provide a comprehensive understanding of the risks involved.

Data Synthesis and Interpretation

After data extraction, the collected information was synthesized qualitatively. A comparative approach was used to identify trends, similarities, and differences among various studies. Findings were organized into coherent sections to provide a clear understanding of the current state of research. Emphasis was placed on critically analyzing the advantages and limitations of different nanoparticle systems, rather than merely summarizing the results.

Quality Assessment

To ensure the reliability of the included studies, the quality of each article was assessed based on factors such as study design, sample size, methodology, and clarity of results. Preference was given to well-designed experimental studies, systematic reviews, and meta-analyses. Articles published in high-impact journals were considered more reliable, although relevant studies from other sources were also included if they met the quality criteria.

Limitations of the Methodology

While efforts were made to ensure a comprehensive and unbiased review, certain limitations exist. The restriction to English-language publications may have excluded some relevant studies. Additionally, the rapid evolution of nanotechnology means that new findings may emerge after the completion of this review. Despite these limitations, the methodology adopted provides a thorough and reliable overview of the current knowledge in the field.

Ethical Considerations

As this study is based solely on previously published data, no ethical approval was required. Proper citation and acknowledgment of original sources were maintained throughout the review process to avoid plagiarism and ensure academic integrity.

Literature review

Cancer remains a major global health challenge, driving continuous efforts to develop more effective diagnostic and therapeutic strategies. Conventional approaches such as chemotherapy, radiotherapy, and surgery have significantly contributed to cancer management; however, their limitations—including poor specificity, systemic toxicity, and drug resistance—have prompted the exploration of advanced technologies. In this context, nanotechnology has emerged as a promising field, offering innovative solutions through the application of nanoparticles in oncology.

Recent literature highlights that nanoparticles possess unique physicochemical properties, including nanoscale size, high surface-area-to-volume ratio, and tunable surface chemistry, which make them highly suitable for biomedical applications. These characteristics enable nanoparticles to interact effectively with biological systems and facilitate targeted delivery of therapeutic agents. Studies have consistently reported that nanoparticles can improve drug solubility, enhance stability, and prolong circulation time in the bloodstream, thereby increasing therapeutic efficiency while minimizing adverse effects.

A significant body of research has focused on the role of nanoparticles in cancer diagnosis. Early detection is critical for improving survival rates, yet traditional imaging techniques often lack sufficient sensitivity and specificity. Nanoparticles have been extensively studied as contrast agents in imaging modalities such as magnetic resonance imaging (MRI), computed tomography (CT), and optical imaging. According to recent reviews, nanoparticles can enhance signal intensity and provide more accurate visualization of tumor tissues, enabling earlier and more precise diagnosis.

Additionally, functionalization of nanoparticles with targeting ligands such as antibodies and peptides has been shown to improve selective binding to cancer cells, thereby reducing false-positive results and enhancing diagnostic accuracy.
Another key concept discussed in the literature is the enhanced permeability and retention (EPR) effect, which allows nanoparticles to accumulate preferentially in tumor tissues due to leaky vasculature and poor lymphatic drainage. This passive targeting mechanism has been widely reported as a major advantage in both diagnostic and therapeutic applications. Furthermore, active targeting strategies involving surface modification of nanoparticles have demonstrated improved specificity by enabling direct interaction with tumor-specific receptors. These combined targeting approaches contribute to more efficient tumor localization and treatment outcomes.

In the therapeutic domain, nanoparticles have gained considerable attention as drug delivery systems. Traditional chemotherapy is associated with significant toxicity due to its non-specific distribution, affecting both cancerous and healthy cells. Literature suggests that nanoparticle-based drug delivery systems can overcome these limitations by enabling targeted delivery of anticancer drugs directly to tumor sites. This targeted approach not only enhances drug efficacy but also reduces systemic side effects and improves patient compliance.

Various types of nanoparticles have been explored for cancer therapy, including liposomes, polymeric nanoparticles, metallic nanoparticles, dendrimers, and carbon-based nanomaterials. Each type offers distinct advantages depending on its composition and functional properties. For instance, liposomes are known for their biocompatibility and ability to encapsulate both hydrophilic and hydrophobic drugs, while polymeric nanoparticles provide controlled and sustained drug release. Metallic nanoparticles, particularly gold nanoparticles, have attracted significant attention due to their optical properties and potential use in imaging and thermal therapies. Studies have shown that gold nanoparticles can be utilized in photothermal therapy, where they convert light energy into heat to selectively destroy cancer cells.

In addition to conventional drug delivery, nanoparticles have been widely investigated for advanced therapeutic approaches such as photodynamic therapy (PDT) and photothermal therapy (PTT). These techniques involve the use of nanoparticles to generate reactive oxygen species or localized heat upon external stimulation, leading to targeted destruction of cancer cells. Literature indicates that these minimally invasive therapies offer improved precision and reduced damage to surrounding healthy tissues compared to traditional treatments. Moreover, combining these approaches with nanoparticle-based drug delivery systems has shown synergistic effects, further enhancing therapeutic outcomes.

Another important advancement highlighted in recent studies is the development of theranostic nanoparticles. These multifunctional systems integrate diagnostic and therapeutic capabilities into a single platform, enabling simultaneous imaging and treatment of cancer. Theranostics allows real-time monitoring of drug distribution and therapeutic response, facilitating personalized treatment strategies. Researchers have emphasized that this approach represents a significant step toward precision medicine, as it enables clinicians to tailor treatments based on individual patient characteristics.

Despite the promising potential of nanoparticles, the literature also identifies several challenges that hinder their clinical translation. One of the primary concerns is toxicity and biocompatibility. The interaction of nanoparticles with biological systems is complex and can lead to unintended accumulation in vital organs such as the liver, spleen, and kidneys. Studies have reported that factors such as particle size, shape, surface charge, and composition play a crucial role in determining the safety profile of nanoparticles. Therefore, thorough evaluation of these parameters is essential to ensure their safe application in clinical settings.

Another challenge highlighted in the literature is the limited number of nanoparticle-based therapies that have successfully reached clinical use. While numerous studies have demonstrated promising results in vitro and in vivo, only a few have progressed to clinical trials and regulatory approval. This gap is attributed to issues related to large-scale production, reproducibility, stability, and regulatory complexities. Researchers have emphasized the need for standardized protocols and comprehensive safety assessments to facilitate the translation of nanoparticle-based technologies from laboratory research to clinical practice.

Recent advances in nanotechnology have also focused on overcoming multidrug resistance, a major obstacle in cancer therapy. Nanoparticles have been shown to bypass drug resistance mechanisms by delivering drugs directly into cancer cells and protecting them from degradation. Additionally, the use of combination therapies, where nanoparticles carry multiple therapeutic agents, has been explored to enhance treatment efficacy and reduce the likelihood of resistance development. Studies have reported that such strategies can significantly improve treatment outcomes, particularly in aggressive and resistant forms of cancer.

Environmental and ethical considerations are also discussed in the literature. The long-term effects of nanoparticle exposure on human health and the environment remain uncertain, necessitating further research in this area. The development of eco-friendly and biocompatible nanoparticles, such as those synthesized using green chemistry approaches, has been proposed as a potential solution to these concerns.

In summary, the literature clearly demonstrates that nanoparticles hold immense potential in revolutionizing cancer diagnosis and therapy. Their unique properties enable improved imaging, targeted drug delivery, and the development of advanced therapeutic techniques. While significant progress has been made, challenges related to safety, scalability, and regulatory approval must be addressed to fully realize their clinical potential. Ongoing research and interdisciplinary collaboration are expected to further advance this field, paving the way for more effective and personalized cancer treatment strategies.

CONCLUSION

In conclusion, nanoparticles have emerged as a promising and innovative approach in the field of cancer diagnosis and therapy, offering significant improvements over conventional methods. Their unique physicochemical properties, including nanoscale size, high surface area, and the ability to be functionalized with targeting molecules, enable precise interaction with cancer cells and the tumor microenvironment. These features contribute to enhanced imaging, early detection, and accurate diagnosis of cancer, which are critical for improving patient outcomes.

In therapeutic applications, nanoparticles have demonstrated great potential in targeted drug delivery, allowing anticancer agents to be delivered directly to tumor sites while minimizing damage to healthy tissues. This targeted approach reduces systemic toxicity and improves treatment efficacy. Additionally, nanoparticles support advanced treatment strategies such as controlled drug release, photothermal therapy, and photodynamic therapy, further expanding their role in cancer management. The development of multifunctional systems, such as theranostic nanoparticles, has also enabled the integration of diagnosis and therapy into a single platform, promoting more personalized and efficient treatment approaches.

Despite these advantages, several challenges remain, including concerns related to toxicity, long-term safety, large-scale production, and regulatory approval. Addressing these issues is essential for the successful translation of nanoparticle-based technologies into clinical practice. Continued research and collaboration across disciplines will play a key role in overcoming these limitations.

Overall, nanoparticles represent a transformative advancement in oncology, with the potential to significantly improve the accuracy of diagnosis, effectiveness of treatment, and overall quality of life for cancer patients in the future.

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11. **Note for Figures**

Some figures included in this review article are created using artificial intelligence (AI) tools for illustrative and educational purposes. These images are schematic representations designed to enhance understanding of nanoparticle mechanisms in cancer diagnosis and therapy.