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Review Article

Nanotechnology-Enabled Precision Oncology: From Cancer Diagnosis to Targeted Therapy and Nanotheranostics

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Abstract

Cancer is an important public health problem worldwide and the limitations of conventional therapies continue to stimulate the search for more precise and effective treatments. Nanotechnology-enabled precision oncology, which uses engineered nanomaterials for improving cancer diagnosis, treatment, and monitoring of therapeutic response, has emerged as a promising approach. This review highlights the recent breakthroughs in nanobiotechnology and its expanding impact on cancer care. First, it describes basic principles of nanoparticle-based systems and their use for targeted medication administration, imaging and cancer diagnosis. Particular focus is paid to nano biosensors, nano-enhanced imaging and liquid biopsy methods that potentially enable early identification and real-time monitoring of disease progression. The paper also discusses therapeutic uses of nanobiotechnology as targeted chemotherapy, photothermal and photodynamic therapy, immunotherapy and nanoparticle mediated gene transfer. Nanotheranostics is emerging as an approach that integrates diagnostic, imaging, therapy and response monitoring in a single nanoscale platform enabling more personalized therapeutic decisions. However, major obstacles remain for clinical translation, including nanoparticle toxicity, biodistribution, repeatability, large-scale manufacturing, regulatory approval, cost, and long-term safety. The overview includes emergent trends such as AI-assisted design of nanoparticles, patient-specific nanotherapeutics, optogenetic strategies and sustainable green synthesis. To summarize, the integration of nanobiotechnology with precision medicine holds promise for more tailored, adaptive, and patient-oriented approaches to cancer care. Ongoing collaboration among researchers, physicians, industry and regulatory agencies will be required to translate these promising technologies from experimental research into clinically useful applications.

1. Introduction

Despite decades of advancements in conventional therapies, cancer continues to be one of the most urgent global health challenges, as both incidence and mortality rates continue to increase. Chemotherapy, radiotherapy and surgery have saved millions of lives but are often associated with severe side effects, poor tumour specificity and inevitable development of drug resistance. Such limitations have promoted

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the search for novel strategies that may provide more accurate, less toxic and more effective interventions. Nanobiotechnology, a new paradigm in oncology [1] that combines nanoscale materials with biological systems, is emerging as a revolutionary approach.

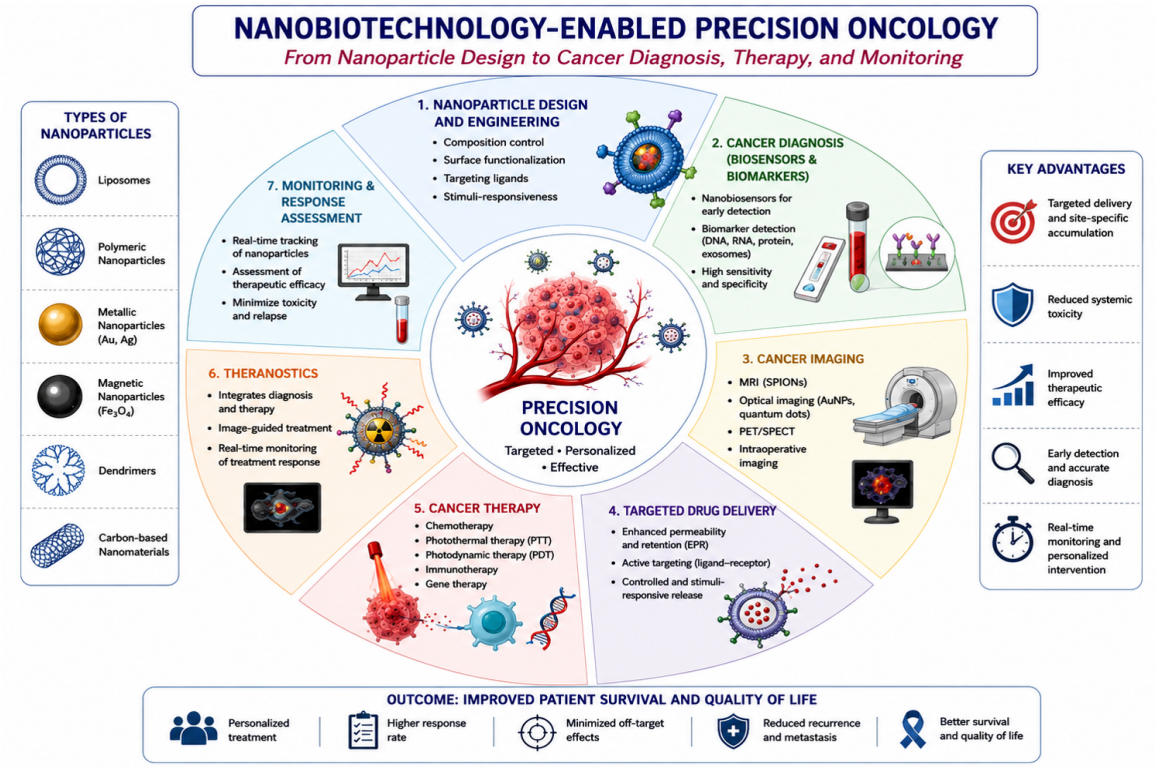

Figure 1: Nanobiotechnology-Enabled Precision Oncology

Nanoparticles (NPs) possess unique physicochemical properties such as large surface to volume ratios, quantum effects and tunable optical or magnetic properties that render them ideal candidates for cancer diagnosis, drug delivery, imaging and immunotherapy. This review provides an overview of the fundamentals of nanobiotechnology, therapeutic approaches, diagnostic innovations, and future directions in the changing landscape of cancer care. Figure 1 Nanobiotechnology-enabled precision oncology: an integrated framework encompassing nanoparticle design, cancer diagnosis, imaging, targeted drug delivery, therapeutic intervention, nanotheranostics, and treatment-response monitoring. Figure guide: The framework illustrates the progression from rational nanoparticle design and functionalization to cancer diagnosis, molecular/targeted imaging, precision drug delivery, therapeutic intervention, integrated nanotheranostics, and subsequent monitoring of treatment response. Arrows indicate the interconnected and iterative nature of these nanobiotechnology-enabled approaches in precision oncology. The figure was generated using AI-assisted image-generation technology and scientifically reviewed and refined by the authors.

2. Foundations of Nanobiotechnology in Oncology

2.1. Role of Nanobiotechnology in Modern Cancer Care

Nanoparticles in the range of 1-1000 nm have unique properties which distinguish them from the bulk materials. Their small size allows them to transverse biological barriers, infiltrate tissues and interact with cellular components on a molecular scale [2, 3]. The enhanced permeability and retention (EPR) effect, a hallmark of tumour vasculature, enables nanoparticles of standard chemistry to preferentially accumulate within tumour tissues [4], thus minimizing systemic toxicity. Unlike conventional drugs, nanocarriers can be designed to respond to stimuli such as pH, temperature or light, releasing therapeutic agents only at the tumour site [5, 6]. Such accuracy limits damage to healthy tissue and increases therapeutic efficacy [2, 7, 8]. Bibliometric studies confirm that nanomedicine has become a dominant research frontier in oncology, with applications ranging from drug delivery and imaging to immunotherapy and biosensing [2, 8, 9]. Nanotechnology's application to oncology is a paradigm shift from generalized to highly specific treatments [2, 9].

2.2. Nanoparticle-Based Strategies for Cancer Diagnosis and Treatment

Metallic nanoparticles such as silver (AgNPs) and gold (AuNPs) are extensively studied for their anticancer and imaging properties [2, 8, 9]. Green synthesized AgNPs using plant extracts or probiotic exopolysaccharides (EPS) showed high cytotoxicity against cancer cells [5, 6] and maintained biocompatibility [2, 9]. The generation of reactive oxygen species (ROS) and the disruption of mitochondrial function by them makes them effective anticancer agents. However, gold nanoparticles are widely used for photothermal therapy and intraoperative imaging because of their surface plasmon resonance properties, which allow efficient absorption and scattering of light [1, 6]. Metal oxide nanoparticles, notably zinc oxide (ZnONPs), have shown potential in colorectal cancer by targeting oncogenes like KRAS and BCL9, and tumour suppressors such as PTEN and PDCD4 [2, 8, 9]. Polymeric nanocarriers such as gelatin-alginate hydrogels encapsulating AgNPs improve stability, reduce aggregation, and allow for controlled release, thus improving therapeutic outcomes [1, 10]. Optogenetic

nanoplatforms are the new frontier where light-sensitive proteins are engineered into the cancer cells to induce apoptosis when stimulated, which would open avenues for non-invasive therapies [8, 11].

2.3. Major Nanoplatforms for Cancer Diagnosis and Therapy

Examples of effective translation of nanomedicine into oncology are clinically approved liposomal drugs Doxil (liposomal doxorubicin), ThermoDox (heat-sensitive liposomal doxorubicin), Abraxane (albumin-bound paclitaxel) and Vyxeos (liposomal cytarabine/daunorubicin). The nanocarrier systems for these drugs improve pharmacokinetics, reduce toxicity and improve efficacy [8, 10, 12]. Experimental nanoplatforms are nanocrystals for renal cancer, nanodots for therapy of prostate cancer, and optogenetic constructs for breast and brain cancer [2, 10, 13, 14]. These platforms exemplify the versatility of nanobiotechnology and its capacity to bridge fundamental research and clinical application [8, 11]. The variety of nanoplatforms exemplifies the flexibility of nanotechnology for different cancers and therapeutic demands [2, 9]. The major characteristics, applications, advantages, and limitations of these nanoplatforms are summarized in Table 1.

Table 1: Representative nanoplatforms used in oncology and their major characteristics, applications, advantages, and limitations

Nanoplatform	Key characteristics	Major oncology application	Advantages	Major limitations
Liposomes	Phospholipid bilayer; drug encapsulation	Drug delivery, targeted therapy	Biocompatibility, improved solubility	Stability, premature drug leakage
Polymeric nanoparticles	Biodegradable polymer matrix	Controlled/targeted drug delivery	Controlled release, surface modification	Manufacturing complexity
Metallic nanoparticles	Au, Ag, etc.	Imaging, drug delivery, PTT	Optical/photothermal properties	Potential toxicity
Magnetic nanoparticles	Fe_3O_4/SPIONs	MRI, magnetic targeting, hyperthermia	Imaging + therapeutic potential	Biodistribution and long-term safety
Dendrimers	Highly branched architecture	Drug/gene delivery	High functionalization capacity	Toxicity and synthesis cost
Carbon- based nanomaterials	Graphene, CNTs, etc.	Imaging, drug delivery, phototherapy	High surface area	Biocompatibility concerns

3. Nanobiotechnology-Enabled Precision Oncology

3.1. Nano biosensors for Early Cancer Biomarker Detection

Early detection of cancer is critical to improving survival rates. Particularly, gold nanoparticle-based nano biosensors have allowed the detection of biomarkers at very low concentrations. AuNP sensors have been used for early-stage detection of lung cancer by analysis of exhaled breath, providing a non-invasive diagnostic tool [8, 15]. The nanoparticle-based bioassays in hepatocellular carcinoma are useful to enhance the sensitivity of alpha-fetoprotein detection, which is limited by conventional imaging and serum tests [2, 8, 9]. Nano biosensors are capable of detecting very low concentrations of biomarkers [16], which makes them valuable for early diagnosis, monitoring of disease progression and assessment of treatment response [8, 15].

3.2. Nanotechnology-Enhanced Cancer Imaging

Nanoparticles also transform imaging modalities. Magnetic nanoparticles and other such nanoparticles revolutionize imaging modalities. Magnetic nanoparticles, such as superparamagnetic iron oxide nanoparticles (SPIONs), have been employed to improve the contrast of MRI [17] in liver cancer, which leads to earlier diagnosis and better monitoring [2, 8, 9]. Gold nanoparticles as a contrast agent for intraoperative imaging in lung cancer surgery: better localization of tumour and surgical accuracy. These improvements reduce the risk of both tumour recurrence and of leaving any tumour behind. Nanoparticles can be functionalized with targeting ligands [18, 19] that bind specifically to tumour cells and enable real-time imaging of tumour dynamics [2, 8, 9].

3.3. Nano-Enabled Liquid Biopsy for Cancer Detection

Liquid biopsy is a new diagnostic tool based on circulating tumour DNA, exosomes or proteins. Nanoparticles improve the sensitivity and specificity of liquid biopsy platforms by capturing and amplifying signals from rare biomarkers [8, 15]. Green-synthesized nanoparticles for biosensors are being investigated for minimally invasive diagnostics. However, clinical translation is hampered by challenges such as reproducibility, regulatory approval and large-scale validation [19, 20]. Liquid biopsy and nanotechnology are a promising approach to personalized healthcare, enabling real-time monitoring of tumor evolution and treatment response [8, 15].

4. Nanobiotechnology-Based Therapeutic Approaches in Cancer

Nanobiotechnology has paved new avenues in cancer therapy by providing novel approaches other than conventional chemotherapy and radiotherapy. Nanoparticles for selective drug delivery, modulation of the tumour microenvironment and integration with advanced modalities such as photothermal therapy, photodynamic therapy, immunotherapy and gene therapy have opened new vistas within oncology [9, 21]. These strategies may enhance therapeutic efficacy and lower systemic toxicity, providing patients with safer and more personalized therapeutic

options [2, 8, 9]. Each therapeutic avenue is discussed in detail to underline the breadth and depth of the role of nanobiotechnology in cancer care [2, 9].

4.1. Targeted Nanocarrier-Mediated Drug Delivery

Specific nanocarrier systems for drug delivery is one of the most important contributions of nanobiotechnology to oncology. Conventional chemotherapeutic agents tend to circulate non-specifically, leading to damage to healthy tissues and severe side effects [2, 10, 13, 14]. However, nanocarriers can be engineered to take advantage of the enhanced permeability and retention (EPR) effect, resulting in their preferential accumulation in tumor tissues. For this reason, nanocarriers such as liposomes, polymeric nanoparticles and dendrimers [22] have been widely investigated [2, 10, 14]. A more sophisticated approach is stimuli responsive nanocarriers where the drug is released in response to a specific trigger such as pH, temperature or external light. For example, ThermoDox, a heat-sensitive formulation of doxorubicin in liposomes, releases its payload in the presence of hyperthermia and thus concentrates the drug at the tumour site [21]. The spatiotemporal control over drug release by optogenetic nanocarriers responsive to light stimuli enables precise induction of apoptosis in cancer cells. Another promising avenue is targeting the tumour microenvironment [23, 24], especially immunosuppressive cells such as M2 macrophages [2, 14]. Reprogramming these cells to improve the immune system's ability to fight cancer is one of the major barriers to effective therapy that nanocarriers can overcome [25, 26]. The major nanobiotechnology-based diagnostic and therapeutic strategies, their benefits, and translational challenges are summarized in Table 2.

Table 2: Nanobiotechnology-based diagnostic and therapeutic strategies in cancer: mechanisms, applications, benefits, and translational challenges

Application	Nanotechnology approach	Representative biomarkers/ targets or payloads	Major benefit	Key challenges
Early diagnosis	Nanobiosensors	DNA, RNA, proteins, exosomes	High sensitivity and specificity	Clinical validation
Liquid biopsy	Nano - enabled enrichment/ detection	ctDNA, CTCs, exosomes	Minimally invasive monitoring	Low abundance, standardization
MRI	Magnetic nanoparticles	SPIONs	Enhanced imaging contrast	Safety/ biodistribution
Optical imaging	AuNPs/quantum dots	Tumor- associated signals	High sensitivity	Tissue penetration
Targeted chemotherapy	Functionalized nanocarriers	Chemotherapeutic drugs	Improved tumor delivery	Tumor heterogeneity
PTT	Photothermal nanomaterials	NIR - responsive nanoparticles	Localized heat generation	Light penetration
PDT	Photosensitizer-loaded nanoplatforms	ROS generation	Spatially controlled therapy	Oxygen availability
Immunotherapy	Immunomodulatory nanoplatforms	Immune/TME targets	Enhanced antitumor immunity	Immune complexity
Gene therapy	Nanocarriers	siRNA/miRNA/CRISPR components	Nucleic- acid delivery	Stability and off-target effects

4.2. Nanotechnology-Mediated Enhancement of Chemotherapy

Chemotherapy continues to be a mainstay in treating cancer but is often restricted by systemic toxicity and drug resistance. Nanotechnology can help overcome these challenges by encapsulating chemotherapeutic agents in nanoparticles and thus optimizing their pharmacokinetics and biodistribution [2, 9, 21]. Nanocarriers have been used to reformulate drugs to reduce toxicity and improve efficacy, such as cisplatin, paclitaxel and doxorubicin. For example, albumin-bound paclitaxel (Abraxane) increases solubility and reduces hypersensitivity reactions compared with conventional paclitaxel [10, 12, 14]. Nanocarriers also help in safe delivery of increased doses of the drug and thus improve therapeutic indices in cancers such as lung, bladder and liver [8, 10, 12]. Moreover, nanoparticles can be conjugated with targeting ligands that recognize tumour-specific receptors, allowing the delivery of chemotherapy drugs to cancer cells, minimizing damage to healthy tissues. This approach is targeted and therefore more efficacious and less likely to develop resistance, making chemotherapy more effective for a longer period [2, 9].

4.3. Nanoparticle-Assisted Photothermal Cancer Therapy

Photothermal therapy (PTT) is a non-invasive method where nanoparticles are used to convert sunlight into heat to destroy tumour, In particular, gold and magnetic nanoparticles are promising for this modality [27] because they can absorb light and generate localized hyperthermia [11, 28]. Gold nanoparticles heat up and kill cancer cells while sparing much of the surrounding healthy tissue when exposed to near-infrared light. The application of external magnetic fields in directing magnetic nanoparticles into tumors provides an additional level of accuracy [1, 11, 29]. PTT has shown promise as an alternative to surgery with lower complications in the treatment of prostate and lung cancers. PTT offers an effective way to accurately destroy tumors because it can control the heat generation at the nanoscale, which can reduce the recurrence rate and improve the outcomes of patients [2, 9].

4.4. Nanotechnology-Enhanced Photodynamic Therapy

Photodynamic therapy (PDT) is based on the use of light-activated photosensitizers (PSs) that generate reactive oxygen species (ROS) to kill cancer cells. Nanoparticles enhance PDT by increasing light penetration, increasing photosensitizer stability and amplifying ROS generation. Such as, nanoparticles can be engineered for targeted delivery of photosensitizers to tumour cells so that ROS can be generated locally upon light activation [1, 6]. This targeted approach reduces damage to healthy tissues and increases therapeutic efficacy. PDT has been successfully used in bladder and breast cancers in which nanoparticles enhance the treatment outcome by overcoming the limitations of poor light penetration and photosensitizer degradation. Nanotechnology combined with PDT is a synergistic approach that provides maximum precision with minimum toxicity [28, 30].

4.5. Nanotechnology-Enabled Cancer Immunotherapy

Immunotherapy has revolutionized cancer treatment by recruiting the body's immune system to battle tumors. Nanotechnology improves immunotherapy through modulation of immune pathways and reprogramming of the tumour microenvironment. Exopolysaccharide-coated zinc oxide nanoparticles (EPS-ZnONPs) derived from probiotics have shown promise in colorectal cancer by regulating immune-related genes and enhancing anti-tumor immunity [2, 8, 9]. Likewise, in breast cancer, macrophage-targeted nanocarriers can reprogram immunosuppressive M2 macrophages into pro- inflammatory M1 macrophages, thus enhancing immune responses against tumors [1, 10]. Nanoparticles may also be used to deliver immune checkpoint inhibitors or cytokines to tumors, thus improving efficacy and minimizing systemic side effects [2, 10, 13, 14]. Researchers hope to leverage nanotechnology with immunotherapy to overcome resistance and generate durable responses in non-responders to conventional immunotherapies [2, 8, 9].

4.6. Nanoparticle-Mediated Gene Delivery and Cancer Therapy

Gene therapy: Frontier of personalized healthcare. Gene therapy could potentially fix aberrations in genes that cause cancer. Nanoparticles provide a safe and effective means of gene delivery, overcoming problems such as degradation and low cellular uptake [31, 32]. The zinc oxide nanoparticles and polymeric nanocarriers have been used to regulate the oncogenes and tumour suppressors in colorectal and hepatocellular carcinoma. For instance, ZnONPs can downregulate oncogenes such as KRAS and upregulate tumour suppressors such as PTEN, which results in the restoration of normal cellular function. Nanocarriers can also be used for delivering siRNA or CRISPR-Cas9 components to cancer cells to achieve precise genetic modifications [1, 10]. This approach has the potential for highly individualized therapies based on the genetic profile of each patient's tumour and represents a major step forward in precision oncology [2, 7, 8].

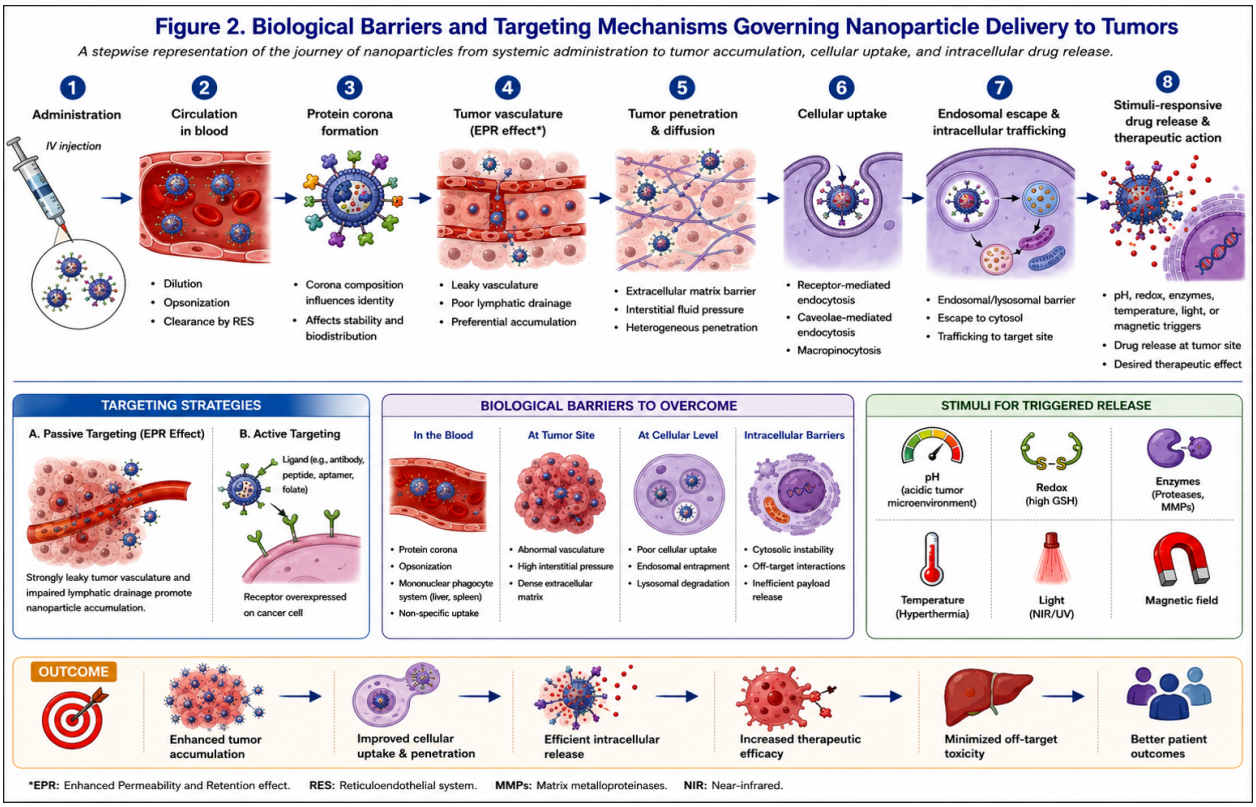

Figure 2: Biological Barriers and Targeting Mechanisms Governing Nanoparticle Delivery to Tumors

Figure 2 Biological Barriers and Targeting Mechanisms Governing Nanoparticle Delivery to Tumors. Figure guide: The schematic illustrates the major biological barriers encountered by nanoparticles following systemic administration, including protein corona formation, mononuclear phagocyte system clearance, vascular barriers, abnormal tumor vasculature, elevated interstitial fluid pressure, dense extracellular matrix, cellular uptake barriers, and the immunosuppressive tumor microenvironment. The figure further highlights passive targeting through the enhanced permeability and retention (EPR) effect, active targeting through ligand–receptor interactions, and emerging active transport

and retention (ATR) mechanisms that facilitate nanoparticle entry, penetration, and retention within tumors. The figure was generated using AI-assisted image-generation technology and subsequently reviewed and refined by the authors for scientific accuracy and clarity.

5. Nanotheranostics: Integrating Cancer Diagnosis and Therapy

Nanotheranostics is one of the most exciting frontiers in nanobiotechnology involving integration of diagnostic and therapeutic functions in a single nanoplatform. Unlike traditional approaches in which diagnosis and treatment are carried out separately, nanotheranostics enables simultaneous detection of cancer biomarkers, real-time imaging of the tumours and delivery of therapeutic agents [20, 33, 34]. This dual functionality streamlines patient care and allows clinicians to monitor treatment efficacy in real time, thereby decreasing delays and improving clinical outcomes [2, 8, 9]. The ability to incorporate both diagnosis and therapy into a single system is highly consistent with the principles of precision oncology, in which treatment is designed to match the specific molecular and cellular properties of an individual's tumour. A large variety of nanomaterials have been investigated for theranostics, such as metallic nanoparticles, polymeric nanocarriers or hybrid systems. For example, gold nanoparticles (AuNPs) are particularly suitable for theranostics due to their strong optical properties, which make them good candidates for both imaging agents and mediators of photothermal therapy [2, 7, 8]. Likewise, plant extract or probiotic exopolysaccharides (EPS)-mediated green synthesis of silver nanoparticles (AgNPs) are also found to have anticancer activity and diagnostic potential which make them ideal candidates for eco-friendly theranostic systems [20, 33, 34]. Polymeric nanocarriers such as gelatin-alginate hydrogel encapsulating AgNPs are utilized for enhanced stability, biocompatibility and controlled release thereby enabling efficient delivery of therapeutic cargo and strong diagnostic signals [1, 11, 29].

One of the most promising examples of nanotheranostics is the synthesis of Gel-Alg-AgNPs using Calendula officinalis extract. This green nanoplatform shows anticancer activity, biocompatibility and diagnostic capabilities at the same time, and exemplifies the potential of sustainable nanotechnology in oncology [20, 33, 34]. Such multifunctional systems can be engineered to release drugs in response to specific stimuli (e.g., pH changes in the tumour microenvironment) while also providing imaging contrast for real-time monitoring. This combination reduces the need for multiple interventions, lessens systemic toxicity, and enhances patient compliance. Nanotheranostics have immense clinical implications. Such realtime monitoring of drug delivery and therapeutic response allows clinicians to adjust treatment strategies in real time for maximal benefit. For instance, a nanotheranostics system could identify whether a tumour is responding to chemotherapy and, at the same time, deliver additional [20, 33, 34] therapeutic agents in case of resistance. This flexibility is particularly useful in aggressive cancers where rapid changes in tumour biology often overcome standard therapies [2, 9]. Moreover, nanotheranostics can facilitate personalized healthcare by adjusting the diagnostic and therapeutic functions to the genetic and molecular profile of individual tumour. However, the promise of nanotheranostics is tempered by several challenges that need to be overcome before widespread clinical application. There are still major challenges in the area of nanoparticle toxicity, long term stability, reproducibility and regulatory approval [20, 33, 34].

Technical hurdles also arise from the complexity of designing multifunctional systems that balance diagnostic sensitivity with therapeutic efficacy. However, research and clinical trials are still underway, showing the feasibility of nanotheranostics, with multiple platforms showing promise in preclinical models of breast, liver and colorectal cancers [20, 33, 34]. Overall, nanotheranostics are a paradigm shift in cancer care, integrating diagnosis and therapy into a single, multifunctional system. Its real-time monitoring, targeted drug delivery and integrated imaging make it a foundation for future precision oncology. With the continuous development of green synthesis, biomaterial engineering and clinical translation, nanotheranostics is expected to become one of the major weapons in cancer treatment, providing patients with more efficient, safer and personalized treatment options.

6. Challenges, Safety Concerns, and Translational Barriers

The promise of nanobiotechnology in oncology has been astounding, however, the clinical translation of such works is accompanied with a plethora of challenges ranging from safety, manufacturing and regulatory hurdles [35]. The translation of laboratory innovation to bedside application is often a long and uncertain journey, with only a handful of nanomedicines reaching the market, despite thousands of pre-clinical studies [19, 20]. It is critical to overcome these barriers to translate nanomedicine from experimental platforms to widely used cancer therapies [2, 9].

6.1. Clinically Approved Nanomedicines

The approval of liposomal nanomedicine formulations including Doxil (liposomal doxorubicin) [36], Abraxane (albumin-bound paclitaxel), ThermoDox (heat-sensitive liposomal doxorubicin) and Vyxeos (liposomal cytarabine/daunorubicin) demonstrates that nanomedicine can be translated into clinical practice. These drugs have improved pharmacokinetics, decreased systemic toxicity and enhanced therapeutic efficacy compared to the conventional counterparts [8, 10, 12]. However, the limited number of approved nanomedicines shows the difficulty of translating preclinical promise into clinical reality. Many nanoparticle-based therapies never progress beyond the clinical trials due to issues such as reproducibility, unexpected toxicity or lack of a significant advantage over existing therapies [5, 6]. However, regulatory bodies insist on rigorous proof of safety, efficacy and consistency of manufacturing, which can be difficult to show given the complexity of the nanoparticle systems. Thus, approved nanomedicines are proof-of-concept but also point to the difficulties of scaling nanotechnology for widespread clinical use.

6.2. Mechanisms and Biological Implications of Nanoparticle Toxicity

Safety issues still remain as one of the most important barriers for the clinical application of nanobiotechnology. Due to their small size and unique physicochemical properties, nanoparticles can interact with biological systems in unpredictable ways [5, 6]. It has been reported that some nanoparticles, such as copper oxide nanoparticles, can induce cytotoxicity in lung cancer cells, while the others may induce hemolysis in blood assays or developmental toxicity in zebrafish embryos [37]. The long-time stability, biodistribution and clearance of nanoparticles are often not well understood, and it raises concerns about accumulation in important organs such as liver, spleen and kidney. Moreover,

nanoparticles may be recognized by the immune system as foreign bodies, leading to inflammatory responses or hypersensitivity reactions [2, 5, 6]. The toxicity assessments are further complicated by the variation in nanoparticle composition, size and surface chemistry, which hinders the development of universal safety guidelines. These concerns must be tackled with thorough toxicological studies, standardized testing protocols, and long-term monitoring of patients receiving nanoparticle-based therapies [2, 9].

6.3. GMP and Manufacturing Considerations

Another big challenge is the large-scale manufacture of nanoparticles. Laboratory synthesis methods usually yield small batches with high variability, which is not suitable for clinical applications that require reproducibility and consistency. Good Manufacturing Practice (GMP) requires that the size, shape, surface chemistry and purity of nanoparticles are stringently controlled, which is difficult to achieve during large-scale production [19, 20]. Moreover, the cost of making complex nanocarriers may be prohibitively expensive and limit access for patients. Green synthetic techniques such as plant extracts or probiotic exopolysaccharides are eco-friendly alternatives that decrease reliance on toxic chemicals [1, 29]. However, these methods also face challenges in terms of standardization, scalability and regulatory approval.

It is important to guarantee GMP compliance of nanoparticles synthesized through green synthesis for clinical translation. For nanomedicine to be widely adopted, academia, industry, and regulatory agencies will need to collaborate to create scalable, cost-effective, and standardized manufacturing processes [19, 20].

6.4. Regulatory and Translational Barriers

In addition to safety and manufacturing, regulatory hurdles are major barriers to the clinical translation of nanobiotechnology. For regulatory bodies such as the Food and Drug Administration (FDA) and the European Medicines Agency (EMA) to approve new therapies, a large amount of data on pharmacokinetics, biodistribution, toxicity and efficacy is required. The complex nature of nanoparticle systems, which often involve the combination of multiple functions such as drug delivery, imaging and immunomodulation, makes it difficult to fit them into existing regulatory structures. Further, the lack of standardized guidelines for nanoparticle characterization and testing adds uncertainty for developers [2, 8, 9]. Clinical trials for nanomedicines are often costly and time-consuming, with high attrition rates. In an effort to close the gap between laboratory innovation and clinical translation, new regulations that consider the unique properties of nanomedicine and increased collaboration between researchers, clinicians and policymakers will be necessary [19, 20].

6.5. Ethical and Patient-Centric Considerations

Last but not least, the ethical issues arising from the clinical translation of nanobiotechnology should be taken into consideration. Patients should be made aware of the potential risks and benefits of nanoparticle-based therapies, especially considering the uncertainties of long-term safety. Problems of accessibility and affordability are also encountered, since complex nanomedicines may be unaffordable for patients in low- and middle-income countries. Equal access to nanomedicine will be crucial for its worldwide adoption [19, 20]. Trust in nanobiotechnology will also depend on patient-centered approaches that emphasize safety, transparency, and informed consent [2, 9]. Emerging nanobiotechnology strategies relevant to nanotheranostics, personalized medicine, and future precision oncology are summarized in Table 3.

Table 3: Emerging nanobiotechnology strategies for nanotheranostics, personalized medicine, and future precision oncology

Emerging strategy	Nanotechnology component	Function	Potential precision-oncology application	Current challenge
Nanotherano stics	Multifunctional nanoparticles	Diagnosis + therapy + monitoring	Personalized treatment	Platform complexity
AI - driven nanomedicine	AI/ML + nanoparticle datasets	Formulation/ design optimization	Patient- specific nanotherapeutics	Data quality/ validation
Patient-specific nanotherapeutics	Targeted multifunctional nanoplatforms	Individualized treatment	Precision cancer therapy	Patient heterogeneity
Optogenetic nanomedicine	Light - responsive nanoplatforms	Spatially controlled therapy	Localized treatment	Tissue penetration
Green nanotechnology	Biological/sustainable synthesis	Eco-friendly nanoparticle production	Sustainable nanomedicine	Reproducibi lity/ scaling
Nano-enabled liquid biopsy	Nano-biosensors	Biomarker detection	Disease monitoring	Clinical standardization
Image-guided nanotherapy	Imaging + therapeutic nanoplatform	Treatment guidance	Real-time treatment adaptation	Clinical integration

7. Future Directions and Emerging Trends in Cancer Nanobiotechnology

The future of nanobiotechnology in oncology is set to be transformational, with emerging trends pointing to more personalized, intelligent, and sustainable approaches to cancer care. Nanomedicines that are already in existence have demonstrated the potential for improved drug

delivery and imaging. The next generation of innovations, however, will combine artificial intelligence, customization to the individual patient, eco-friendly synthesis and advanced therapeutic modalities, such as optogenetics. These advances are anticipated to overcome existing limitations in toxicity, scalability and regulatory approval, ultimately transforming the landscape of precision oncology [5, 6].

7.1. Artificial Intelligence-Driven Nanomedicine

Artificial intelligence (AI) is expected to play a major role in the design and optimization of nanomedicines. Machine learning algorithms may utilize large datasets from bibliometric studies, clinical trials and molecular simulations to identify promising nanoparticle designs and to predict their behavior in biological systems [2, 8, 20]. The AI based models may optimize nanoparticle size, shape and surface chemistry for maximum tumour targeting and minimum toxicity. Moreover, predictive algorithms assist in predicting potential adverse effect, which can facilitate the regulatory approval process [6, 17]. Previous bibliometric analyses have identified research hotspots, such as green synthesis, macrophage-targeted therapy and optogenetics, and artificial intelligence can be applied to primacies these areas for further development. Combination of computational power and experimental research will allow AI-driven nanomedicine to accelerate the translation of nanotechnology to clinical practice, making it more effective and safer [2, 9].

7.2. Personalized and Patient-Specific Nanotherapeutics

Personalized therapy is emerging as an essential component of modern oncology, and nanobiotechnology is uniquely suited for the delivery of patient-specific therapies. Tumors are highly heterogeneous, with genetic alterations, microenvironmental factors and immune profiles varying widely between patients [2, 7, 8]. Nanocarriers can be designed to these individual features for therapies to be precisely tailored to each patient's tumour biology. For example, nanoparticles can be designed to deliver drugs or genetic material that target mutations such as KRAS or TP53 directly, or to modify immune cells in the tumour microenvironment. Personalized nanomedicine is also relevant to the diagnostics, where nano biosensors can sense patient-specific biomarkers and guide in real time the treatment decisions. Such level of customization promises increased efficacy, decreased adverse effects and improved patient outcomes, which is a major step ahead in the direction of true individualized cancer care [8, 15].

7.3. Clinical Translation and Evaluation

Preclinical studies have shown great promise for nanomedicine, but its translation to clinical settings is slow and challenging. We will continue our efforts to bridge this gap by performing large-scale clinical trials to assess the safety, efficacy and reproducibility of nanoparticle-based therapies. Nanocarrier-drug combinations are under trial in ongoing studies for lung and liver cancers with early results being encouraging with improvements in therapeutic indices. But regulatory approval hinges on more than proof of efficacy. Standardized manufacturing processes and cost-effectiveness analyses are also needed, as is data on long-term safety. Future directions of clinical translation will probably involve closer collaboration between academia, industry, and regulatory agencies to develop frameworks that accommodate the unique properties of nanomedicine. As these efforts progress, more nanoparticle-based therapies are expected to enter mainstream oncology, expanding treatment options for patients worldwide.

7.4. Nanobiotechnology in Precision Cancer Medicine

The combination of nanotheranostics, immunotherapy, and optogenetics is a major emerging trend in precision cancer medicine. Nanotheranostics combines diagnostic and therapeutic functionalities on a single platform, allowing real-time monitoring of treatment response with dynamic adjustment of therapy. Nanoparticle delivery systems can augment the effect of immunotherapy, overcome resistance to immunotherapy and reprogram the tumour microenvironment to an anti-tumor state. Optogenetics is a technique utilizing light-sensitive proteins to manipulate cellular processes that provides unmatched accuracy in triggering apoptosis or modifying gene expression. These modalities work together to establish a synergistic framework for highly individualized treatment strategies. Nanotechnology together with precision medicine will revolutionize oncology enabling the development of effective and personalized therapies based on the specific molecular and cellular signature of the tumour in each patient.

8. Conclusion

Nanobiotechnology, one of the most promising frontiers of oncology, presents novel solutions to long-standing problems in cancer diagnosis and therapy. Researchers have leveraged the unique physicochemical characteristics of nanoparticles in order to design systems for targeted drug delivery, enhanced imaging, immunomodulation and combined theranostic. These advances represent a paradigm shift from traditional, often generic and toxic, treatments, to precision therapies that are safer, more effective, and tailored to the molecular and cellular characteristics of individual tumours. The application of nanotechnology to oncology has already resulted in clinically approved formulations such as Doxil, Abraxane and Vyxeos, demonstrating proof-of-concept for the feasibility of nanomedicine in real-world practice. But the true power of nanobiotechnology is its capability to merge diagnosis and therapy, customize treatment strategies and dynamically adapt to tumour evolution. But these advances have not eliminated significant challenges. Nanoparticle toxicity, long term stability, biodistribution and clearance issues must be addressed by rigorous preclinical and clinical studies. Manufacturing barriers, especially the requirement for reproducibility and scalability under Good Manufacturing Practice (GMP) standards, still remain a bottleneck to translation from laboratory to clinic. Regulatory systems have not yet caught up with the complexity of multifunctional nanoplatforms, resulting in uncertainty for developers. Ethical considerations such as patient safety, transparency and equitable access should also be prioritized to ensure nanomedicine benefits patients across different socioeconomic contexts. To solve these barriers will require an interdisciplinary approach that includes scientists, clinicians, engineers, policymakers and industry leaders. Looking ahead, several emerging trends will define the future of cancer nanobiotechnology. Artificial intelligence will help speed up the design and optimization of nanoparticles by predicting their behaviour within biological systems, thus aiding clinical translation. Personalized nanotherapeutics will target individual tumour's genetic and immune profiles, to optimize efficacy and reduce toxicity. Nanotheranostics will integrate diagnosis and therapy in single platforms for real time

monitoring and dynamic treatment adjustment. Advances in optogenetics and other modalities will enable unprecedented precision in controlling cellular processes and will open new avenues for non-invasive therapies. The use of green synthesis methods, plant extracts and probiotic exo-polysaccharides will guarantee sustainability and decrease the dependence of toxic chemicals, thus making nanomedicine compatible with the global environmental goals. To digests, nanobiotechnology is not just a new frontier in oncology, but a paradigm shift in the way cancer is diagnosed, treated and monitored. It converges with artificial intelligence, personalized healthcare, and sustainable synthesis and heralds a new era of precision oncology. Despite safety, scalability and regulatory challenges, the trajectory of research and innovation indicates that nanomedicine will be a fundamental component of cancer care in the coming decades. Looking forward, a cautious optimism remains, with continued interdisciplinary collaboration and patient-centered approaches poised to translate the promise of nanobiotechnology into real benefits for patients worldwide.

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