Review Article

BIOMEDICAL Journal of Scientific & Technical Research

ISSN: 2574 -1241

DOI: 10.26717/BJSTR.2026.67.010464

# Nanobiotechnology for Cancer Diagnosis and Therapy: A Review of Recent Advances in Nanoparticle-Based Delivery Systems and Imaging Techniques

**Hamisu Shuaibu Idris[1], Nsisanobari Gomba Awa[2], Moses Adondua Abah[3,4]*, Ochuele Dominic Agida[3,4] and Micheal Oladosu Abimbola[4,5]**

[1]*Department of Microbiology/Biotechnology, Faculty of Life Sciences, Federal University Dutse, Jigawa State, Nigeria*

[2]*Department of Biomedical Science Laboratory Technology, School of Science Laboratory Technology, University of Port Harcourt, Rivers State, Nigeria*

[3]*Department of Biochemistry, Faculty of Biosciences, Federal University Wukari, Taraba State, Nigeria*

[4]*ResearchHub Nexus Institute, Nigeria*

[5]*Department of Chemical Sciences, Faculty of Science, Anchor University, Ayobo, Lagos State, Nigeria*

***Corresponding author:** Moses Adondua Abah, Department of Biochemistry, Faculty of Biosciences, Federal University Wukari, Taraba State, Nigeria. ResearchHub Nexus Institute, Nigeria

**ARTICLE INFO**

**Received:** October 13, 2026

**Published:** October 30, 2026

**Citation:** Hamisu Shuaibu Idris, Nsisanobari Gomba Awa, Moses Adondua Abah, Ochuele Dominic Agida and Micheal Oladosu Abimbola. Nanobiotechnology for Cancer Diagnosis and Therapy: A Review of Recent Advances in Nanoparticle-Based Delivery Systems and Imaging Techniques. Biomed J Sci & Tech Res 67(2)-2026. BJSTR. MS.ID.010464.

**ABSTRACT**

Cancer remains one of the leading causes of morbidity and mortality worldwide, with conventional diagnostic and therapeutic approaches often constrained by limited specificity, systemic toxicity, poor drug bioavailability, and treatment resistance. Nanobiotechnology has emerged as a transformative field that integrates nanotechnology with biomedical sciences to overcome these challenges through the development of multifunctional nanoparticle-based platforms for targeted cancer diagnosis and therapy. This review provides a comprehensive overview of recent advances in nanoparticle engineering, emphasizing the influence of physicochemical properties, tumor-targeting strategies, and biological interactions on therapeutic efficacy and diagnostic performance. Major nanoparticle delivery systems, including lipid-based, polymeric, inorganic, biomimetic, and hybrid nanocarriers, are critically discussed with respect to their applications in targeted drug delivery, gene therapy, immunotherapy, photothermal therapy, photodynamic therapy, and theranostic interventions. The review also examines the expanding role of nanoparticles in cancer imaging, highlighting recent developments in magnetic resonance imaging, computed tomography, optical and fluorescence imaging, and positron emission tomography/single-photon emission computed tomography for improved tumor detection and disease monitoring. Furthermore, emerging innovations such as smart stimuli-responsive nanoplatforms and artificial intelligence-assisted nanomedicine are evaluated alongside current challenges associated with nanotoxicity, biological barriers, large-scale manufacturing, regulatory approval, and clinical translation. By integrating recent evidence across diagnostic and therapeutic applications, this review underscores the potential of nanoparticle-based technologies to enhance precision oncology through improved targeting, imaging accuracy, and therapeutic outcomes. It also identifies key research priorities and translational opportunities that are expected to accelerate the safe and effective clinical implementation of next-generation cancer nanomedicine.

**Keywords:** Cancer Nanobiotechnology; Nanoparticle-Based Drug Delivery; Cancer Imaging; Theranostics; Targeted Cancer Therapy; and Precision Oncology

**Abbreviations:** SLNs: Solid Lipid Nanoparticles; NLCs: Nanostructured Lipid Carriers; PLGA: Poly Lactic-Co-Glycolic Acid; PEG: Polyethylene Glycol; PCL: Polycaprolactone; MSNs: Mesoporous Silica Nanoparticles; PTT: Photothermal Therapy; PDT: Photodynamic Therapy; NIR: Near-Infrared; ROS: Reactive Oxygen Species; CT: Computed Tomography; MRI: Magnetic Resonance Imaging; SPIONs: Superparamagnetic Iron Oxide Nanoparticles; PET: Positron Emission Tomography; SPECT: Single-Photon Emission Computed Tomography; AI: Artificial Intelligence

## Introduction

Cancer remains one of the leading causes of morbidity and mortality worldwide, posing a significant burden on healthcare systems and economies. Despite considerable advances in surgery, chemotherapy, radiotherapy, immunotherapy, and targeted therapies, many cancers continue to exhibit poor prognosis due to late diagnosis, tumor heterogeneity, drug resistance, and treatment-associated toxicity. Conventional diagnostic techniques often lack the sensitivity and specificity required for early detection, while traditional therapeutic approaches may damage healthy tissues and produce severe adverse effects. These limitations have stimulated the search for innovative strategies capable of improving diagnostic accuracy and therapeutic efficacy. In this context, nanobiotechnology has emerged as a promising interdisciplinary field that combines nanotechnology with biological sciences to develop advanced platforms for cancer diagnosis and treatment [1]. The ability of engineered nanomaterials to interact with biological systems at the molecular and cellular levels has opened new opportunities for precision oncology [2]. The growing interest in nanoparticle-based systems is largely attributed to their unique physicochemical properties, including nanoscale size, high surface-area-to-volume ratio, tunable surface characteristics, and versatile functionalization capabilities [3].

These features enable nanoparticles to improve drug solubility, enhance therapeutic stability, and facilitate controlled drug release at tumor sites [4]. Furthermore, nanoparticles can be engineered to selectively target cancer cells through passive accumulation within tumor tissues or active interactions with specific cellular receptors, thereby reducing off-target toxicity and improving treatment outcomes [5]. Advances in nanoparticle design have also contributed to overcoming biological barriers that traditionally limit the effectiveness of anticancer therapeutics, making nanotechnology an increasingly attractive approach for modern cancer management [6]. Recent developments in nanobiotechnology have resulted in a diverse range of nanoparticle-based delivery systems, including lipid-based nanoparticles, polymeric nanoparticles, inorganic nanoparticles, and biomimetic nanocarriers [4]. These systems have demonstrated considerable potential for delivering chemotherapeutic drugs, nucleic acids, proteins, and immunomodulatory agents with enhanced precision and efficacy [3]. Beyond therapeutic applications, nanoparticles have revolutionized cancer diagnosis through their integration into advanced imaging modalities.

Functionalized nanomaterials have been successfully employed as contrast agents and imaging probes in magnetic resonance imaging, computed tomography, fluorescence imaging, positron emission tomography, and single-photon emission computed tomography, thereby improving tumor visualization and disease monitoring [7]. The emergence of theranostic nanoparticles, which integrate diagnostic and therapeutic functions within a single platform, further highlights the transformative potential of nanobiotechnology in personalized cancer care [2]. Despite these promising advances, several challenges continue to hinder the widespread clinical translation of nanoparticle-based technologies. Concerns regarding nanoparticle toxicity, immune system interactions, biodistribution variability, long-term biosafety, and large-scale manufacturing remain significant obstacles to clinical implementation [1]. Moreover, the complex mechanisms governing nanoparticle transport, tumor penetration, and cellular uptake require further investigation to optimize therapeutic performance and improve patient outcomes [5]. Recent research has therefore focused on developing smart and stimuli-responsive nanoplatforms, improving targeting efficiency, and integrating artificial intelligence into nanoparticle design and optimization processes [3]. These innovations are expected to accelerate the translation of nanomedicine from laboratory research to routine clinical practice [6].

This review provides a comprehensive and up-to-date synthesis of recent advances in nanobiotechnology for cancer diagnosis and therapy, with particular emphasis on nanoparticle-based delivery systems and imaging techniques. It begins by examining the fundamental design principles that govern nanoparticle performance, including physicochemical characteristics, tumor-targeting strategies, biological interactions, biodistribution, and cellular uptake, all of which influence therapeutic efficacy and diagnostic accuracy. The review subsequently explores the major classes of nanoparticle delivery platforms, highlighting their structural features, functional advantages, and biomedical applications in targeted drug delivery, gene therapy, immunotherapy, photothermal therapy, photodynamic therapy, and theranostic interventions. Furthermore, it evaluates the expanding role of nanoparticle-enabled imaging technologies in enhancing early cancer detection, accurate tumor characterization, molecular imaging, and real-time treatment monitoring through advanced imaging modalities. Emerging innovations, including smart and stimuli-responsive nanoparticles, biomimetic nanocarriers, multifunctional theranostic systems, and artificial intelligence-assisted nanomedicine, are also critically discussed alongside current challenges associated with clinical translation, biosafety, regulatory approval, and large-scale manufacturing.

By integrating recent developments across both therapeutic and diagnostic applications, this review provides a balanced perspective on the current landscape of cancer nanobiotechnology, identifies existing knowledge gaps, and highlights promising research directions and translational opportunities that are expected to accelerate the development of safe, effective, and precision-guided nanomedicine for improved cancer management.

## Nanoparticle Design for Cancer Applications

The successful application of nanobiotechnology in cancer diagnosis and therapy is fundamentally dependent on the rational design of nanoparticles capable of overcoming complex biological barriers while maximizing therapeutic and diagnostic performance. Nanoparticle design encompasses the optimization of physicochemical char-

acteristics, surface engineering, targeting strategies, and biological interactions that collectively determine circulation time, tumor accumulation, cellular internalization, drug release, imaging efficiency, and overall clinical efficacy [4]. Advances in nanomaterial engineering have enabled the development of multifunctional nanoplatforms with precisely controlled size, morphology, surface charge, composition, and functionalization, thereby improving their ability to selectively target malignant tissues while minimizing off-target effects [8]. Furthermore, growing evidence indicates that nanoparticle transport, biodistribution, and clearance are regulated by dynamic interactions with the vascular system, immune components, and the tumor microenvironment rather than by passive accumulation alone [5,6] The formation of a protein corona following exposure to biological fluids further modifies nanoparticle identity, influencing biodistribution, cellular uptake, immune recognition, and therapeutic outcomes [9,10].

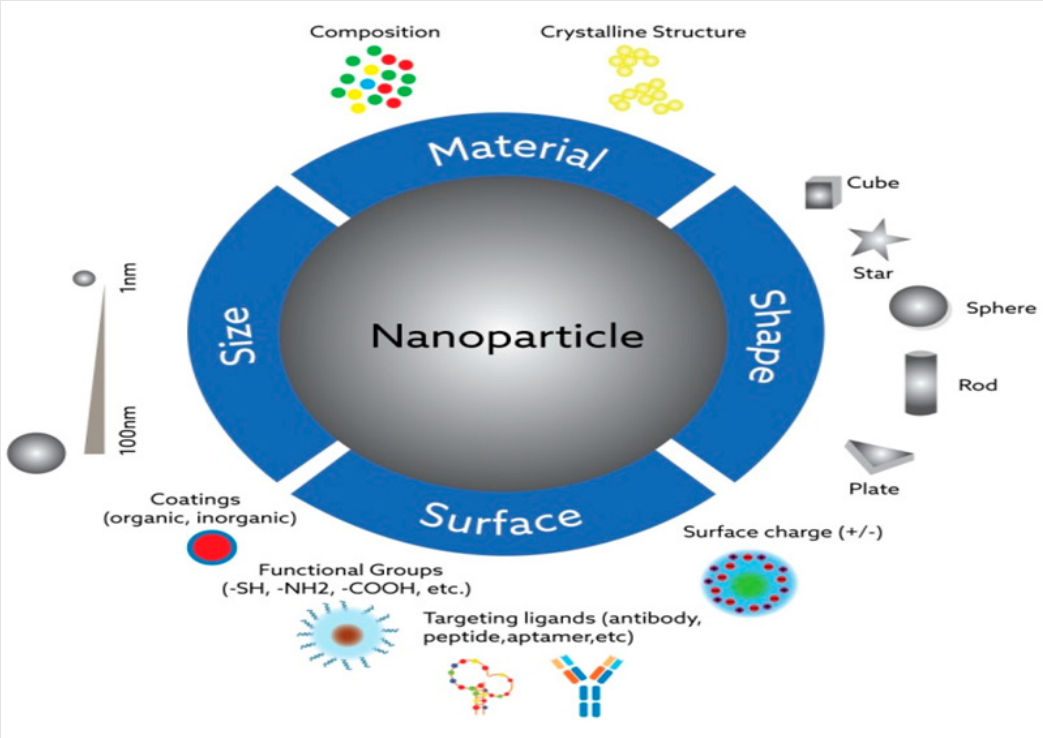
In addition, maintaining nanoparticle colloidal stability under physiological conditions is essential for preserving delivery efficiency and preventing aggregation-induced loss of functionality [11]. Consequently, understanding the interplay between nanoparticle physicochemical properties and biological behavior is critical for designing safe, efficient, and clinically translatable nanomedicines. (Table 1) The following sections discuss the key design principles that govern nanoparticle performance, focusing on physicochemical characteristics, tumor-targeting strategies, and biological fate following systemic administration.

**Table 1:** Relationship between nanoparticle design, tumor targeting, biological fate, and clinical outcomes in cancer nanobiotechnology.

| Nanoparticle design | Tumor targeting | Biological fate | Clinical benefit |
|---|---|---|---|
| Size | Penetration | Biodistribution | Higher efficacy |
| Shape | Cellular interaction | Uptake | Better delivery |
| Surface charge | Receptor interaction | Immune recognition | Lower toxicity |
| Functionalization | Active targeting | Prolonged circulation | Improved specificity |
| Composition | Payload compatibility | Biodegradation | Better imaging and therapy |

## Physicochemical Characteristics

The physicochemical characteristics of nanoparticles are fundamental determinants of their biological behavior and clinical performance in cancer diagnosis and therapy. Properties such as particle size, shape, surface charge, composition, and surface chemistry directly influence circulation time, drug loading capacity, imaging efficiency, biodistribution, and interactions with biological systems [4]. Careful optimization of these characteristics is therefore essential for developing nanoparticle systems capable of achieving effective tumor targeting, controlled payload release, and improved therapeutic outcomes [1]. Particle size is a key factor influencing nanoparticle transport, tumor penetration, and clearance. Nanoparticles within an appropriate size range generally exhibit prolonged circulation and enhanced tumor accumulation, whereas excessively large particles are more susceptible to rapid uptake by the mononuclear phagocyte system and very small particles may be rapidly eliminated through renal filtration [5]. In addition to size, nanoparticle shape and material composition affect cellular interactions, intracellular trafficking, drug encapsulation efficiency, and imaging performance, allowing the development of multifunctional nanoplatforms for diverse oncological applications [3]. Surface properties are equally important in determining nanoparticle stability and functionality. Surface modification with polymers, targeting ligands, antibodies, peptides, or other biomolecules improves colloidal stability, enhances biocompatibility, and facilitates selective interactions with cancer cells [9]. Maintaining colloidal stability under physiological conditions is particularly important because nanoparticle aggregation can reduce circulation efficiency, impair tumor delivery, and compromise therapeutic efficacy [12]. Collectively, the rational design and optimization of physicochemical characteristics provide the structural foundation for nanoparticle-based delivery systems and imaging agents, supporting their application in precision cancer diagnosis and therapy (Figure 1).




Note: Source: [40].

**Figure 1:** Physicochemical features influencing nanoparticle interactions with biological systems. The physicochemical properties of nanoparticles, including particle size, shape, morphology, surface charge, coating materials, functional groups, hydrophilic/hydrophobic characteristics, chemical composition, and crystalline structure, collectively govern their interactions with biological systems and influence biodistribution, cellular uptake, stability, targeting efficiency, and therapeutic performance in cancer diagnosis and therapy.

## Tumor-Targeting Strategies

Tumor-targeting strategies are central to the success of nanoparticle-based cancer diagnosis and therapy, as they enhance the selective accumulation of therapeutic and imaging agents within malignant tissues while minimizing systemic toxicity. Effective targeting requires nanoparticles to overcome biological barriers, including vascular transport, immune surveillance, and cellular internalization, before reaching tumor cells [5]. Advances in nanoparticle engineering have therefore focused on improving targeting efficiency through passive, active, and stimuli-responsive approaches that collectively enhance therapeutic precision and diagnostic performance [1]. Passive targeting exploits the abnormal vasculature and impaired lymphatic drainage associated with many solid tumors, promoting preferential nanoparticle accumulation. However, recent studies have demonstrated that efficient tumor delivery also depends on active transvascular transport and endothelial interactions, indicating that passive accumulation alone is insufficient to achieve optimal therapeutic outcomes [6]. These findings have shifted nanoparticle design toward strategies that improve transport across biological barriers and increase tumor penetration [5]. Active targeting further enhances delivery specificity through surface functionalization with antibodies, peptides, aptamers, and other ligands that recognize receptors overexpressed on cancer cells or within the tumor microenvironment [4].

In addition, stimuli-responsive nanoparticles are engineered to release therapeutic payloads in response to tumor-specific conditions, such as acidic pH, redox imbalance, enzyme activity, or external triggers including light, heat, ultrasound, and magnetic fields, thereby improving treatment selectivity and reducing off-target effects [1]. The integration of these targeting strategies with multifunctional nanoparticle platforms has significantly advanced precision oncology by enabling more efficient drug delivery, enhanced molecular imaging, and personalized cancer management [3].

### Biological Fate and Cellular Uptake

The biological fate of nanoparticles following systemic administration plays a critical role in determining their therapeutic efficacy, imaging performance, and clinical safety. After entering the bloodstream, nanoparticles interact with biological fluids, immune cells, and vascular barriers, which collectively influence their circulation, biodistribution, tumor accumulation, and clearance [12]. These processes are governed by nanoparticle characteristics such as size, shape, surface chemistry, and composition, highlighting the importance of rational design in optimizing in vivo performance [5]. A key event influencing nanoparticle behavior is the formation of a protein corona, which occurs when plasma proteins adsorb onto the nanoparticle surface, altering its biological identity and interactions with cells [9]. The composition of the protein corona affects immune recognition, circulation time, cellular uptake, and targeting efficiency, making it an important consideration in nanoparticle engineering [10]. Surface modification with hydrophilic polymers and biomimetic coatings has therefore been widely employed to minimize undesirable protein adsorption, prolong systemic circulation, and enhance selective tumor delivery [8]. Successful nanoparticle delivery also depends on efficient transport across vascular barriers and subsequent cellular internalization within tumor tissues.

Recent studies have shown that nanoparticle accumulation is regulated by active transvascular transport and endothelial interactions in addition to passive extravasation, providing new insights into tumor-targeting mechanisms [6]. Once internalized through endocytic pathways, nanoparticles release their therapeutic or imaging payloads before undergoing biodegradation and elimination via hepatic, renal, or immune-mediated pathways [12]. Maintaining colloidal stability throughout these processes is equally important, as nanoparticle aggregation can reduce delivery efficiency and increase off-target accumulation [11]. Collectively, understanding the biological fate and cellular uptake of nanoparticles is essential for developing safe, effective, and clinically translatable nanomedicines for precision cancer diagnosis and therapy.

## Nanoparticle-Based Delivery Systems

Nanoparticle-based delivery systems have become fundamental to modern cancer nanobiotechnology by addressing the limitations of conventional therapeutic and diagnostic strategies, including poor drug solubility, rapid systemic clearance, non-specific biodistribution, and dose-limiting toxicity. Through precise engineering of their composition, structure, and surface characteristics, these nanocarriers enhance drug stability, improve pharmacokinetic behavior, facilitate targeted delivery, and enable controlled payload release, thereby maximizing therapeutic efficacy while minimizing adverse effects [12,13]. Beyond drug delivery, advances in nanobiotechnology have enabled multifunctional platforms capable of integrating molecular imaging, gene delivery, immunotherapy, and theranostic applications within a single nanosystem, supporting the evolution of precision oncology [14, 15]. The growing diversity of nanoparticle platforms reflects the need to overcome distinct biological barriers and meet specific clinical objectives. Consequently, lipid-based, polymeric, inorganic, biomimetic, and hybrid nanocarriers have been developed with unique structural and functional characteristics that influence their drug-loading capacity, targeting efficiency, biological interactions, and translational potential [12,16]. Collectively, these delivery systems form the foundation of contemporary cancer nanomedicine and continue to drive innovations in targeted diagnosis, personalized therapy, and clinical translation.

### Lipid-Based Nanoparticles

Lipid-based nanoparticles remain the most clinically established nanocarriers owing to their excellent biocompatibility, biodegradability, formulation flexibility, and proven ability to enhance the delivery of a broad spectrum of therapeutic and diagnostic agents. Their biomimetic lipid composition facilitates efficient encapsulation of hydrophilic and hydrophobic payloads, protects sensitive biomolecules from premature degradation, and prolongs systemic circulation while reducing off-target toxicity [13,14]. Continuous improvements in lipid engineering have also enabled the development of multifunctional platforms capable of integrating targeted drug delivery, controlled release, molecular imaging, and immunomodulation within a single nanosystem, thereby strengthening their role in precision cancer management [15].

**Liposomes:** Liposomes remain the benchmark lipid nanocarrier because of their structural versatility and extensive clinical validation. Their phospholipid bilayer architecture enables simultaneous encapsulation of hydrophilic drugs within the aqueous core and hydrophobic compounds within the lipid membrane, improving drug stability, bioavailability, and pharmacokinetic performance. Recent advances in PEGylation, ligand conjugation, and stimuli-responsive formulations have substantially improved tumor selectivity, intracellular drug delivery, and therapeutic efficacy. Furthermore, multifunctional liposomes capable of co-delivering chemotherapeutic agents, nucleic acids, immunotherapeutics, and imaging probes have accelerated the development of personalized and image-guided cancer therapy [13-15].

**Solid Lipid Nanoparticles (SLNs):** SLNs provide a stable solid lipid matrix that enhances the protection and sustained release of encapsulated therapeutic agents while improving the delivery of poorly water-soluble anticancer drugs. Compared with conventional formulations, SLNs offer improved chemical stability, controlled drug release, and enhanced compatibility with biological systems. Recent advances in surface functionalization and ligand-mediated targeting have further increased their capacity for selective tumor accumulation and efficient intracellular delivery, supporting their application in both targeted chemotherapy and nanoparticle-assisted imaging [13,17].

**Nanostructured Lipid Carriers (NLCs):** NLCs were developed to overcome the limited drug-loading capacity and potential drug expulsion associated with SLNs. By incorporating both solid and liquid lipids into a partially disordered matrix, NLCs provide greater encapsulation efficiency, improved formulation stability, and enhanced control over drug release. Recent innovations involving multifunctional surface modification, ligand-directed targeting, and co-delivery strategies have further expanded their application in cancer theranostics, enabling simultaneous therapeutic intervention and diagnostic imaging while improving treatment precision and clinical translation [13,14,17].

## Polymeric Nanoparticles

Polymeric nanoparticles have gained considerable attention in cancer nanomedicine because of their structural versatility, tunable physicochemical properties, and ability to support controlled and stimuli-responsive drug delivery. Their adaptable molecular architecture allows precise regulation of particle size, degradation rate, drug release kinetics, and surface functionality, enabling the delivery of diverse therapeutic agents while improving pharmacokinetic performance and reducing systemic toxicity [8,12]. Continuous advances in polymer engineering have further expanded their applications to targeted chemotherapy, gene delivery, immunotherapy, and molecular imaging, making polymeric nanocarriers indispensable components of precision oncology [16].

**Natural and Synthetic Polymeric Nanoparticles:** Natural polymers, including chitosan, alginate, gelatin, and hyaluronic acid, are valued for their excellent biocompatibility, biodegradability, and intrinsic biological activity, which facilitate the delivery of proteins, nucleic acids, and other sensitive therapeutic molecules. In contrast, synthetic polymers such as poly (lactic-co-glycolic acid) (PLGA), polyethylene glycol (PEG), and polycaprolactone (PCL) offer greater mechanical stability, reproducible manufacturing, and precisely controlled degradation profiles. Recent advances in polymer modification and ligand conjugation have significantly improved tumor targeting, intracellular uptake, and controlled drug release, enhancing therapeutic efficacy while minimizing off-target effects [12,16].

**Polymeric Micelles:** Polymeric micelles are self-assembled nanostructures formed from amphiphilic block copolymers, featuring a hydrophobic core surrounded by a hydrophilic shell. This architecture enables efficient encapsulation of poorly water-soluble anticancer drugs, improves aqueous solubility, and prolongs systemic circulation. Recent developments in pH-, enzyme-, and redox-responsive micellar systems have enabled site-specific drug release within the tumor microenvironment, thereby increasing therapeutic precision and reducing systemic toxicity. Multifunctional polymeric micelles capable of co-delivering chemotherapeutics, nucleic acids, and imaging agents have further strengthened their role in integrated cancer diagnosis and therapy [12,15].

**Dendrimers:** Dendrimers are highly branched polymeric nanostructures with well-defined architectures and abundant surface functional groups that permit the conjugation of multiple therapeutic agents, targeting ligands, and imaging molecules. Their monodisperse structure, high drug-loading capacity, and multivalent surface interactions promote efficient cellular uptake and selective tumor targeting. Recent innovations in dendrimer surface engineering have enabled multifunctional nanoplatforms capable of simultaneously supporting drug delivery, gene therapy, and molecular imaging, thereby advancing personalized cancer treatment and theranostic applications [8,16].

## Inorganic Nanoparticles

Inorganic nanoparticles have become integral to cancer nanobiotechnology because of their unique optical, magnetic, electrical, and physicochemical properties that extend beyond conventional drug delivery. Unlike lipid-based and polymeric nanocarriers, inorganic nanoparticles possess intrinsic functionalities that support multimodal imaging, stimuli-responsive therapy, biosensing, and theranostic applications. Their highly tunable composition and surface chemistry facilitate precise functionalization with therapeutic agents, targeting ligands, and contrast materials, enabling simultaneous cancer diagnosis and treatment while improving targeting accuracy and therapeutic outcomes [8,12]. Among the diverse inorganic nanocarriers, gold nanoparticles, magnetic nanoparticles, silica nanoparticles, and quantum dots have demonstrated remarkable translational potential in precision oncology.

**Gold Nanoparticles:** Gold nanoparticles (AuNPs) are among the most extensively investigated inorganic nanocarriers because of their excellent biocompatibility, chemical stability, localized surface plasmon resonance, and ease of surface modification. These properties enableefficient conjugation with chemotherapeutic agents, nucleic acids, antibodies, peptides, and imaging probes, facilitating targeted drug delivery and multimodal cancer imaging. In addition, their exceptional photothermal conversion efficiency has positioned AuNPs as leading candidates for photothermal therapy, where localized heat generation selectively destroys tumor cells while minimizing damage to surrounding healthy tissues [8,11].

**Magnetic Nanoparticles:** Magnetic nanoparticles, particularly iron oxide-based nanomaterials, play a dual role in cancer diagnosis and therapy by combining targeted drug delivery with magnetic resonance imaging (MRI). Their responsiveness to external magnetic fields enables site-specific accumulation within tumors, thereby improving therapeutic precision and reducing systemic exposure. Recent advances in magnetic surface functionalization and multifunctional formulations have further enhanced their application in magnetic hyperthermia, image-guided therapy, and combined therapeutic strategies, supporting more accurate treatment planning and monitoring [11,12].

**Silica Nanoparticles:** Mesoporous silica nanoparticles (MSNs) have attracted significant attention because of their large surface area, tunable pore structure, high drug-loading capacity, and excellent chemical stability. These characteristics permit the efficient encapsulation of diverse therapeutic agents while supporting controlled and stimuli-responsive drug release. Functionalization with targeting ligands and imaging molecules has expanded the application of MSNs in precision drug delivery, molecular imaging, and combination therapy, making them versatile platforms for integrated cancer management [12,16].

**Quantum Dots:** Quantum dots are semiconductor nanocrystals distinguished by their exceptional optical properties, including size-dependent fluorescence, high photostability, and broad excitation with narrow emission spectra. These features make them valuable probes for high-resolution molecular imaging, multiplex biomarker detection, and real-time visualization of tumor progression. Recent developments in biocompatible quantum dot formulations and surface engineering have reduced toxicity concerns while expanding their application in image-guided drug delivery and theranostic systems, reinforcing their contribution to next-generation precision oncology [8,11].

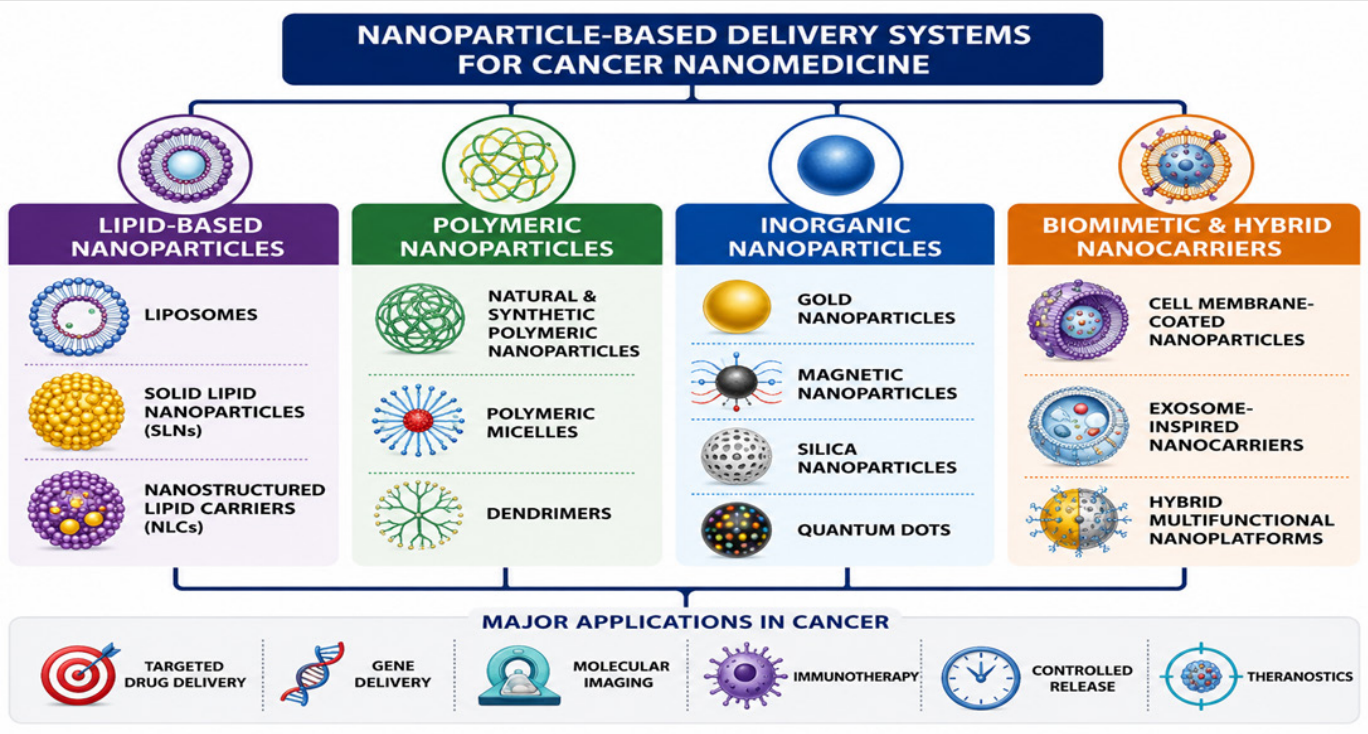
## Biomimetic and Hybrid Nanocarriers

Biomimetic and hybrid nanocarriers represent the latest generation of nanoparticle delivery systems, designed to overcome the biological limitations of conventional nanocarriers by integrating natural biological components with engineered nanomaterials. By mimicking endogenous cellular structures or combining complementary material properties, these platforms exhibit prolonged circulation, enhanced immune evasion, improved tumor targeting, and greater multifunctionality. Recent advances in bioengineering and nanofabrication have accelerated their development as versatile platforms for targeted drug delivery, molecular imaging, immunotherapy, and theranostic applications, positioning them at the forefront of precision cancer nanomedicine [8,12,16].

**Cell Membrane-Coated Nanoparticles:** Cell membrane-coated nanoparticles are fabricated by cloaking synthetic nanocarriers with membranes derived from erythrocytes, leukocytes, platelets, stem cells, or cancer cells. This biomimetic strategy preserves the biological functions of the source cells, enabling prolonged systemic circulation, immune evasion, and enhanced interactions with the tumor microenvironment. Functional membrane proteins also facilitate homologous targeting and improved cellular uptake, making these nanocarriers highly effective for selective drug delivery and image-guided cancer therapy. Their ability to integrate multiple therapeutic modalities within a single platform has further strengthened their potential for personalized oncology [18,19].

**Exosome-Inspired Nanocarriers:** Exosome-inspired nanocarriers exploit the intrinsic communication pathways of naturally secreted extracellular vesicles to achieve efficient intracellular delivery and high biological compatibility. Their lipid bilayer structure protects therapeutic payloads while promoting cellular internalization and minimizing immunogenicity. Recent advances in exosome engineering have enabled the delivery of chemotherapeutic agents, nucleic acids, proteins, and immunomodulatory molecules with enhanced targeting specificity and therapeutic efficiency. Their inherent capacity to cross complex biological barriers has also expanded their potential in precision drug delivery and minimally invasive cancer management [16,19].

**Hybrid Multifunctional Nanoplatforms:** Hybrid multifunctional nanoplatforms combine two or more classes of nanomaterials to integrate the complementary advantages of lipid-based, polymeric, inorganic, and biomimetic systems within a single carrier. This integrated design improves drug-loading efficiency, targeting capability, controlled release, imaging performance, and therapeutic versatility while enabling the co-delivery of multiple therapeutic agents. Recent developments in hybrid nanotechnology have facilitated the construction of smart, stimuli-responsive, and theranostic platforms capable of simultaneously supporting targeted therapy, multimodal imaging, and treatment monitoring. These multifunctional systems represent a significant step toward personalized cancer management by providing adaptable and highly efficient solutions for complex oncological challenges [12,14,16] (Figure 2).

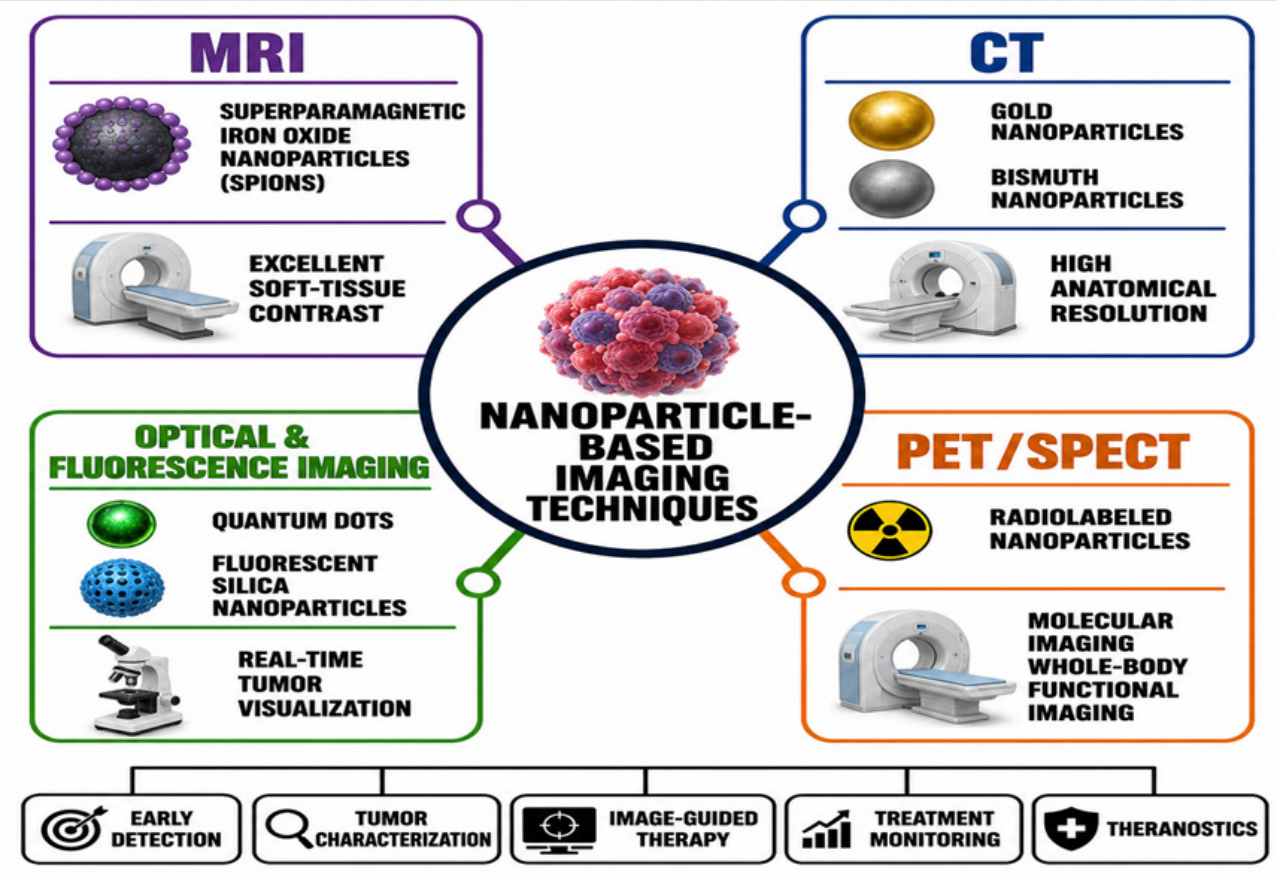



Note: Source: Adopted from (Gajbhiye, et al. [14]).

**Figure 2:** Classification and major applications of nanoparticle-based delivery systems in cancer nanomedicine. This figure presents the major classes of nanoparticle-based delivery systems used in cancer nanomedicine, including lipid-based, polymeric, inorganic, and biomimetic/hybrid nanocarriers. It highlights representative nanoparticle platforms within each class and summarizes their principal applications in targeted drug delivery, gene delivery, molecular imaging, immunotherapy, controlled release, and theranostic strategies.

## Therapeutic Applications of Nanobiotechnology in Cancer

Nanoparticle-based therapeutic systems have significantly transformed cancer treatment by enabling more precise, effective, and personalized therapeutic interventions. As illustrated in Figure 3, the diversity of lipid-based, polymeric, inorganic, biomimetic, and hybrid nanocarriers provides a versatile foundation for delivering therapeutic molecules and integrating multiple treatment modalities. Building on their unique physicochemical properties and biological interactions, these platforms have been developed to overcome major challenges associated with conventional cancer therapies, including poor drug solubility, limited tumor accumulation, systemic toxicity, and therapeutic resistance [1,4]. The therapeutic potential of nanobiotechnology extends beyond conventional chemotherapy through the incorporation of advanced strategies such as targeted drug delivery, nucleic acid therapeutics, immunomodulation, phototherapy, and combination treatment approaches. By enabling controlled payload release, enhanced tumor penetration, and selective interaction with cancer cells and the tumor microenvironment, nanoparticle systems have improved the efficacy and safety profiles of various anticancer interventions [5,20]. Moreover, the integration of therapeutic and diagnostic capabilities within single nanoplatforms has accelerated the development of theranostic approaches, allowing real-time monitoring of treatment response while optimizing therapeutic outcomes [1,7].




Note: Source: Modified from (Bai, et al. [26]).

**Figure 3:** Nanoparticle-enabled imaging modalities for cancer diagnosis and theranostic applications. This figure summarizes the major nanoparticle-enabled imaging modalities and their roles in enhancing cancer detection, tumor characterization, image-guided therapy, treatment monitoring, and theranostic applications.

## Targeted Drug Delivery

Targeted drug delivery represents one of the most established applications of cancer nanobiotechnology, aiming to improve therapeutic selectivity by directing anticancer agents preferentially toward tumor tissues while reducing exposure to healthy organs. Nanoparticle-based delivery systems enhance drug accumulation through passive and active targeting mechanisms, including exploitation of tumor-associated physiological characteristics and incorporation of specific ligands that recognize cancer-related receptors [1,5]. These strategies improve drug localization, intracellular uptake, and therapeutic efficiency compared with conventional systemic chemotherapy. The effectiveness of targeted delivery depends strongly on nanoparticle design parameters, including particle size, surface modification, protein corona formation, and interaction with biological barriers. Recent studies have demonstrated that controlling nanocarrier biodistribution and clearance is essential for achieving prolonged circulation and improved tumor delivery efficiency [12]. In addition, advances in ligand-functionalized nanoparticles, biomimetic coatings, and engineered surface properties have enhanced selective recognition of tumor cells and improved penetration into complex tumor microenvironments [6,22].

Lipid-based, polymeric, inorganic, and hybrid nanoparticles have all contributed to targeted drug delivery applications by enabling the encapsulation and controlled release of diverse anticancer agents. Liposomal formulations have demonstrated clinical success through improved drug delivery and reduced toxicity, while polymeric and inorganic nanocarriers provide additional opportunities for controlled release, combination therapy, and imaging-guided treatment. Emerging strategies involving cell membrane-coated nanoparticles and advanced biomimetic systems further improve immune evasion and tumor-specific accumulation, representing promising approaches for next-generation targeted cancer therapy [21,22].

## Gene Therapy

Nanoparticle-mediated gene delivery has emerged as a transformative strategy in cancer treatment by addressing the major limitations associated with conventional nucleic acid therapeutics, including poor stability, rapid enzymatic degradation, limited cellular uptake, and inefficient intracellular transport. Several nanoparticle platforms, particularly lipid-based and polymeric systems, provide adaptable vehicles for the delivery of genetic materials, including messenger RNA (mRNA), small interfering RNA (siRNA), microRNA, and plasmid DNA. By protecting nucleic acids during systemic circulation and facilitating their transport into target cells, these nanocarriers have expanded the therapeutic potential of gene-based approaches in precision oncology [1,23]. Lipid nanoparticles (LNPs) represent the most advanced nanoplatform for clinical gene delivery due to their efficient nucleic acid encapsulation, endosomal escape capability, and favorable biological compatibility. Recent advances in ionizable lipid design, surface modification, and formulation optimization have improved delivery efficiency and enabled the translation of mRNA-based therapeutics into clinical applications. In cancer therapy, LNPs are being explored for the delivery of tumor suppressor genes, immune-stimulatory mRNA, and gene-editing components to modulate tumor progression and enhance antitumor immune responses [20,23].

Polymeric nanoparticles and dendrimer-based systems provide additional advantages through their tunable structures, controlled release properties, and capacity for surface functionalization. These features enable the development of targeted gene delivery systems capable of selectively transporting therapeutic nucleic acids to tumor cells while minimizing systemic exposure. Furthermore, nanoparticle-assisted RNA interference strategies have demonstrated potential for silencing oncogenic pathways involved in tumor growth, metastasis, and resistance to conventional therapies. The combination of gene delivery with chemotherapy, immunotherapy, or molecular imaging has further strengthened the role of nanotechnology in developing multifunctional cancer treatment platforms [8,20]. Despite significant progress, the clinical translation of nanoparticle-based gene therapy remains challenged by biological barriers, including heterogeneous tumor distribution, immune recognition, intracellular trafficking limitations, and long-term safety considerations. Continued improvements in nanoparticle engineering, tumor-specific targeting, and personalized formulation strategies are expected to enhance the precision and effectiveness of gene-based cancer therapies. Overall, nanoparticle-enabled gene delivery represents a critical component of next-generation cancer nanomedicine by providing a platform for regulating disease-associated genetic pathways and integrating therapeutic strategies within personalized treatment frameworks [12,23].

## Cancer Immunotherapy

Nanoparticle-based immunotherapy has emerged as a transformative approach in cancer treatment by improving immune recognition, enhancing antitumor immune responses, and overcoming limitations associated with conventional immunotherapeutic strategies. Nanoparticle platforms provide adaptable systems for delivering immune-modulating agents, antigens, and nucleic acids, thereby enabling precise regulation of immune activity within the tumor microenvironment. Unlike traditional therapies that directly target tumor cells, nanoparticle-mediated immunotherapy focuses on activating or reprogramming immune components to achieve durable and systemic antitumor effects [20,24]. Nanoparticles enhance cancer immunotherapy through multiple mechanisms, including efficient antigen delivery, immune checkpoint modulation, activation of antigen-presenting cells, and stimulation of innate immune pathways. Their ability to protect fragile biological molecules from degradation and promote targeted accumulation in immune-responsive tissues has significantly improved the performance of cancer vaccines and immune-based therapies [23,24]. Lipid-based nanoparticles, in particular, have gained substantial attention following their successful application in nucleic acid delivery, demonstrating their potential for transporting mRNA, tumor-associated antigens, and immune-regulatory molecules with high efficiency and controlled immune activation [23].

Nanoparticles have also facilitated the development of personalized cancer vaccines by enabling co-delivery of tumor antigens and adjuvants to dendritic cells, thereby enhancing antigen presentation and cytotoxic T-cell responses. Beyond vaccination, biomimetic and hybrid nanocar riers have been explored to improve immune cell targeting, prolong circulation, and modulate immunosuppressive tumor environments. Cell membrane-coated nanoparticles and other biologically inspired systems provide additional advantages by exploiting natural cellular interactions to improve immune compatibility and therapeutic precision [22]. Despite these advances, challenges including immune-related toxicity, complex manufacturing processes, tumor heterogeneity, and limited clinical translation remain important barriers. Current research is therefore focused on developing smart nanoparticles capable of responding to tumor-specific signals, integrating immunotherapy with chemotherapy or phototherapy, and improving personalized treatment strategies. Through these innovations, nanoparticle-based immunotherapy continues to expand the potential of precision oncology by combining targeted delivery with durable immune-mediated tumor control [21,25].

## Photothermal and Photodynamic Therapy

Nanoparticle-assisted photothermal therapy (PTT) and photodynamic therapy (PDT) have emerged as promising non-invasive therapeutic strategies that exploit the unique optical properties of nanomaterials to achieve localized tumor destruction. Unlike conventional treatments that rely primarily on systemic drug exposure, nanoparticle-mediated phototherapies provide spatial and temporal control over therapeutic activation, thereby improving treatment precision and reducing damage to healthy tissues [20,21]. Photothermal

therapy utilizes nanoparticles capable of absorbing external light energy, particularly in the near-infrared (NIR) region, and converting it into localized heat to induce cancer cell death. Gold nanoparticles, carbon-based nanomaterials, and other photothermal agents have received considerable attention because of their efficient light absorption, tunable surface properties, and potential for tumor targeting. Surface modification of these nanoparticles with ligands, polymers, or biomimetic coatings enhances tumor accumulation and improves therapeutic selectivity. Furthermore, the combination of photothermal agents with drug delivery systems enables controlled drug release triggered by thermal stimulation, creating multifunctional platforms that integrate chemotherapy and photothermal ablation within a single nanosystem [8,20].

Photodynamic therapy involves the activation of photosensitizing agents by specific wavelengths of light to generate reactive oxygen species (ROS), which induce oxidative damage and promote tumor cell elimination. Nanoparticle-based delivery of photosensitizers has addressed several limitations of conventional PDT, including poor water solubility, limited tumor accumulation, and premature degradation. Lipid-based, polymeric, and inorganic nanocarriers have been engineered to improve photosensitizer delivery, enhance cellular uptake, and provide controlled activation within the tumor microenvironment. Recent developments in nanoparticle-mediated photo-immunotherapy have further demonstrated that PDT-induced immune activation can enhance antitumor responses by promoting immunogenic cell death and improving immune system recognition of tumor cells [21,25]. Despite their therapeutic potential, clinical translation of nanoparticle-assisted phototherapies remains influenced by challenges related to light penetration depth, long-term nanoparticle safety, tumor heterogeneity, and optimization of treatment parameters. Current research is therefore focused on developing multifunctional nanoplatforms that combine photothermal or photodynamic effects with drug delivery, immune modulation, and diagnostic imaging. These advances are expected to strengthen the role of nanoparticle-based phototherapies as components of personalized and precision cancer treatment strategies [20,25] (Table 2).

**Table 2:** Therapeutic applications of nanoparticle-based delivery systems in cancer treatment.

| Therapeutic approach | Nanoparticles | Mechanism of action | Applications |
|---|---|---|---|
| Targeted drug delivery | Lipid-based, polymeric, biomimetic nanoparticles | Selective delivery and controlled release of anticancer agents at tumor site | Improved chemotherapy efficacy and reduced systemic toxicity |
| Gene therapy | Lipid nanoparticles, polymeric nanoparticles | Delivery of nucleic acids for gene regulation or correction | mRNA therapy, siRNA delivery, gene silencing |
| Cancer immunotherapy | Lipid, polymeric, biomimetic and hybrid nanoparticles | Modulation of immune responses and enhanced tumor recognition | Immune checkpoint modulation, cancer vaccines |
| Photothermal therapy | Gold and other inorganic nanoparticles | Light-induced heat generation for tumor cell destruction | Localized tumor ablation |
| Photodynamic therapy | Photosensitizer-loaded nanoparticles | Reactive oxygen species generation after light activation | Targeted tumor killing with minimal invasiveness |
| Combination therapy and theranostics | Hybrid and multifunctional nanoparticles | Integration of multiple therapeutic and diagnostic functions | Personalized treatment and real-time therapy monitoring |

## Nanoparticle-Based Imaging Techniques

Nanoparticle-based imaging techniques have significantly improved cancer diagnosis by enhancing the sensitivity, specificity, and functional performance of conventional imaging modalities. Their unique physicochemical properties, including tunable size, surface functionalization, and favorable optical and magnetic characteristics, enable efficient tumor targeting, improved image contrast, and prolonged circulation, thereby facilitating early tumor detection, accurate disease characterization, and real-time treatment monitoring [1,26,27]. Furthermore, advances in nanobiotechnology have enabled multifunctional imaging platforms that integrate diagnostic and therapeutic capabilities, supporting image-guided therapy, multimodal imaging, and theranostic applications for precision oncology [7,28,29]. The following subsections discuss recent advances and clinical applications of nanoparticle-enabled magnetic resonance imaging (MRI), computed tomography (CT), optical and fluorescence imaging, and PET/SPECT-based multimodal imaging in cancer diagnosis.

### Magnetic Resonance Imaging (MRI)

Magnetic resonance imaging (MRI) is one of the most widely used non-invasive imaging modalities for cancer diagnosis because of its excellent soft-tissue contrast and high spatial resolution. The incorporation of nanoparticles as contrast agents has substantially enhanced MRI sensitivity by improving signal intensity, tumor specificity, and imaging accuracy, thereby facilitating earlier tumor detection and more precise disease characterization [1,26]. Magnetic nanoparticles, particularly superparamagnetic iron oxide nanoparticles (SPIONs), have been extensively investigated owing to their favorable magnetic properties, biocompatibility, and ability to accumulate selectively within tumor tissues through passive and active targeting strate-

gies [30,31]. Recent advances in nanoparticle engineering have led to the development of multifunctional MRI contrast agents capable of integrating targeted imaging with drug delivery and therapeutic functions. Surface modification with antibodies, peptides, and other targeting ligands has improved tumor-specific accumulation, while hybrid nanoplatforms combining magnetic materials with therapeutic payloads have enabled image-guided therapy and treatment monitoring [28,29].

Furthermore, responsive magnetic nanomaterials capable of altering their imaging performance in response to changes within the tumor microenvironment have enhanced diagnostic precision and supported personalized treatment strategies. These innovations continue to strengthen the role of nanoparticle-enhanced MRI in precision oncology by improving diagnostic confidence and facilitating more effective clinical decision-making [1,7].

### Computed Tomography (CT)

Computed tomography (CT) remains a cornerstone of cancer imaging because of its rapid image acquisition, high spatial resolution, and ability to visualize anatomical structures with remarkable accuracy. The integration of nanoparticles as CT contrast agents has significantly improved imaging sensitivity by enhancing X-ray attenuation, prolonging circulation time, and increasing tumor-specific accumulation compared with conventional iodine-based contrast media [1,31]. High-atomic-number nanomaterials, particularly gold- and bismuth-based nanoparticles, have demonstrated superior contrast enhancement, enabling more accurate tumor localization, delineation, and disease staging [28,30]. Recent advances in nanobiotechnology have facilitated the development of multifunctional CT nanoprobes capable of combining imaging with targeted drug delivery and therapeutic interventions. Surface-functionalized nanoparticles improve selective tumor targeting while reducing non-specific accumulation, thereby enhancing diagnostic accuracy and minimizing adverse effects. Moreover, hybrid nanoplatforms integrating CT with complementary imaging modalities have expanded the application of CT in image-guided therapy and theranostic medicine, providing comprehensive structural and functional information for improved clinical decision-making [7,29]. These innovations continue to strengthen the clinical value of nanoparticle-enhanced CT in precision cancer diagnosis and treatment.

### Optical and Fluorescence Imaging

Optical and fluorescence imaging have emerged as powerful techniques for cancer detection because of their high sensitivity, real-time imaging capability, and ability to visualize molecular and cellular processes. Nanoparticle-based fluorescent probes have significantly improved imaging performance by enhancing signal stability, increasing tumor specificity, and reducing photobleaching, thereby enabling accurate tumor detection and image-guided surgical interventions [1,26]. Quantum dots, fluorescent silica nanoparticles, and other engineered nanomaterials have been widely explored owing to their superior optical properties and capacity for surface functionalization with targeting ligands and therapeutic agents [30,31]. Recent developments in multifunctional fluorescent nanoplatforms have enabled the integration of molecular imaging with targeted therapy, supporting simultaneous tumor visualization and therapeutic monitoring. The combination of fluorescence imaging with other imaging modalities has further enhanced diagnostic accuracy by providing complementary structural and molecular information while facilitating theranostic applications and personalized cancer management [1,28,29]. These advances continue to expand the clinical potential of nanoparticle-assisted optical imaging in precision oncology.

### PET/SPECT and Multimodal Imaging

Positron emission tomography (PET) and single-photon emission computed tomography (SPECT) are highly sensitive molecular imaging modalities that enable the non-invasive visualization of tumor metabolism, receptor expression, and biological processes. The incorporation of radiolabeled nanoparticles has significantly enhanced the diagnostic performance of PET/SPECT by improving tracer stability, prolonging circulation time, increasing tumor-specific accumulation, and enabling targeted molecular imaging [27,32]. These advantages facilitate early cancer detection, accurate disease staging, treatment planning, and longitudinal assessment of therapeutic response [1,7]. Recent advances in nanobiotechnology have accelerated the development of multimodal imaging platforms that integrate PET/SPECT with MRI, CT, or optical imaging within a single nanoparticle system. Such platforms provide complementary anatomical, functional, and molecular information while supporting image-guided therapy and theranostic applications. The combination of targeted radiolabeled nanomaterials with multifunctional imaging probes has further improved diagnostic precision and personalized cancer management, although challenges related to large-scale production, regulatory approval, and clinical translation remain to be fully addressed [7,28,29].

## Recent Advances and Future Perspectives

Rapid advances in nanobiotechnology continue to reshape cancer diagnosis and therapy through the development of intelligent nanoplatforms with enhanced targeting, imaging, and therapeutic capabilities. Emerging innovations, including stimuli-responsive nanomaterials, artificial intelligence-assisted nanomedicine, and multifunctional theranostic systems, are expanding the scope of precision oncology while addressing limitations associated with conventional nanoparticle platforms. Despite these advances, challenges related to clinical translation, large-scale manufacturing, long-term safety, and regulatory approval remain key barriers to widespread clinical implementation. The following subsections highlight recent technological developments, ongoing translational challenges, and future directions expected to drive the next generation of cancer nanomedicine.

## Smart and Stimuli-Responsive Nanoparticles

Smart and stimuli-responsive nanoparticles represent a major advancement in cancer nanomedicine by enabling controlled drug release in response to specific internal or external stimuli, thereby improving therapeutic precision while minimizing systemic toxicity. Unlike conventional nanocarriers, these intelligent nanosystems are engineered to respond to tumor-associated conditions such as acidic pH, redox potential, enzymatic activity, hypoxia, temperature, or externally applied light and magnetic fields, allowing site-specific activation and enhanced treatment efficacy [33,34]. Their ability to release therapeutic payloads selectively within the tumor microenvironment reduces off-target effects and improves drug bioavailability, making them promising platforms for precision oncology [1,6]. Recent advances in nanobiotechnology have expanded the functionality of stimuli-responsive systems through the development of multifunctional nanogels, hybrid nanocarriers, and immunomodulatory nanoparticles capable of integrating targeted drug delivery, molecular imaging, and cancer immunotherapy within a single platform. These smart nanoplatforms also support combination therapies by synchronizing the delivery of multiple therapeutic agents while adapting to the dynamic characteristics of the tumor microenvironment, thereby enhancing therapeutic outcomes and reducing the likelihood of treatment resistance [35,36]. Continued innovations in materials engineering and nanosystem design are expected to further improve the clinical applicability of smart nanoparticles and accelerate their translation into personalized cancer therapy [3].

## AI-Assisted Nanomedicine

Artificial intelligence (AI) is increasingly transforming cancer nanomedicine by enabling the rational design, optimization, and clinical translation of nanoparticle-based therapeutic and diagnostic systems. Machine learning and deep learning algorithms can integrate complex biological, physicochemical, and clinical datasets to predict nanoparticle behavior, optimize formulation parameters, and improve targeting efficiency, thereby accelerating nanomedicine development while reducing reliance on conventional trial-and-error approaches [37]. AI also facilitates the optimization of nanoparticle size, surface functionalization, drug-loading capacity, and biodistribution, supporting the development of safer and more effective nanocarriers for precision oncology [5,37]. Beyond nanoparticle design, AI enhances cancer diagnosis and therapeutic decision-making through advanced image analysis, predictive modeling, and patient-specific treatment planning. The integration of AI with nanoparticle-based imaging and drug delivery platforms enables intelligent theranostic systems capable of predicting therapeutic responses, monitoring treatment outcomes, and supporting personalized cancer management.

Although challenges related to data quality, model interpretability, standardization, and regulatory implementation remain, continued advances in AI are expected to accelerate the clinical translation of next-generation nanomedicines and improve outcomes in precision cancer therapy [5,37].

## Clinical Translation and Ongoing Challenges

Despite remarkable advances in cancer nanobiotechnology, the clinical translation of nanoparticle-based systems remains constrained by several scientific, technological, and regulatory challenges. Although numerous nanomedicines have demonstrated promising preclinical efficacy, only a limited number have progressed to routine clinical use because of difficulties associated with large-scale manufacturing, batch-to-batch reproducibility, quality control, and regulatory standardization [36]. Furthermore, the biological complexity of the tumor microenvironment, interpatient variability, and heterogeneous nanoparticle biodistribution continue to influence therapeutic efficacy and clinical outcomes, highlighting the need for more predictive preclinical models and standardized evaluation protocols [38]. Long-term biosafety, pharmacokinetics, immunogenicity, and biodegradability also remain critical considerations for the successful clinical implementation of nanoparticle-based therapeutics and imaging agents. Addressing these challenges will require multidisciplinary collaboration among material scientists, engineers, clinicians, regulatory agencies, and industry partners to establish robust manufacturing strategies, harmonized regulatory frameworks, and evidence-based clinical validation. Continued advances in nanomaterial engineering, precision medicine, and translational research are expected to facilitate the safe and effective integration of next-generation nanomedicines into routine oncology practice [33,38].

## Future Perspectives

The future of cancer nanobiotechnology will be driven by the development of intelligent, multifunctional nanoplatforms capable of integrating targeted drug delivery, molecular imaging, immunotherapy, and real-time therapeutic monitoring within a single system. Continued advances in stimuli-responsive nanomaterials, biomimetic nanocarriers, and precision engineering are expected to improve tumor specificity, therapeutic efficacy, and patient safety while supporting increasingly personalized treatment strategies [33,36]. The integration of artificial intelligence with nanomedicine is anticipated to further accelerate nanoparticle design, optimize treatment selection, and facilitate predictive modeling for individualized cancer management. Future research should also prioritize scalable manufacturing, standardized safety evaluation, regulatory harmonization, and well-designed clinical trials to bridge the gap between laboratory innovation and routine clinical practice. Through continued interdisciplinary collaboration, next-generation nanobiotechnology is expected to play an increasingly important role in advancing precision oncology and improving clinical outcomes for patients with cancer [37-40].

## Conclusion

Nanobiotechnology has transformed the landscape of cancer diagnosis and therapy by enabling the development of multifunctional nanoparticle platforms that improve targeted drug delivery, molecular imaging, and therapeutic precision. Advances in lipid-based, polymeric, inorganic, and biomimetic nanocarriers have enhanced the efficacy, specificity, and safety of anticancer interventions while supporting the integration of diagnostic and therapeutic functions within single nanosystems. Recent progress in smart nanomaterials, stimuli-responsive platforms, artificial intelligence-assisted nanomedicine, and theranostic technologies has further accelerated the evolution of precision oncology. Despite these achievements, challenges related to large-scale manufacturing, long-term safety, regulatory approval, and clinical translation continue to limit the widespread adoption of many nanoparticle-based technologies. Addressing these barriers through interdisciplinary collaboration, standardized evaluation strategies, and robust clinical validation will be essential for translating promising laboratory discoveries into routine clinical practice. Continued innovation in nanobiotechnology is expected to drive the development of safer, more effective, and highly personalized cancer management strategies, ultimately improving diagnostic accuracy, therapeutic outcomes, and the quality of life of patients with cancer.

## Authors' Contributions

The authors of this research have significantly contributed to the study's conception, data collection, and manuscript development. All authors were involved in writing the manuscript or critically reviewing it for its intellectual value. They have reviewed and approved the final version for submission and publication and accepted full responsibility for the content and integrity of the work.

## Acknowledgement

We thank all the researchers who contributed to the success of this research work.

## Conflict of Interest

The authors declared that there are no conflicts of interest.

## Funding

No funding was received for this research work.

## References

1. Wang B, Hu S, Teng Y, Chen J, Wang H, et al. (2024) Current advance of nanotechnology in diagnosis and treatment for malignant tumors. Signal transduction and targeted therapy 9(1): 200.
2. Mukhopadhyay B, Singh S, Singh A (2024) Utilizing nanomaterials for cancer treatment and diagnosis: an overview. Discover nano 19(1): 215.
3. Zhu J, Lee H, Huang R, Zhou J, Zhang J, et al. (2025) Harnessing nanotechnology for cancer treatment. Frontiers in bioengineering and biotechnology 12: 1514890.
4. Al Thani AN, Jan AG, Abbas M, Geetha M, Sadasivuni KK (2024) Nanoparticles in cancer theragnostic and drug delivery: A comprehensive review. Life Sciences 352: 122899.
5. Nguyen L N M, Ngo W, Lin Z P, Sindhwani S, MacMillan P, et al. (2024) The mechanisms of nanoparticle delivery to solid tumours. Nature Reviews Bioengineering 2: 201-213.
6. Li X, Hu Y, Zhang X, Shi X, Parak W J, et al. (2024) Transvascular transport of nanocarriers for tumor delivery. Nature communications 15(1): 8172.
7. Najdian A, Beiki D, Abbasi M, Gholamrezanezhad A, Ahmadzadehfar H, et al. (2024) Exploring innovative strides in radiolabeled nanoparticle progress for multimodality cancer imaging and theranostic applications. Cancer imaging: the official publication of the International Cancer Imaging Society 24(1): 127.
8. Lee D, Huntoon K, Lux J, Kim BYS, Jiang W (2023) Engineering nanomaterial physical characteristics for cancer immunotherapy. Nature Reviews Bioengineering 1: 499-517.
9. Mahmoudi M, Landry M P, Moore A, Coreas R (2023) The protein corona from nanomedicine to environmental science. Nature Reviews Materials 8: 422-438.
10. Zhao T, Ren M, Shi J, Wang H, Bai J, et al. (2024) Engineering the protein corona: Strategies, effects, and future directions in nanoparticle therapeutics. Biomedicine & pharmacotherapy 175: 116627.
11. Lim SH, Wong TW, Tay WX (2024) Overcoming colloidal nanoparticle aggregation in biological milieu for cancer therapeutic delivery: Perspectives of materials and particle design. Advances in Colloid and Interface Science 325: 103094.
12. Cabral H, Li J, Miyata K, Kataoka K (2024) Controlling the biodistribution and clearance of nanomedicines. Nature Reviews Bioengineering 2: 214-232.
13. Waheed I, Ali AA, Tabassum H, Khatoon N, Lai WF, et al. (2024) Lipid-based nanoparticles as drug delivery carriers for cancer therapy. Frontiers in Oncology 14: 1296091.
14. Gajbhiye KR, Rajesh Salve, Mahavir Narwade, Afsana Sheikh, Prashant Kesharwani, et al. (2023) Lipid polymer hybrid nanoparticles: A custom-tailored next-generation approach for cancer therapeutics. Molecular Cancer 22(1): 160.
15. Sunoqrot S, Abdel Gaber SA, Abujaber R, Al Majawleh M, Talhouni S (2024) Lipid- and polymer-based nanocarrier platforms for cancer vaccine delivery. ACS Applied Bio Materials 7(8): 4998-5019.
16. Hou H, Liu X, Liu J, Wang Y (2025) Carbohydrate polymer-based nanoparticles with cell membrane camouflage for cancer therapy: A review. International Journal of Biological Macromolecules 289: 138620.
17. Karati D, Mukherjee S, Prajapati B, Bose A, Paul S, et al. (2024) A review on lipid-polymer hybrid nanocarriers in cancer. Journal of Drug Delivery Science and Technology 97: 105827.
18. Guo Q, Wang S, Xu R, Tang Y, Xia X (2024) Cancer cell membrane-coated nanoparticles: A promising anti-tumor bionic platform. RSC Advances 14(15): 10608-10637.
19. Qiu S, Zhu F, Tong L (2024) Application of targeted drug delivery by cell membrane-based biomimetic nanoparticles for inflammatory diseases and cancers. European Journal of Medical Research 29(1): 523.
20. Sun L, Liu H, Ye Y, Lei Y, Islam R, et al. (2023) Smart nanoparticles for cancer therapy. Signal Transduction and Targeted Therapy 8: 418.
21. Guo Z, Zhu AT, Fang R H, Zhang L (2023) Recent developments in nanoparticle-based photo-immunotherapy for cancer treatment. Small Methods 7(5): e2300252.

22. Fang RH, Gao W, Zhang L (2023) Targeting drugs to tumours using cell membrane-coated nanoparticles. Nature Reviews Clinical Oncology 20: 33-48.

23. Kon E, Ad El N, Hazan Halevy I, Stotsky Oterin L, Peer D (2023) Targeting cancer with mRNA–lipid nanoparticles: Key considerations and future prospects. Nature Reviews Clinical Oncology 20(11): 739-754.

24. Sun Z, Zhao H, Ma L, Shi Y, Ji M, et al. (2024) The quest for nanoparticle-powered vaccines in cancer immunotherapy. Journal of Nanobiotechnology 22(1): 61.

25. Thiruppathi J, Vijayan V, Park IK, Lee SE, Rhee JH (2024) Enhancing cancer immunotherapy with photodynamic therapy and nanoparticle: Making tumor microenvironment hotter to make immunotherapeutic work better. Frontiers in Immunology 15: 1375767.

26. Bai J W, Qiu S Q, Zhang G J (2023) Molecular and functional imaging in cancer-targeted therapy: Current applications and future directions. Signal Transduction and Targeted Therapy 8(1): 89.

27. Schwenck J, Sonanini D, Cotton JM, Hans Georg Rammensee, Christian la Fougère, et al. (2023) Advances in PET imaging of cancer. Nature Reviews Cancer 23: 474-490.

28. Gawne PJ, Ferreira M, Papaluca M, Jan Grimm, Paolo Decuzzi, et al. (2023) New opportunities and old challenges in the clinical translation of nanotheranostics. Nature Reviews Materials 8(12): 783-798.

29. Yasir M, Mishra R, Tripathi AS, Rahul K Maurya, Ashutosh shahi, et al. (2024) Theranostics: A multifaceted approach utilizing nano-biomaterials. Discover Nano 19(1): 35.

30. Khorasani A, Shahbazi Gahrouei D, Safari A (2023) Recent Metal Nanotheranostics for Cancer Diagnosis and Therapy: A Review. Diagnostics 13(5): 833.

31. Andoh V, Ocansey DKW, Naveed H, Wang N, Chen L, et al. (2024) The advancing role of nanocomposites in cancer diagnosis and treatment. International Journal of Nanomedicine 19: 6099-6126.

32. Goel M, Mackeyev Y, Krishnan S (2023) Radiolabeled nanomaterial for cancer diagnostics and therapeutics: Principles and concepts. Cancer Nanotechnology 14(1): 15.

33. Chen X, Wu D, Chen Z (2024) Biomedical applications of stimuli-responsive nanomaterials. Med Comm 5(8): e643.

34. Kim C H, Lee E S, Ko H, Soyoung Son, So Hee Kim, et al. (2024) Stimuli-Responsive Polymeric Nanomedicine for Enhanced Cancer Immunotherapy. Chemistry of Materials 36(3): 1088-1112.

35. Rana P, Singh C, Kaushik A, Saleem S, Kumar A (2024) Recent advances in stimuli-responsive tailored nanogels for cancer therapy; from bench to personalized treatment. Journal of Materials Chemistry B 12(2): 382-412.

36. Sandbhor P, Palkar P, Bhat S, John G, Goda JS (2024) Nanomedicine as a multimodal therapeutic paradigm against cancer: On the way forward in advancing precision therapy. Nanoscale 16(13): 6330-6364.

37. Perez-Lopez R, Ghaffari Laleh N, Mahmood F (2024) A guide to artificial intelligence for cancer researchers. Nat Rev Cancer 24(6): 427-441.

38. Kobzev D, Kulyk O, Barmin RA, Tatarets A, Pallares RM, et al. (2026) Clinical translation and landscape of stimuli-responsive nanomedicines and microscale therapeutics. Chemical Society reviews 55(12): 6704-6738.

39. Li X P, Hou DY, Jiong Cheng Wu, Peng Zhang, Yue Ze Wang, et al. (2024) Stimuli-Responsive Nanomaterials for Tumor Immunotherapy. ACS Biomaterials Science & Engineering 10(9): 5474-5495.

40. Yagublu V, Karimova A, Hajibabazadeh J, Reissfelder C, Muradov M, et al. (2022) Overview of Physicochemical Properties of Nanoparticles as Drug Carriers for Targeted Cancer Therapy. Journal of Functional Biomaterials 13(4): 196.

**ISSN: 2574-1241**

DOI: 10.26717/BJSTR.2026.67.010464

**Moses Adondua Abah .** Biomed J Sci & Tech Res

This work is licensed under Creative *Commons* Attribution 4.0 License

**Submission Link**: https://biomedres.us/submit-manuscript.php




**Assets of Publishing with us**

- Global archiving of articles
- Immediate, unrestricted online access
- Rigorous Peer Review Process
- Authors Retain Copyrights
- Unique DOI for all articles

https://biomedres.us/