International Journal of Research and Applied Innovations (IJRAI)

| ISSN: 2455-1864 | www.ijrai.org | editor@ijrai.org | A Bimonthly, Scholarly and Peer-Reviewed Journal |

||Volume 8, Issue 6, November–December 2025||

DOI:10.15662/IJRAI.2025.0806017

Nanoparticles Application in Cancer Therapy: An Update Overview

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ABSTRACT: The NLRP3 inflammasome has emerged as a pivotal driver of inflammation through activation of caspase-1 and subsequent maturation of the pro-inflammatory cytokines IL-1β and IL-18. Dysregulated or persistent NLRP3 activation contributes to the onset and progression of numerous chronic disorders, particularly within the cardiovascular and neurological systems, including myocardial infarction, heart failure, atherosclerosis, stroke, Alzheimer's disease, and diabetes-associated complications. As a result, the development of selective NLRP3 inhibitors has become an important therapeutic pursuit aimed at mitigating sustained inflammatory damage while avoiding broad immunosuppression. This review highlights recent advancements in the discovery, optimization, and early clinical evaluation of small-molecule NLRP3 inhibitors such as MCC950, dapansutrile (OLT1177), NT-0796, and emerging next-generation candidates. Preclinical and phase I data demonstrate encouraging outcomes, including attenuation of inflammatory pathways, stabilization of atherosclerotic lesions, improved cardiac and cognitive performance, and enhanced safety profiles relative to non-specific anti-inflammatory agents. Furthermore, ongoing research is focused on overcoming challenges involving limited brain penetration, allelic resistance variants, and off-target activity. Integrating biomarker-guided patient selection, improved drug delivery technologies, and precision pharmacology is expected to strengthen therapeutic predictability and clinical translation. Despite the progress made, achieving long-term safety, optimized tissue targeting, and individualized treatment regimens remains a critical objective. Continued advancements in molecular insight and translational science are poised to redefine therapeutic strategies for inflammation-driven cardiovascular and neurodegenerative diseases through targeted NLRP3 inflammasome inhibition.

KEYWORDS: Nanotechnology, Nanoparticles, Liposomes, Cancer, Dendrimers, Solid-lipid nanoparticles

I. INTRODUCTION

Cancer remains one of the most formidable health challenges worldwide, characterized by uncontrolled cellular proliferation, genetic instability, and the ability to invade distant organs. Despite significant advances in early diagnosis and molecular characterization, cancer continues to cause millions of deaths annually. Conventional therapeutic modalities such as surgery, chemotherapy, and radiotherapy have undoubtedly improved survival rates in certain malignancies; however, they often fall short of achieving complete remission due to issues like poor selectivity, systemic toxicity, and multidrug resistance [1, 2].

In recent decades, the emergence of nanotechnology has provided a revolutionary platform for addressing these long-standing limitations in oncology. Nanoparticles, with their unique physicochemical properties, such as tunable size, large surface area-to-volume ratio, and capability for functionalization, have opened new avenues for precision-targeted drug delivery, imaging, and theranostics. By enabling site-specific drug accumulation and controlled release, nanotechnology-based systems aim to enhance therapeutic efficacy while minimizing adverse effects on healthy tissues.

According to the latest GLOBOCAN 2024 estimates by the International Agency for Research on Cancer (IARC), approximately 20 million new cancer cases and 9.7 million deaths occurred globally, with projections suggesting that the global cancer incidence may exceed 30 million by 2040. The rising prevalence is attributed to multiple factors, including aging populations, environmental exposures, urban lifestyles, and genetic predispositions. Cancers of the breast, lung, colorectal region, prostate, and stomach represent the most common types, collectively accounting for nearly half of all diagnosed cases [3, 4].

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Traditional cancer treatments, surgery, chemotherapy, radiotherapy, and, more recently, immunotherapy, remain the backbone of clinical management. However, each has inherent shortcomings that limit therapeutic success. Surgical resection is effective only when tumors are localized and accessible, while radiotherapy, though precise, can inadvertently damage adjacent healthy tissues. Chemotherapy, perhaps the most widely used systemic treatment, is hindered by non-specific cytotoxicity, rapid drug clearance, and the development of resistance mechanisms such as enhanced efflux pump activity and DNA repair in tumor cells [5].

Furthermore, many anticancer agents suffer from poor solubility, low bioavailability, and unfavorable pharmacokinetics. As a result, achieving therapeutic drug concentrations at the tumor site often necessitates high systemic doses, leading to severe side effects such as myelosuppression, gastrointestinal toxicity, and cardiotoxicity. The tumor microenvironment (TME) also presents physiological barriers, such as abnormal vasculature, hypoxia, and acidic pH, that impede effective drug penetration and uniform distribution. Collectively, these factors underscore the pressing need for innovative strategies capable of selectively targeting tumor tissues, improving therapeutic outcomes, and reducing systemic toxicity [3, 4].

II. TYPES OF NANOTECHNOLOGY IN CANCER THERAPY

Nanoparticle systems represent a diverse class of engineered materials designed to enhance the selectivity, bioavailability, and therapeutic efficiency of anticancer drugs. Each nanoparticle type possesses distinct structural, physicochemical, and functional attributes that influence its biological performance. Depending on their composition and design, nanoparticles can be classified into polymeric, lipid-based, metallic, inorganic, dendrimeric, micellar, and hybrid or biomimetic systems.

2.1 Polymeric nanoparticles

Polymeric nanoparticles have gained immense attention in oncology due to their biocompatibility, tunable physicochemical properties, and ability to provide controlled drug release. They are typically synthesized from biodegradable polymers such as poly(lactic-co-glycolic acid) (PLGA), polylactic acid (PLA), polycaprolactone (PCL), and natural polymers like chitosan or alginate. These nanoparticles can encapsulate hydrophobic and hydrophilic drugs within their matrix, thereby protecting therapeutic agents from degradation and improving their pharmacokinetic profile. Their surface can be readily modified with polyethylene glycol (PEG) or tumor-targeting ligands, enabling prolonged circulation and selective tumor accumulation [6, 7].

In cancer therapy, polymeric nanoparticles offer significant advantages in sustained drug release and reduction of systemic toxicity. For instance, doxorubicin-loaded PLGA nanoparticles have demonstrated improved tumor suppression and reduced cardiotoxicity compared with conventional formulations. Furthermore, polymeric nanoparticles can be engineered as stimuli-responsive systems, releasing drugs in response to environmental triggers such as pH, temperature, or enzymatic activity. [8, 9].

2. 2 Lipid-Based nanoparticles (Liposomes, SLNs, NLCs)

Lipid-based nanoparticles are among the most extensively studied and clinically translated systems for cancer therapy. Liposomes, solid lipid nanoparticles (SLNs), and nanostructured lipid carriers (NLCs) constitute the major types within this category. Liposomes are spherical vesicles composed of one or more phospholipid bilayers enclosing an aqueous core, capable of carrying both hydrophilic and lipophilic drugs. The first FDA-approved nanoparticle drug, *Doxil*®—a pegylated liposomal doxorubicin—set the foundation for liposomal therapeutics by demonstrating reduced toxicity and improved therapeutic index in cancer patients [10].

Solid lipid nanoparticles and nanostructured lipid carriers represent next-generation lipid systems developed to overcome the stability limitations of conventional liposomes. SLNs consist of lipids that remain solid at body temperature, providing a rigid matrix for controlled drug release. NLCs, on the other hand, incorporate a mixture of solid and liquid lipids, resulting in improved drug loading and reduced crystallization during storage. Lipid-based nanoparticles are inherently biocompatible, biodegradable, and capable of crossing biological membranes efficiently. Their ability to integrate targeting ligands, imaging agents, and multiple drugs further enhances their utility in combination therapies and theranostics. Continuous advances in lipid formulation technology and large-scale manufacturing have positioned lipid-based nanoparticles as the most clinically successful nanocarrier systems to date [11, 12].

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2.3 Metallic and Metal Oxide Nanoparticles

Metallic and metal oxide nanoparticles occupy a distinct niche in cancer nanomedicine owing to their unique optical, electrical, and magnetic properties. Gold nanoparticles (AuNPs), silver nanoparticles (AgNPs), and iron oxide nanoparticles (Fe_3O_4) are among the most widely explored for diagnostic and therapeutic purposes. Gold nanoparticles, in particular, have been extensively investigated for drug delivery, photothermal therapy, and imaging applications. Their high surface area allows for dense drug loading, and their strong surface plasmon resonance enables efficient conversion of light into heat, facilitating localized tumor ablation when exposed to near-infrared radiation [13, 14].

Iron oxide nanoparticles have gained prominence in magnetic resonance imaging (MRI) and magnetic hyperthermia therapy due to their superparamagnetic nature. They can generate localized heat under an alternating magnetic field, selectively killing tumor cells while sparing surrounding tissues. Additionally, metal oxide nanoparticles such as titanium dioxide (TiO_2) and zinc oxide (ZnO) exhibit photodynamic and photocatalytic activities that can be harnessed for oxidative stress-mediated tumor cell death [15, 16]. Despite their functional advantages, metallic nanoparticles require careful surface modification to enhance biocompatibility and minimize potential cytotoxicity caused by metal ion release or oxidative stress. Research is increasingly focusing on biodegradable and hybrid metal nanostructures that maintain functional efficiency while improving safety profiles for clinical translation [17].

2.4 Inorganic Nanocarrier (Silica, Quantum Dots, Carbon Nanotubes)

Inorganic nanocarriers encompass a broad category of nanostructures that exhibit superior mechanical strength, chemical stability, and tunable surface chemistry. Among these, mesoporous silica nanoparticles (MSNs) are widely studied for drug delivery due to their high surface area, adjustable pore size, and facile surface functionalization. MSNs can encapsulate a variety of therapeutic molecules and release them in response to environmental stimuli, making them suitable for controlled and targeted cancer therapy. Their surface can be modified with polymers, peptides, or antibodies to achieve active targeting and reduced off-target toxicity [18, 19].

Quantum dots (QDs) are semiconductor nanocrystals with size-dependent optical properties, making them highly suitable for cancer imaging and diagnostics. Their ability to emit bright, stable fluorescence enables real-time tracking of tumor cells and nanoparticle distribution in vivo. However, concerns over their heavy metal content and long-term toxicity have limited their widespread therapeutic use [20].

Carbon nanotubes (CNTs), including single-walled and multi-walled structures, possess unique electrical conductivity, high aspect ratios, and strong mechanical properties. They have been investigated as drug delivery vehicles, photothermal agents, and biosensors in oncology. Functionalization of CNT surfaces with biocompatible polymers and targeting ligands improves solubility and reduces toxicity, enhancing their potential for clinical applications. Collectively, inorganic nanocarriers provide versatile platforms for multimodal cancer treatment, integrating therapeutic and diagnostic functionalities within a single nanosystem [21, 22].

2.5 Dendrimers and Polymeric Micelles

Dendrimers and polymeric micelles are self-assembled nanosystems that have shown great promise in enhancing the solubility, stability, and targeted delivery of anticancer drugs. Dendrimers are highly branched, monodisperse macromolecules with a well-defined, tree-like architecture and a central core surrounded by multiple surface functional groups. This structural precision allows for controlled drug encapsulation within interior cavities or attachment on the surface through covalent bonding. Poly(amidoamine) (PAMAM) dendrimers are among the most studied, offering high drug-loading capacity and tunable surface chemistry for targeted delivery. However, unmodified dendrimers can exhibit cytotoxicity due to their cationic surface, necessitating modifications such as PEGylation or acetylation to improve safety [23].

Polymeric micelles, in contrast, are formed by the self-assembly of amphiphilic block copolymers in aqueous environments. Their hydrophobic cores serve as reservoirs for poorly soluble drugs, while hydrophilic shells stabilize the nanoparticles in circulation. Polymeric micelles have been particularly effective in delivering hydrophobic anticancer agents such as paclitaxel, docetaxel, and doxorubicin. Their nanoscale size and stealth properties promote passive tumor targeting through the EPR effect, while ligand modification enables active targeting. Both dendrimers and polymeric micelles exemplify precision nanocarriers capable of improving therapeutic index and reducing systemic adverse effects [24].

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2.6 Hybrid and Biomimetic Nanoparticles

Hybrid and biomimetic nanoparticles represent the next frontier in cancer nanomedicine, integrating the advantages of multiple nanomaterial systems or biological components to achieve superior therapeutic outcomes. Hybrid nanoparticles are typically composed of combinations such as polymer–lipid, metal–polymer, or inorganic–organic composites. These multifunctional systems can simultaneously offer structural stability, controlled drug release, imaging capabilities, and stimuli-responsive behavior. For example, polymer–lipid hybrids combine the biocompatibility of liposomes with the structural robustness of polymeric cores, resulting in enhanced circulation stability and targeted delivery efficiency [25, 26].

Biomimetic nanoparticles, on the other hand, are inspired by natural biological systems. They are often camouflaged with cell membranes derived from red blood cells, platelets, cancer cells, or immune cells to evade immune recognition and exploit the natural targeting pathway. Such systems can inherit the homing capabilities and surface proteins of their source cells, enhancing tumor accumulation and biocompatibility. Moreover, exosome-based nanoparticles, naturally secreted vesicles from cells, have recently attracted attention for their intrinsic ability to transfer bioactive molecules across biological barriers with minimal immunogenicity [27, 28].

Hybrid and biomimetic nanocarriers, by combining synthetic precision with biological adaptability, hold tremendous potential for personalized and precision-based cancer therapy. Their versatility allows for the co-delivery of drugs, genes, and imaging agents, enabling integrated treatment and diagnosis within a single platform. Continued advancements in their design, manufacturing, and functional evaluation are expected to accelerate their translation into clinical oncology.

III. TARGETING STRATEGIES IN NANOPARTICLE-MEDIATED THERAPY

The primary objective of nanoparticle-based drug delivery in oncology is to achieve selective accumulation of therapeutic agents within tumor tissues while minimizing exposure to healthy organs. Conventional chemotherapy lacks this specificity, often resulting in systemic toxicity and suboptimal efficacy. Nanoparticles, through their unique physicochemical and surface-modifiable properties, provide a versatile platform for targeted drug delivery. The targeting process can be broadly classified into passive**,** active**,** and stimulus-responsive approaches, with recent innovations further extending to tumor microenvironment modulation. Each strategy leverages distinct biological mechanisms to enhance therapeutic localization and improve treatment outcomes [29].

3.1 Passive Targeting and the EPR Effect

It is a phenomenon arising from the leaky vasculature and poor lymphatic drainage characteristic of solid tumors. Nanoparticles within the 10–200 nm range can penetrate through these permeable vessels and remain trapped within tumor tissues for extended periods. This allows for higher local drug concentrations and reduced systemic exposure compared to free drugs (Figure 1). Clinically approved formulations such as *Doxil* (pegylated liposomal doxorubicin) and *Abraxane* (albumin-bound paclitaxel) demonstrate the therapeutic success of this principle. However, the EPR effect varies across tumor types and patients due to differences in vascularization and interstitial pressure, limiting its universal applicability. Combining passive targeting with active or stimuli-responsive mechanisms can significantly enhance tumor penetration and retention [30, 31].

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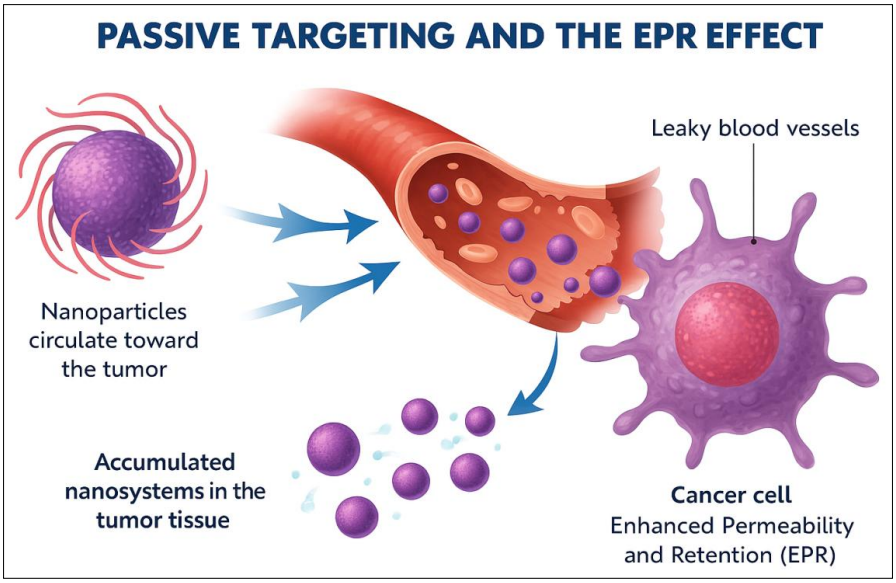

Figure 1: Passive Targeting and the EPR Effect

3.2 Active Targeting: Ligand and Receptor-Mediated Approaches

Active targeting employs molecular recognition between nanoparticle-bound ligands and receptors overexpressed on cancer cells or tumor vasculature (Figure 2) [30]. This strategy enables receptor-mediated endocytosis, leading to improved cellular uptake of therapeutic agents. Commonly used targeting ligands include monoclonal antibodies (e.g., trastuzumab targeting HER2), peptides (such as RGD sequences binding integrins), aptamers, and small molecules like folic acid and transferrin. These ligands confer specificity, reduce off-target effects, and enhance intracellular drug delivery. Despite their advantages, active targeting systems face challenges including ligand instability, steric hindrance, and potential immunogenicity, which necessitate optimization of ligand density and linker chemistry for consistent receptor binding [32, 33].

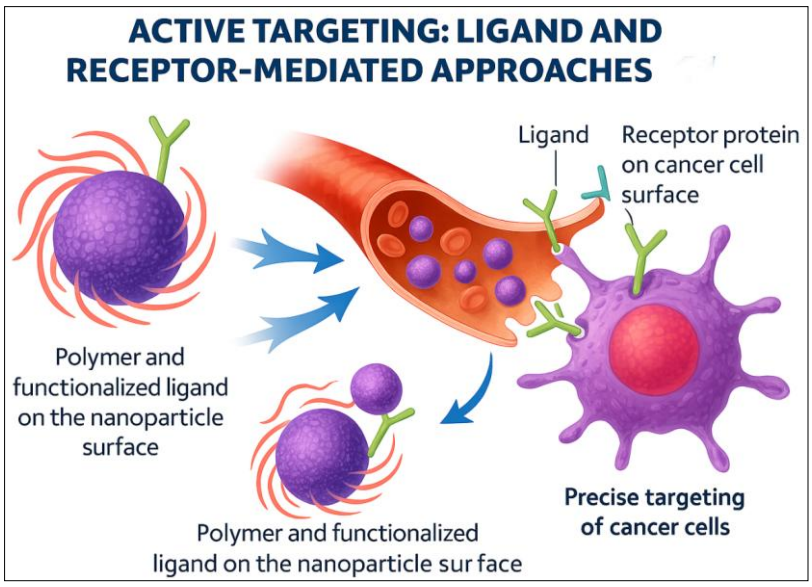

Figure 2: Active targeting: Ligand and Receptor-Mediated Approaches

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3.3 Stimuli-Responsive and Smart Nanocarriers

Stimuli-responsive or smart nanocarriers represent an advanced targeting approach that allows controlled drug release in response to specific triggers. Internal stimuli such as acidic pH, enzymatic activity, or redox gradients within tumors can activate drug release, while external stimuli, such as light, heat, magnetic fields, or ultrasound, offer precise temporal control. For instance, pH-sensitive nanoparticles release drugs in acidic tumor environments, while gold nanoparticles and magnetic nanocarriers enable photothermal and magnetothermal therapies. These "smart" systems enhance site-specific action and can integrate diagnostic and therapeutic functions (theranostics), offering new possibilities for personalized oncology [34].

3.4 Tumor Microenvironment Modulation

Tumor microenvironment modulation has recently emerged as a complementary strategy to improve nanoparticle performance. The TME is characterized by abnormal vasculature, dense extracellular matrix, and immunosuppressive cells that hinder drug penetration. Nanoparticles can normalize tumor blood vessels, remodel extracellular matrix components, or deliver agents that reprogram tumor-associated macrophages to boost antitumor immunity. Some formulations also deliver oxygen-generating compounds to alleviate hypoxia and enhance responses to radiotherapy and photodynamic therapy [35].

IV. RECENT ADVANCEMENT

Between 2020 and 2025, nanomedicine has rapidly evolved through innovations in design, functionality, and clinical translation.

4.1 Novel Nanoparticle Formulation and Functional Modifications

Novel nanoparticle formulations have incorporated smart polymers, stimuli-responsive coatings, and biomimetic membranes that enhance stability, biocompatibility, and selective tumor targeting. Advances in surface engineering such as ligand conjugation, PEG alternatives, and charge-switchable coatings have improved circulation time and cellular uptake, while biodegradable inorganic nanoparticles have addressed long-term toxicity concerns (Table 1) [36].

Table 1: Novel Nanoparticle Formulations and Functional Modifications in Cancer Therapy

S. No	Type of Nanoparticle	Novel Formulation / Modification	Functional Innovation	Therapeutic Advantage	Ref.
1.	**Polymeric Nanoparticles**	PEG-free zwitterionic and pH-responsive polymers	Improved stability, pH-triggered drug release in acidic tumor sites	Enhanced tumor accumulation and reduced off-target toxicity	[37]
2.	**Lipid-Based Nanoparticles (LNPs)**	Ionizable lipids and biodegradable lipid cores	Enhanced RNA and siRNA delivery efficiency, reduced immunogenicity	Effective gene silencing and mRNA-based immunotherapy	[38]
3.	**Hybrid Nanoparticles**	Lipid–polymer and metal–organic framework (MOF) hybrids	Combined mechanical stability and controlled release	Improved bioavailability and sustained therapeutic effect	[39]
4.	**Gold and Metallic Nanoparticles**	PEGylated and antibody-functionalized gold nanorods	Dual photothermal and drug delivery functions	Synergistic chemo-photothermal therapy with minimal side effects	[40]
5.	**Silica Nanoparticles**	Mesoporous silica with enzyme-responsive gates	Controlled drug release based on tumor-specific enzymatic activity	Increased selectivity and reduced premature leakage	[41]

4.2 Combination Therapies (Chemo, Gene, Photothermal, and Immunotherapy)

Combination therapies integrating chemotherapy, gene therapy, photothermal therapy, and immunotherapy have gained prominence for overcoming multidrug resistance and achieving synergistic efficacy. For instance, gold nanorods combined with checkpoint inhibitors or siRNA-loaded polymeric nanoparticles have demonstrated potent immune activation and tumor regression in preclinical studies (Table 2) [31, 42].

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Table 2: Nanoparticle-Based Combination Therapies in Cancer Treatment

S. No	Type of Combination Therapy	Nanoparticle System / Carrier	Therapeutic Mechanism	Key Advantages	Ref.
1.	**Chemo–Photothermal Therapy (CPTT)**	Gold nanorods, graphene oxide, and polymer-coated gold nanoparticles	Co-delivery of cytotoxic drugs (e.g., doxorubicin) and heat generation via near-infrared irradiation	Synergistic tumor ablation, minimized drug dose, reduced systemic toxicity	[43]
2.	**Chemo–Gene Therapy**	Polymeric nanoparticles and lipid–polymer hybrids carrying siRNA or miRNA with chemotherapeutics	Silencing of resistance genes (e.g., MDR1) with simultaneous cytotoxic drug release	Overcomes multidrug resistance, enhances apoptosis	[44]
3.	**Chemo–Immunotherapy**	Liposomal or exosome-based nanoparticles loaded with chemotherapeutic drugs and immune checkpoint inhibitors	Combines cytotoxic killing with immune activation (e.g., PD-L1 blockade)	Induces systemic antitumor immunity, prevents metastasis	[45]
4.	**Photothermal–Immunotherapy**	Gold or carbon-based nanoparticles conjugated with immune adjuvants or antibodies	Localized heat induces tumor cell death and enhances antigen presentation	Stimulates long-term immune memory and tumor regression	[46]
5.	**Gene–Photothermal Therapy**	DNA- or RNA-loaded gold nanoshells or graphene oxide composites	Photothermal heating triggers endosomal escape and gene release	High transfection efficiency and localized control	[47]

4.3 Personalized and precision Nanomedicine Approaches

The emergence of personalized and precision nanomedicin**e** has been fueled by genomic profiling, artificial intelligence, and patient-derived tumor models, enabling individualized nanoparticle designs based on tumor genetics and microenvironmental features. This approach enhances therapeutic predictability and minimizes off-target effects [48].

4.4 Nano-Bio Hybrid System and Multifunctional Platform

Finally, nano–bio hybrid systems have introduced multifunctional platforms integrating synthetic nanomaterials with biological components [49].such as cell membranes, exosomes, and proteins. These hybrids mimic natural biological interfaces, offering immune evasion, targeted delivery, and combined diagnostic–therapeutic capabilities. Collectively, these innovations mark a paradigm shift toward safer, adaptive, and patient-specific nanotechnologies poised to redefine precision oncology [50, 51].

V. PRECLINICAL AND CLINICAL STUDIES

5.1 In Vitro and In Vivo Models Used

In vitro and in vivo models, including 3D tumor spheroids, patient-derived organoids, zebrafish embryos, and xenograft mouse models, have been instrumental in evaluating nanoparticle biodistribution, cytotoxicity, and tumor penetration. These advanced systems better replicate the human tumor microenvironment, enabling accurate prediction of therapeutic performance.

5.2 Key Findings from Preclinical Studies

Preclinical studies during this period have highlighted significant advancements in multifunctional nanoparticles combining chemotherapy with photothermal or immunomodulatory agents. Lipid-polymer hybrids, dendrimer-based gene carriers, and exosome-mimetic nanovesicles have shown superior tumor regression, reduced systemic toxicity,

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and improved immune activation. Furthermore, studies focusing on microRNA and CRISPR-Cas9 delivery have demonstrated the potential of nanoparticles in precise genetic modulation of cancer pathways [52].

5.3 Ongoing and Completed Clinical Trials

Clinical trials from 2020–2025 have advanced several formulations into late-stage evaluation. Examples include lipid nanoparticles for siRNA-based therapy (such as patisiran analogues), albumin-stabilized paclitaxel, and gold nanoparticle-assisted radiotherapy systems. Phase I/II studies have reported enhanced tolerability, prolonged circulation, and improved survival outcomes, validating translational potential. However, interpatient variability and differences in nanoparticle pharmacokinetics remain key limitations [53].

5.4 Translational Challenges and Success Stories

Despite these challenges, translational success stories such as mRNA vaccine nanoplatforms adapted for cancer immunotherapy and biomimetic nanoparticles achieving targeted drug release—demonstrate tangible progress. Continued integration of nanotechnology with precision medicine, regulatory standardization, and real-time imaging will be crucial for bridging laboratory success to clinical oncology [54].

VI. SAFETY, TOXICITY AND REGULATORY PERSPECTIVES

The clinical translation of nanoparticle-based cancer therapeutics demands a thorough evaluation of their safety, toxicity, and regulatory compliance. Although nanoparticles offer targeted delivery and reduced systemic toxicity, their interactions with biological systems can lead to unforeseen immunological, hematological, or organ-specific effects. These safety aspects require extensive preclinical and clinical investigations to ensure patient protection and therapeutic reliability [55, 56].

6.1 Biocompatibility and Long-Term Toxicity Concerns

The biocompatibility of nanoparticles is influenced by their size, surface charge, coating, and biodegradability. Metallic and inorganic nanoparticles may accumulate in organs such as the liver, spleen, or kidneys, potentially inducing oxidative stress and inflammation. In contrast, biodegradable polymeric and lipid-based systems tend to exhibit lower long-term toxicity. Chronic exposure studies remain essential to understand their fate, persistence, and excretion from the body.

6.2 Pharmacovigilance and Regulatory Guidelines

Regulatory agencies such as the U.S. FDA, EMA, and India's CDSCO emphasize Good Manufacturing Practice (GMP) compliance, nanomaterial characterization, and post-marketing surveillance. Pharmacovigilance frameworks are being strengthened to monitor delayed or cumulative adverse effects, ensuring continuous assessment of nanoparticle safety profiles [57, 58].

6.3 Ethical and Environmental Considerations

Nanomedicine research must adhere to ethical principles of patient safety, transparency, and informed consent. Additionally, environmental concerns related to nanoparticle disposal and potential bioaccumulation in ecosystems necessitate responsible manufacturing, waste management, and sustainable design approaches to minimize ecological impact [59, 60].

VII. CONCLUSION

Nanotechnology has revolutionized cancer therapy by enabling precise, targeted, and multifunctional drug delivery systems that overcome the inherent limitations of conventional treatments. Advances in polymeric, lipid-based, metallic, inorganic, dendrimeric, and biomimetic nanoparticles have significantly improved drug loading, stability, tumor specificity, and controlled release. Emerging strategies, including active targeting, stimuli-responsive systems, tumor microenvironment modulation, and nano–bio hybrid platforms, offer enhanced therapeutic selectivity with reduced systemic toxicity. Recent innovations integrating chemotherapy, gene therapy, immunotherapy, and photothermal approaches demonstrate strong synergistic potential, supported by promising in vitro, in vivo, and early clinical trial outcomes. However, challenges related to long-term safety, large-scale manufacturing, pharmacokinetic variability, and regulatory compliance must be addressed to ensure successful translation. Continued interdisciplinary

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research combining nanotechnology, molecular oncology, and precision medicine will be crucial for developing safer, smarter, and patient-specific nanotherapeutics that redefine the future of cancer treatment.

Conflict of interest: None

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| ISSN: 2455-1864 | www.ijrai.org | editor@ijrai.org | A Bimonthly, Scholarly and Peer-Reviewed Journal |

||Volume 8, Issue 6, November–December 2025||

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