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# RECENT ADVANCES IN NANOPARTICLE-BASED CANCER THERAPY: INNOVATIONS AND FUTURE PROSPECTS

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## ABSTRACT

Nanoparticles (NPs) have proven to be a promising tool for cancer treatment that offers several advantages over conventional therapies. This review discusses the recent advancements in the use of nanoparticles for cancer treatment, focusing on types, advantage over conventional treatment methods, recent advancements and future perspectives. Different types of nanoparticles, including polymeric, dendrimers, liposomes, albumin, carbon nanotubes, extracellular vesicles, metallic, silica, magnetic, quantum dots, and calcium phosphate nanoparticles, are discussed. Recent advancements include smart and multifunctional nanoparticles, CRISPR-based therapies, mRNA and siRNA nanotherapies, EV-mimicking nanoparticles, nanozymes, AI-driven nanomedicine, and personalized approaches. Future perspectives could be integrating nanomedicine with immunotherapy, developing non-toxic and biodegradable nanoparticles, next-generation nano-biohybrids, and conducting clinical trials for nanomedicine in oncology. Nanoparticle-based cancer therapies represent a paradigm shift in oncology, offering the potential for targeted, efficient, and personalized treatment strategies, while acknowledging the need for further research to address these limitations and explore novel applications.

**Keywords:** Cancer Treatment, Drug Delivery, Targeted Therapy, Enhanced Permeability And Retention (EPR), Extracellular Vesicles, Liposomes.

## I. INTRODUCTION

Cancer is a complex group of diseases characterized by uncontrolled cell growth and the ability to invade surrounding tissues [1]. It arises from acquired or inherited genetic mutations that turn normal cells malignant, with factors such as unhealthy lifestyle choices (poor diet, smoking, inactivity, stress), environmental exposures, and genetic predispositions contributing to its onset [2]. According to the World Health Organization (WHO), cancer was responsible for nearly 10 million deaths in 2020, with lung, colorectal, liver, stomach, and breast cancers being the leading causes. The incidence of cancer and related deaths has been rising over the years.

Cancer treatment plays a critical role in improving survival rates, enhancing quality of life, and preventing the spread of the disease [3]. Traditional therapies like chemotherapy and radiation, although effective, can cause severe side effects, such as nausea, weakness, hair loss, and immune suppression. Additionally, drug resistance reduces chemotherapy's effectiveness, and recurrence and metastasis remain significant challenges. These limitations highlight the urgent need for alternative treatments, with nanotechnology emerging as a promising solution to improve patient outcomes and overcome the drawbacks of conventional therapies [4].

Nanoparticles, ranging from 1 to 100 nanometers in size, have unique properties due to their small size and high surface area, making them ideal for medical applications [5]. In cancer therapy, nanoparticles enable targeted drug delivery, minimizing harm to healthy tissues while maximizing effects on cancer cells. They can penetrate tumors via the enhanced permeability and retention (EPR) effect or by active targeting with cancer-specific ligands [6,7]. Encapsulating chemotherapeutic drugs in nanoparticles shields them from early degradation and enhances tumor penetration, while controlled drug release reduces side effects and administration frequency [8]. Multifunctional nanoparticles also integrate therapeutic and diagnostic functions, enabling real-time imaging and treatment. Some nanoparticles, such as gold or silver-based, possess inherent anticancer properties and can disrupt cancer cell metabolism [9,10].

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## II. TYPES OF NANOPARTICLES USED IN CANCER TREATMENT

The following sections enlist the various types of nanoparticles that are being used in treatment of cancer (figure 1).

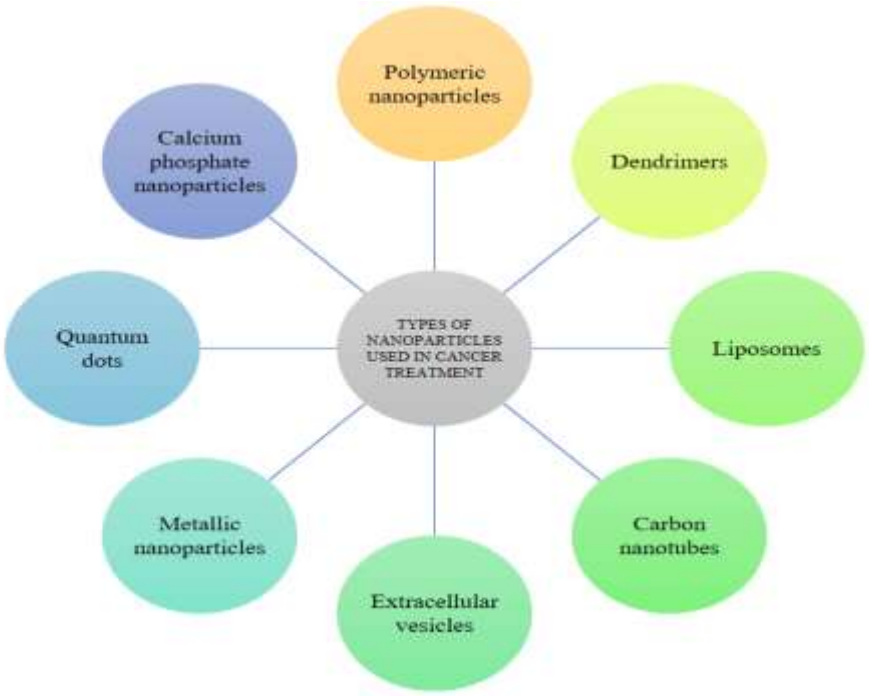


**Figure 1:** Types of Nanoparticles Used in Cancer Treatment

**Polymeric Nanoparticles**

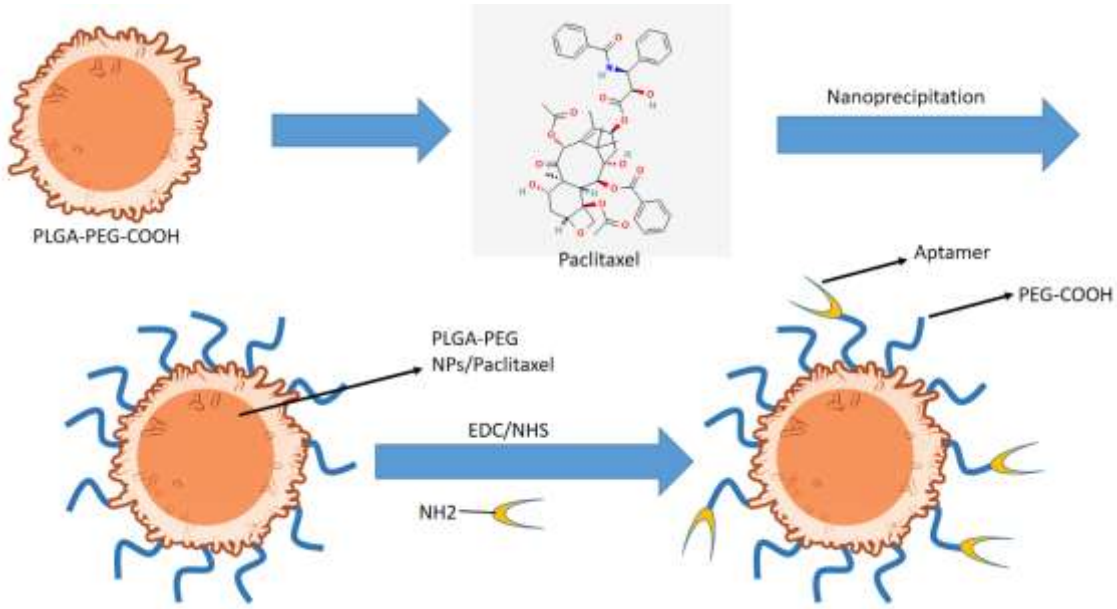


**Figure 2:** The encapsulation of paclitaxel

Polymeric nanoparticles (PNPs) are colloidal macromolecular structures synthesized from various monomers, with therapeutic agents either encapsulated within their core or conjugated to their surfaces [11]. These nanoparticles enhance drug solubility, control release, and enable targeted delivery, making them promising for cancer therapy. Biodegradable polymers such as polylactic acid (PLA), poly(lactic-co-glycolic acid) (PLGA), chitosan, and albumin are favored for their ability to degrade into non-toxic byproducts. A key advantage of PNPs is their surface modification capability for active targeting. Functionalizing their surfaces with ligands like

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antibodies, peptides, or folic acid enables selective binding to tumor-specific receptors, improving drug accumulation at tumor sites while minimizing systemic toxicity [12]. Polyethylene glycol (PEG) modification further enhances circulation time by preventing premature clearance through the mononuclear phagocyte system (MPS) [13, 14]. Several PNP formulations are in clinical development, such as paclitaxel poliglumex (Xyotax), a polymer-drug conjugate that improves paclitaxel's solubility and therapeutic index [15] (figure 2). PEG-camptothecin (Prothecan) is another PEGylated formulation designed to enhance drug stability and circulation time.

**Dendrimers**

Dendrimers are highly branched, monodisperse, nanosized polymeric structures that have gained significant attention for cancer treatment because of their well-defined architecture, multivalency, and ability to encapsulate therapeutic agents [16,17]. These spherical polymeric nanoparticles, typically less than 5 nm in diameter, possess high surface functionality, making them ideal carriers for targeted drug delivery, gene therapy, and imaging applications. Dendrimers can also be functionalized with specific ligands, peptides, or antibodies for active targeting, to improve their selectivity toward cancer cells. Polyamidoamine (PAMAM) dendrimers have been studied extensively. Their structure allows precise control over size, shape, and surface chemistry, enabling efficient drug loading and controlled release [18]. DNA-assembled PAMAM dendrimers have been developed for cancer cell-specific targeting to enhance selective delivery of therapeutic genes or siRNAs to malignant cells. Multifunctional PAMAM dendrimers loaded with paclitaxel and conjugated with fluorescein isothiocyanate and folic acid enabled both drug delivery and tumor imaging on a single platform, thereby improving treatment monitoring and therapeutic outcomes [19]. Dendrimer-based theranostics incorporates imaging agents alongside therapeutic molecules to facilitate simultaneous cancer diagnosis and treatment [20].

**Liposomes**

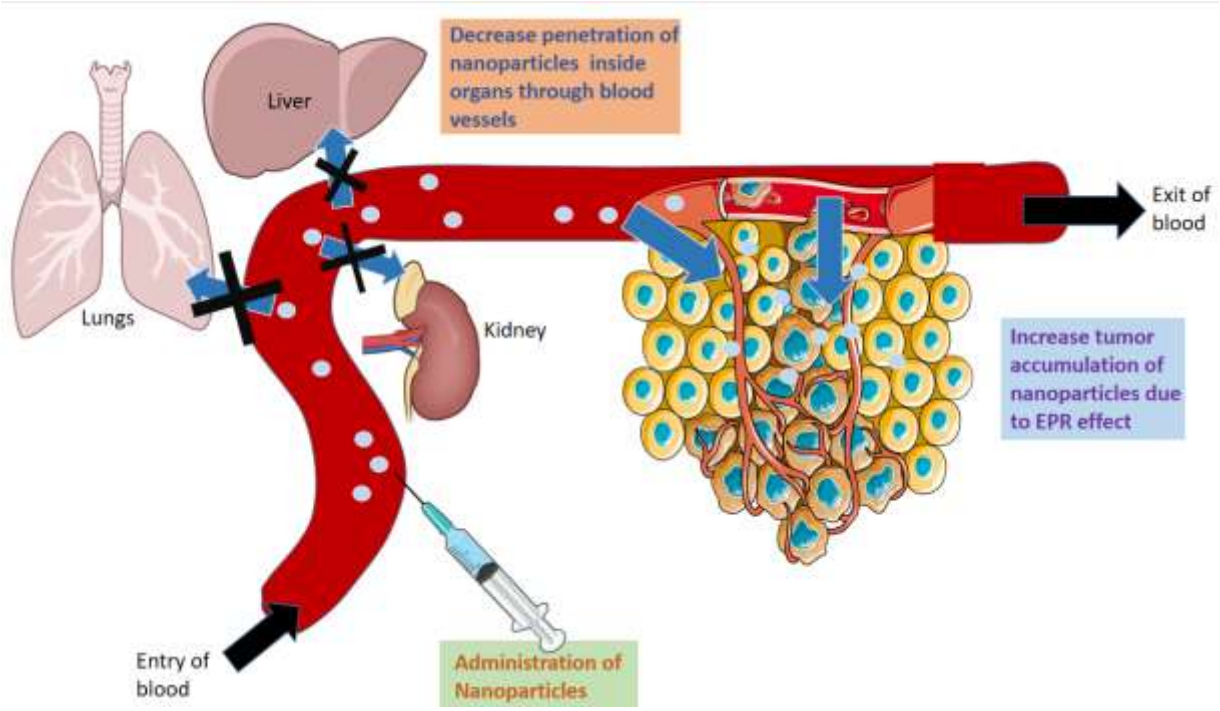


**Figure 3:** The enhanced permeability and retention (EPR) effect in nanoparticle-based cancer treatment

Liposomes are widely studied nanocarriers in cancer treatment due to their biocompatibility, structural versatility, and ability to encapsulate both hydrophilic and hydrophobic drugs [21]. These nanoparticles, ranging from 30 nm to several microns, consist of concentric phospholipid bilayers surrounding an aqueous core, making them ideal for drug delivery [22]. Liposomes can be engineered to enhance stability, control drug release, and improve targeting efficiency. Their nanoscale size allows them to exploit the enhanced permeability and retention (EPR) effect, selectively accumulating in tumor tissues [23] (figure 3). Surface

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modifications like PEGylation further extend circulation time and reduce immune clearance. Notable examples include Doxil, a liposomal doxorubicin formulation, used for ovarian cancer, multiple myeloma, and Kaposi's sarcoma, with reduced cardiotoxicity compared to free doxorubicin. Onivyde, a liposomal irinotecan, is approved for metastatic pancreatic cancer, offering enhanced drug stability and prolonged clearance [24]. Myocet, a non-PEGylated liposomal doxorubicin, provides a safer option for metastatic breast cancer patients with reduced cardiac toxicity. Lysothermosensitive liposomal doxorubicin (ThermoDox), a more advanced formulation, is designed to release its drug payload in response to hyperthermia, especially when combined with radiofrequency ablation (RFA) to target tumor sites, improving therapeutic efficacy [25].

**Carbon nanotubes (CNTs)**

CNTs have emerged as a promising class of nanoparticles for cancer therapy because of their unique physicochemical properties, including high surface area, structural flexibility, and remarkable photothermal capabilities [26]. Their ability to absorb near-infrared (NIR) light and convert it into heat makes them highly effective in photothermal therapy (PTT), a treatment modality that utilizes localized heating to induce cancer cell apoptosis while minimizing damage to surrounding healthy tissues [27]. When combined with chemotherapy, CNTs offer synergistic therapeutic effects, enhance drug efficacy, and reduce the required dosage of chemotherapeutic agents, thereby mitigating the systemic toxicity. They can be functionalized with various targeting ligands such as folic acid or antibodies to improve selectivity toward cancer cells, increase drug accumulation at the tumor site, and reduce off-target effects. Additionally, CNTs have shown potential as nanocarriers for delivering small molecules, proteins, and nucleic acids, making them valuable for gene therapy applications. Despite these advantages, concerns related to biocompatibility, long-term toxicity, and biodegradability remain significant challenges in clinical translation [28].

**Extracellular vesicles (EVs)**

EVs have gained significant attention in cancer therapy owing to their biocompatibility, immune evasion properties, and ability to facilitate efficient drug transport [29]. These naturally occurring nanoparticles derived from cells play a crucial role in intercellular communication by transferring bioactive molecules such as proteins, lipids, and nucleic acids [30]. Their endogenous origin allows them to evade immune detection, providing an advantage over synthetic nanoparticles that often trigger immune responses. EVs can be engineered to encapsulate and deliver chemotherapeutic agents, small interfering RNA (siRNAs), microRNAs (miRNAs), or CRISPR-based gene-editing tools, enabling the precise targeting of cancer cells while minimizing systemic toxicity [31]. Additionally, their inherent homing ability enables them to preferentially accumulate in tumors, enhancing their therapeutic efficacy. Researchers have formulated the use of EVs derived from stem cells and immune cells to optimize drug delivery and modulate the tumor microenvironment for improve treatment outcomes [32]. Moreover, EVs can be modified with surface ligands, antibodies, or peptides to enhance their specificity and increase their cellular uptake by malignant cells. However, challenges such as low yield, complex isolation procedures, and scalability remain barriers to their widespread clinical application [28].

**Metallic nanoparticles**

Metallic Nanoparticles have emerged as crucial tools in cancer therapy because of their unique optical, magnetic, and physicochemical properties, which make them highly effective for targeted drug delivery, imaging, and photothermal therapy [9,33]. These nanoparticles can be engineered to enhance tumor selectivity while minimizing systemic toxicity, thus offering significant advantages over conventional treatments. Gold nanoparticles (Au-NPs) are among the most widely studied metallic nanoparticles, known for their biocompatibility, stability, and ability to facilitate controlled drug transport. They can be conjugated with anticancer drugs, peptides, or nucleic acids to enhance targeted therapy and have been shown to induce cancer cell apoptosis through photothermal effects or direct cellular interactions [24]. Superparamagnetic iron oxide (SPIO) nanoparticles are widely used in magnetic resonance imaging (MRI) for cancer diagnosis. A key application of SPIO nanoparticles is the preoperative diagnosis of pancreatic cancer, which enhances imaging precision and assists surgical planning [25]. Furthermore, metallic nanoparticles can be functionalized for active targeting by modifying their surface with ligands such as folic acid, antibodies, or peptides, thereby increasing their specificity toward tumor cells. They also play a pivotal role in photothermal and photodynamic

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therapy, where they absorb near-infrared (NIR) light and generate localized heat to induce cancer cell death [34]. Although advantages of metallic nanoparticles are many, concerns like toxicity, accumulation in organs, and long-term safety remain active research areas.

**Quantum dots (QDs)**

QDs are semiconductor nanomaterials that have revolutionized cancer imaging and diagnostics, owing to their unique optical and electronic properties. These nanoparticles exhibit bright fluorescence, broad absorption spectra, narrow emission bandwidths, and exceptional photostability, making them ideal for multiplex imaging in which multiple biomarkers can be simultaneously detected with high precision [35]. Their superior fluorescence properties provide significant advantages over conventional organic dyes, such as higher signal intensity, resistance to photobleaching, and longer excitation lifetimes, allowing the real-time and long-term tracking of cancer cells [36]. Their applications extend beyond imaging to theranostics, in which they serve as dual-function agents for both diagnosis and therapy. QDs conjugated with chemotherapeutic agents or photosensitizers enable targeted drug delivery and photodynamic therapy, in which light activation triggers the production of reactive oxygen species (ROS) to kill cancer cells. Additionally, QDs have shown potential in gene delivery applications, where they act as carriers for siRNA or DNA to regulate gene expression in tumors. Despite their promising applications, concerns related to toxicity, heavy-metal composition, and long-term biocompatibility remain key challenges that limit their clinical translation. Ongoing research is focused on developing biodegradable and non-toxic QDs, such as carbon-based or silicon-based quantum dots, to enhance their safety profile while maintaining their superior imaging capabilities.

**Calcium phosphate nanoparticles (CaP NPs)**

Calcium phosphate (CaP) nanoparticles (NPs) have emerged as promising delivery vectors for gene transfer and cancer therapy due to their biocompatibility, biodegradability, and ability to mimic natural bone minerals. These nanoparticles are efficient carriers for nucleic acids, proteins, and chemotherapeutic agents, ensuring targeted delivery while minimizing toxicity [37]. One of their key advantages is their low susceptibility to microbial degradation, which enhances the stability of therapeutic cargo during storage and administration [38]. Their low production costs and ease of synthesis also make them attractive alternatives to polymer-based and metallic nanoparticles. In gene therapy, CaP NPs are widely used for DNA and RNA delivery, facilitating efficient cellular uptake and gene transfection with minimal cytotoxicity. Their pH-sensitive dissolution enables controlled release, as they degrade in the acidic tumor microenvironment, ensuring the therapeutic payload is specifically released at the tumor site. CaP nanoparticles have also been investigated as vaccine adjuvants because of their ability to enhance immune responses while remaining non-immunogenic. Additionally, their high biocompatibility makes them suitable for bone-targeted drug delivery, as they integrate seamlessly with bone tissue, reducing systemic side effects.Despite their advantages, challenges such as particle aggregation, limited circulation time, and potential premature degradation remain. Researchers are actively exploring surface modifications and hybrid formulations to improve the stability and performance of CaP NPs, aiming to optimize their use in cancer therapy and gene delivery applications.

## III. ADVANTAGES OF NANOPARTICLES IN CANCER TREATMENT

**Improved Bioavailability and Stability**

Nanoparticles enhance the bioavailability and stability of chemotherapeutic drugs, particularly those with poor aqueous solubilities. By increasing solubility and dissolution rates, nanoparticles improve drug absorption and distribution, boosting effectiveness [20]. They also protect drugs from enzymatic degradation and chemical instability, extending their half-life and enhancing therapeutic outcomes. This is especially beneficial for biologically unstable drugs. Surface modifications like PEGylation improve nanoparticle circulation time by reducing clearance through the mononuclear phagocyte system (MPS) [39,40]. PEGylation helps nanoparticles evade immune recognition, ensuring efficient drug delivery to the tumor site. Additionally, dry solid nanoparticle formulations offer greater stability than liquid-based ones, improving storage, transport, and shelf life [24]. These features make nanoparticles an effective platform for enhancing cancer treatment pharmacokinetics and efficacy.

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**Targeted Drug Delivery with Reduced Side Effects**

Nanoparticles enable targeted drug delivery by being functionalized with ligands such as antibodies, peptides, and aptamers, which bind selectively to receptors overexpressed on cancer cells [37,41]. This targeting ensures that therapeutic agents are delivered preferentially to cancer cells, improving efficacy while minimizing off-target effects and systemic toxicity [24,41]. By reducing drug exposure to healthy tissues, targeted nanoparticles significantly decrease adverse effects and enhance chemotherapy safety. Stimuli-responsive nanoparticles further refine drug delivery by releasing their payload in response to specific tumor microenvironment triggers, such as acidity, temperature, or enzyme activity. These nanoparticles remain stable in circulation but release drugs upon reaching the tumor, ensuring localized therapy and minimizing systemic toxicity. Additionally, the enhanced permeability and retention (EPR) effect allows nanoparticles to passively accumulate in tumors due to their leaky vasculature and impaired lymphatic drainage [20]. This passive targeting further improves drug concentration at the tumor site [6]. The combination of active targeting, stimuli-responsive release, and passive EPR-mediated accumulation makes nanoparticles a highly effective platform for precise and safe cancer treatment.

**Overcoming Drug Resistance**

Multidrug resistance (MDR) in cancer cells poses a significant challenge to effective chemotherapy. Nanoparticles provide a promising solution by enabling combination therapy, modifying drug release mechanisms, and targeting different cellular compartments [42,43]. They can encapsulate multiple drugs, allowing for the simultaneous delivery of chemotherapeutics and chemosensitizers, reducing the likelihood of resistance by targeting various tumor survival pathways. Nanoparticles can also be engineered to deliver P-glycoprotein (Pgp) inhibitors, preventing drug efflux, a key resistance mechanism. Additionally, nanoparticles can bypass efflux pumps by altering release mechanisms or targeting intracellular compartments. For instance, nanoparticles can release drugs in response to specific stimuli, enhancing retention and treatment efficacy [24]. Furthermore, they can deliver chemomodulators that sensitize cancer cells to chemotherapy by interfering with resistance mechanisms like DNA repair and apoptosis evasion [20].

## IV. RECENT ADVANCEMENTS IN NANOPARTICLE-BASED CANCER THERAPY

Recently, nanoparticle-based cancer therapies are being extensively studied for enhanced drug delivery, targeted treatment, and reduced side effects. CRISPR-based nanoparticles that enable precise gene editing, the development of multifunctional nanoparticles for simultaneous imaging and therapy are some of the many innovations discussed in the succeeding sections for enhancing the precision and effectiveness of treatments (figure 4).


**Figure 4:** Recent Advancements in Nanoparticle-Based Cancer Therapy

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**Smart and multifunctional Nanoparticles**

Nanoparticles are emerging as an advanced platform for dual drug delivery, enabling co-delivery of multiple therapeutic agents to enhance treatment efficacy and overcome drug resistance. Studies have highlighted the combination of chemotherapeutic drugs (e.g., doxorubicin and paclitaxel) with gene therapy agents (e.g., siRNA) in nanoparticle formulations [44]. Another approach involves chemotherapy combined with photothermal therapy (PTT), in which gold nanoparticles act as drug carriers and photothermal agents, inducing hyperthermia upon near-infrared (NIR) laser irradiation to enhance tumor cell death [24,45]. Various nanoparticle platforms, including PLGA liposomes and polymeric nanoparticles, have been utilized for dual-drug delivery. Self-assembled nanoparticles formed from block copolymers offer high drug-loading capacity, stability, and controlled drug release [37]. Stimuli-responsive nanoparticles enable controlled and site-specific drug release in the tumor microenvironment. pH-sensitive nanoparticles take advantage of the acidic tumor environment to trigger drug release through pH-sensitive linkers or charge changes [46]. Temperature-sensitive nanoparticles exploit localized hyperthermia (40-42 °C) to undergo phase transitions, enabling drug release at elevated temperatures. Enzyme-responsive nanoparticles overexpress specific enzymes in tumors to cleave enzyme-sensitive linkers and selectively release their payload. These stimuli-responsive strategies enhance drug accumulation at the tumor site, minimize off-target toxicity, and improve therapeutic efficacy.

**CRISPR-Based Nanoparticle Therapies**

CRISPR-based nanoparticle therapies mark a major advancement in gene editing, offering a promising alternative to traditional viral vector systems. Nanoparticles address viral vector challenges, such as long-term exposure risks, potential off-target effects, and immunogenicity [47,48]. Lipid nanoparticles have delivered CRISPR components in aggressive cancer models, achieving significant gene editing and tumor growth inhibition [49,50]. Nanoparticles co-loaded with CRISPR/Cas9 and chemotherapeutic agents have shown synergistic effects, enhancing antitumor immunity and reducing tumor growth [51]. Nanoparticles can be customized to target specific tissues or cells, as seen in context-responsive nanoparticles for basal-like breast cancer, effectively targeting oncogenic factors. Antibody-targeted approaches further enhance their potential by ensuring precise delivery to tumor sites [37,52]. Integrating CRISPR/Cas9 technology with nanoparticle systems is promising for advancing gene therapy, providing a safer, more efficient approach for treating genetic diseases and cancers.

**mRNA and siRNA Nanotherapies**

The mRNA nanotherapies work by introducing messenger RNA encapsulated in the nanoparticles into cancer cells. This instructs the cancerous cells to produce specific proteins, such as tumor antigens, which then stimulate the immune system to recognize and destroy cancer cells. The siRNA (small interfering RNA) is a type of RNA molecule that plays a crucial role in regulating gene expression by silencing specific genes. It is part of the RNA interference (RNAi) mechanism, where siRNA molecules bind to mRNA and promote its degradation thus preventing the mRNA from being translated into protein. This process allows for the targeted silencing of genes, thereby inhibiting the cancer's progression. By encapsulating mRNA or siRNA within nanoparticles, these therapies enhance the stability, bioavailability, and targeted delivery of the genetic material to the tumor site, improving the overall efficacy and minimizing side effects. [53,54]. These therapies use nanotechnology to improve the delivery and efficacy of RNA-based treatments, thereby addressing challenges such as stability and targeted delivery.

**Extracellular Vesicle-Mimicking Nanoparticles**

Extracellular vesicle-mimicking nanoparticles (EV-mimicking NPs) are a promising frontier in nanomedicine, offering innovative solutions for drug delivery and therapeutic intervention. These nanoparticles emulate natural properties and enhance biomolecule delivery across biological barriers. EV-mimicking NPs development involves strategies like using metal-organic frameworks (MOFs) to encapsulate therapeutic proteins and decorating with EV membranes to enhance targeting and immune evasion [55]. This protects proteins from degradation and improves therapeutic efficacy, as shown by tumor growth inhibition studies. The nucleic acid dilution-induced assembly (NADIA) technique facilitates lipid nanoparticle formation mimicking EVs, enhances transfection efficiency, and uses lipid raft-mediated endocytosis for cellular uptake [56]. The rational design of artificial EV biomimetics aims to maintain EVs' natural lipid composition while

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incorporating artificial cargo to expand theranostic applications. This design uses molecular simulations and machine learning to optimize lipid organization and self-assembly, ensuring reproducibility and regulatory compliance [57]. Integrating superparamagnetic iron oxide nanoparticles (SPIONs) into EVs enhances targeting through magnetic navigation, improving therapeutic agent delivery and accumulation in specific tissues [58].

**Enzyme-mimicking nanoparticles for reactive oxygen species (ROS) generation**

Nanozymes, artificial enzymes from nanoparticles, are used for cancer therapy due to their ability to mimic natural enzyme activities. These engineered nanoparticles can be designed to generate reactive oxygen species (ROS) within tumor cells, offering a targeted approach for cancer treatment [14]. Common nanozymes for ROS generation include iron oxide with peroxidase-like activity, cerium oxide with oxidase-like activity, and gold with catalase-like activity. These nanozymes catalyze ROS production, such as hydroxyl radicals, superoxide anions, and hydrogen peroxide. The ROS induces oxidative stress in cancer cells, leading to damage and cell death. This mechanism offers a novel strategy for combating cancer by exploiting tumor cells' vulnerability to oxidative stress [59,60]. Advantages of using nanozymes in cancer therapy include improved stability over natural enzymes, catalytic activity, potential for targeted delivery, and multifunctional capabilities. However, challenges remain in developing and applying nanozymes in cancer treatment, including enhancing specificity for cancer cells, optimizing biodistribution and clearance, investigating long-term safety, and developing novel designs with improved efficiency and targeting.

**Machine learning for nanoparticle-based drug design and optimization**

Machine learning algorithms have been employed to analyze vast datasets of nanoparticle properties, drug interactions, and biological responses [61]. These algorithms can identify patterns and correlations that human researchers might overlook, leading to more efficient nanoparticle-based drug design [62]. By predicting the behavior of nanoparticles in different biological environments, machine learning models can optimize drug loading, release kinetics, and targeting efficiency. This approach has accelerated the development of novel nanomedicines and has improved their efficacy and safety profiles.

**AI-powered nanoparticle tracking in real-time imaging**

AI algorithms have been used to enhance the tracking and analysis of nanoparticles using real-time imaging techniques [63,64]. These advanced computational methods can process complex imaging data from various modalities, such as fluorescence microscopy or magnetic resonance imaging, to accurately detect and track individual nanoparticles within biological systems [65]. AI-powered tracking enables researchers to monitor nanoparticle distribution, accumulation in target tissues, and clearance from the body with unprecedented precision. This capability provides valuable insights into nanoparticle behavior in vivo, facilitating the optimization of nanomedicine formulations and delivery strategies.

**Personalized Nanomedicine Approaches**

Personalized nanomedicine for cancer treatment involves tailoring nanoparticle formulations to individual patient characteristics, enhancing efficacy, and minimizing side effects [66]. This strategy leverages the unique genetic, molecular, and physiological profiles of each tumor to design customized treatments [67]. Key aspects include genomic and proteomic profiling, tumor microenvironment assessment, drug sensitivity testing, pharmacokinetic considerations, and immune system compatibility [66]. These factors create nanoparticles optimized for each patient's needs, potentially improving outcomes and reducing adverse effects. Biomarker-targeted therapies in nanoproducts involve the development of treatments that target molecular markers overexpressed in cancer cells, enhancing treatment precision and reducing off-target effects. This approach includes receptor-specific targeting, enzyme-responsive nanoparticles, aptamer-mediated targeting, antibody-drug conjugates, and multi-biomarker strategies. By focusing on specific biomarkers, nanoparticles deliver therapeutic agents more effectively to cancer cells while sparing healthy tissues[67]. Personalized nanomedicine offers the potential for more effective and less toxic cancer treatment by tailoring efficient oparticle-based characteristics and tumor bimarkers [68]. The combination of patient-specific formulations and biomarker-targeted approaches represents a significant progress in nanomedicine, presenting new hope for enhanced cancer treatment outcomes and quality of life.

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## V. FUTURE PERPECTIVES

The future of nanoimmunotherapy in cancer treatment holds great promise, with personalized therapies tailored to individual immune profiles through AI and machine learning. Multifunctional nanoplatforms, designed for imaging, drug delivery, and immune modulation, are evolving to adapt to the tumor microenvironment and trigger immune responses. Key areas of focus include targeted delivery to immune cells like T cells and dendritic cells, and integrating nanomedicine with immunotherapies to enhance existing treatments. Researchers are also developing nanoparticles to counteract immunosuppressive factors in the tumor microenvironment and improve cancer vaccines for better antigen presentation and immune activation. Innovations in biocompatible, biodegradable materials are improving safety profiles, while gene editing tools and exosome-based carriers are further advancing immunotherapy. Additionally, scaling and standardizing manufacturing processes are crucial for large-scale production.

## VI. CONCLUSION

In conclusion, nanoparticle-based therapies represent a transformative shift in oncology, offering more targeted, efficient, and personalized treatments. This review highlights the various types of nanoparticles, their mechanisms, and the significant advantages, such as enhanced bioavailability, targeted drug delivery, and overcoming drug resistance. Advances in smart nanoparticles, CRISPR-based therapies, mRNA and siRNA nanotherapies, and EV-mimicking nanoparticles reflect the potential of these therapies in combination with immunotherapy. While challenges like large-scale production, toxicity, and regulatory approval remain, continued research is essential to optimize in vivo performance and overcome biological barriers. Nanoparticle-based cancer treatments are rapidly evolving and may revolutionize cancer care, offering hope for improved outcomes and quality of life for patients.

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