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Nanoparticles In Cancer Drug Delivery: Recent Advances, Therapeutic Applications And Challenges

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ABSTRACT: Cancer is one of the major causes of Mortality around the world, Despite Having significant advances in diagnosis and treatment. Conventional therapeutic-based approaches such as chemotherapy, radiotherapy, and surgeries are often limited due to poor selectivity, Toxicity, inadequate accumulation of drugs at tumor sites, and development of resistance to multi-drugs. Nanotechnology has developed as a better platform for improving Cancer treatment through the development of Nanoparticle based System of drug delivery. These nanoparticles have unique Physical and chemical properties that include It's nano scale size, Large surface area and its characteristics, enhanced drug-loaded capacity and controlled release of the drugs. These kind of properties helps to fight cancer cells by minimising damage to the healthy tissues. Various kinds of nanoparticles, Such as dendrimers, metallic nanoparticles, liposomes, and hybrid nano carriers, result in better therapeutic Outcomes in preclinical and clinical studies. Recent advancements Which include Smart Nanoparticles, gene delivery systems, Immunotherapy based Nanomedicines and environment responsive drug delivery systems for tumors, Etc. These nanoparticle-based therapies have a better potential for multi-drug resistance and enhance the treatment efficiency. Despite having these advancements, there are also some challenges Which includes toxicity, Biological effects, Manufacturing And regulatory approval. This affects its widespread use for clinical treatments. This review therefore summarizes the recent developments, therapeutic applications, challenges, and future perspectives of Nanoparticle based cancer drug delivery systems.

KEYWORDS: cancer, drug delivery, nanoparticle, nanomedicine, targeted therapy.

INTRODUCTION

Cancer is a complex, multilayered disease driven by genetic and environmental factors. It is defined as indefinite cellular growth, Neighbour tissue invasion, and metastasis. Cancer remains a currently trending global health issue, in which Malignancy Causes millions of deaths per year (Yao et al., 2020) . Standard treatments, such as chemotherapy and radiation-targeted therapy, usually affect rapidly dividing cells, but they lack cellular precision. They destroy Cancer tissues along with the healthy ones, causing severe damage to cells, thus limiting of dosages occur. During these therapies, we face severe chemical and biological struggles during treatments (Wang et al., 2024) (Dayani, 2019). Many chemotherapeutic drugs are hydrophobic, which means they are water-insoluble. So they are poorly soluble in water and have low systemic bioavailability. Once it enters the bloodstream, these compounds undergo enzymatic degradation. Thus, they are cleared by the liver and kidneys before they reach the target site. Tumour cells have a powerful defence mechanism, importantly Multi drug resistance. Processes such as cellular efflex Pump, causes flushing out of therapeutic agents. Because of High fluid pressure and a denser extracellular matrix in the tumour areas, they block the incoming drug and act as barriers. Therefore, they lead to Failure of the treatment, rapid development of the disease, and finally causes death of patients.(Hsu et al., 2023) (Elumalai et al., 2024)

Nanotechnology has reshaped clinical oncology by introducing nanoparticle-based drug delivery systems, which help in overcoming the boundaries of classic medicine. These nano-sized carriers act as Engineered Vehicles for transport in the human body. They are encapsulated, protected, and overcome cytotoxic agents and deliver the drug to the target sites. It protects the healthy tissues from damage by the drug, So they reduce the systemic toxicity and the side effects. So therefore these nanoparticles protect healthy tissues from cancerous tissues. Their physical properties, mainly their high surface area to volume ratio allow us for modifying its surface, So Helps us to attach our targeting ligands like antibodies or peptides that binds to Tumor receptor specifically.

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Their nanoscale dimensions are recognised by the tumor tissues, So helps in targeted drug delivery. Malignant tumours cause spreading and leaky blood vessels. Thus, these nanoparticles allow us to target specific tumour sites, thus enhancing permeability and Retention Effect. These nanoparticles penetrate deep into the microenvironment of tumours and possess high efficiency in attacking them. Thus nanotechnology helps us to reduce toxicity caused by tumour cells, maximising the therapeutic effect targeting the tumour cells, and protects healthy tissues. (Yao et al., 2020) (Hong et al., 2023)

The integration Of Oncology with nanotechnology resulted in a significant effect on cancer treatment by optimising the delivery of cytotoxic agents. The traditional method of chemotherapeutics often fails because of the biological Barriers and Poor water solubility, etc. Nanocarriers overcome these difficulties by physically encapsulating the drug molecules, creating a protective Barrier Against Enzymatic degradation by the body. This stabilises the compound in the bloodstream, thus extending Systemic circulation and allowing the active drug to reaching its destination. The Nano Medicine Alters the Old profile of Oncological Drugs by introducing smart Controllable release of the drug in targeting sites. Instead of going around the patient's body, resulting in severe side effects, these engineered Nana particles can release their drugs Slowly overtime at target sites. So they serve as the best for targeted therapy for cancer treatments. They also trigger the release of the drug only when the environment is perfect, Such as pH conditions and enzyme levels in the human body around the tumor sites. Thus, this results in favourable release of Drugs at favourable environment. This replaces the unpredictable Release of Drugs and enhances the absorption of the drug at maximum concentration at the tumour site while protecting healthy tissues. These nanoparticle-based drug delivery systems now serve as one of the best Treatment and has promising results in modern clinical oncology (Elumalai et al., 2024) (Dutta et al., 2025) (Hsu et al., 2023) . Nanotechnology applied in cancer is depicted in fig.1(I) below.

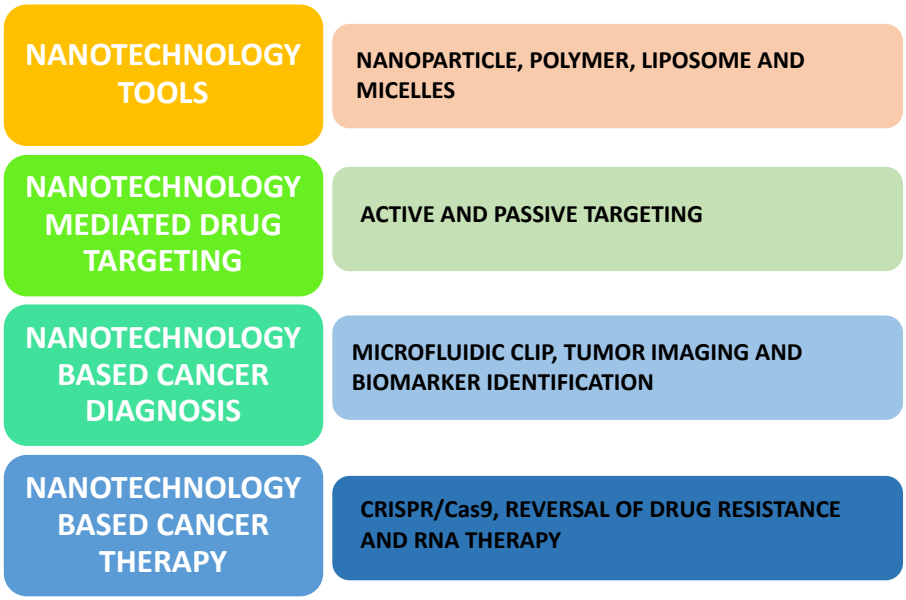

Fig.1(I) Nanotechnology in cancer therapy

CLASSIFICATION AND PROPERTIES OF NANOPARTICLES :

In cancer therapy Kananoparticles Family classified Based on their structure Size composition And their functional characters. Basically nanoparticles Classified into organic inorganic and hybrid nanoparticles. Each one has its own advantages And applications in cancer drug delivery.

ORGANIC NANOPARTICLES :

Organic nanoparticles include dendrimers, liposomes, polymeric nanoparticles, micelles and Lipid nanoparticles. These are usually biocompatible, biodegradable, and capable of carrying both hydrophobic and hydrophilic therapeutic agents.

Dendrimers are highly branched, synthetic macromolecules characterised by well-defined structures and multiple functional groups, which are suitable for the Conjugation of drugs. Liposomes or phospholipid Based molecules that are

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encapsulated many drugs and protect them from the process of degradation. Polymeric nanoparticles are synthesized using biodegradable polymers, basically, Polyethylene Glycol, Chitosan and PLGA. (Dayani, 2019)

Lipid nanoparticles has considerable usage because of its ability to deliver nucleic acids which includes mRNA and siRNA. Because of their special characteristics they are adaptable for cancer therapy because of their biocompatibility, Encapsulation efficiency and surface modifications. (Liu et al., n.d.)

INORGANIC NANOPARTICLES :

Inorganic nanoparticles include Magnetic Nanoparticles, Metallic nanoparticles, Silicon Nanoparticles, Quantum dots, Carbon nanotubes. Goal Nanoparticles have optical and radio sensitising properties which enhance radiation therapy outcomes and facilitate great imaging applications. Its high atomic number enables improved radiation absorption and Dose enhancement within tumours. (Mesbahi, 2010)

Magnetic nanoparticles have advantages such as controlled drug release, Magnetic targeting, and magnetic hypothermia. Iron oxide nanoparticles are one of the best examples. External magnetic fields can help these nanoparticles to reach tumor sites, thus improving treatment precision. (Graham et al., 2025)

Mesoporus Silica nanoparticles has large surface area and high drug loading capacities. These abilities enable efficient drug encapsulation and controlled release of them, making them a valuable tool in cancer therapy. These kind of nanoparticles show potential effects in Colorectal cancer treatments and targeted drug delivery. (Hasan et al., 2024)

HYBRID NANOPARTICLES :

Hybrid nanoparticles combine the advantageous properties of different materials into a single multifunctional unit. These include Polymer-lipid hybrids, Metal-polymer composites, etc., that integrate the therapeutic and diagnostic functions. They exhibit enhanced stability, improved target efficiency, and Increased drug loading capacity. (Yao et al., 2020)

PHYSIO-CHEMICAL PROPERTIES OF NANOPARTICLES :

The nanoparticle-based drug delivery system's effectiveness is influenced by their physiochemical properties.

SIZE :

The size of the nanoparticle significantly affects its biodistribution, Cellular uptake, Circulation time, and penetration into the tumour. Nanoparticles, usually ranging from 10 to 200 nm, are generally considered optimal for cancer drug delivery therapies because they have enhanced permeability and retention effects while avoiding errors.(Hsu et al., 2023)

SURFACE CHARGE :

Surface charges influence the nanoparticles' interaction with biological Cell membranes and proteins. Positively charged type of nanoparticles often has enhanced cellular uptake but sometimes also have increased toxicity. Whereas neutral or slightly negative type of nanoparticles has improved circulation and biocompatibility. (Hong et al., 2023)

SURFACE FUNCTIONALIZATION :

Modification of the surface for targeting ligands such as Antibodies, peptides, and aptamers enables active targeting of Cancer Cells. Functionalization helps for enhanced treatment of specificity and also promotes Cellular uptake through a receptor-mediated method. (Hong et al., 2023)

DRUG LOADING AND RELEASE CHARACTERISTICS:

A nanoparticle system should have high drug-loading capacity, Sustained drug release, and stability under physiological conditions. Controlled release of it minimises Toxicity while also maintaining the therapeutic drug concentrations within tumour cells. (Khan et al., 2025)

MECHANISMS OF TUMOR TARGETING :

In nanoparticle-based drug delivery systems, the therapeutic efficiency depends on their ability to accumulate within tumor tissues while minimizing exposure to healthy cells. They help in enhancing drug concentration at the target site, improving therapeutic outcomes, and reducing toxicity. Nanoparticles achieve targeted delivery through passive targeting, active targeting, and a stimuli-responsive targeting mechanism. (Hsu et al., 2023) (Yao et al., 2020)

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PASSIVE TARGETING :

The passive targeting is based on the Enhanced Permeability and Retention (EPR) effect, which is a basic mechanism of cancer nanomedicine. Tumor vasculature with high permeability and poor lymphatic drainage enables preferential accumulation and prolonged retention of nanoparticles in tumor tissues. Nanoparticles in the range of 10–200 nm can extravasate through leaky blood vessels in tumors and stay localized within the tumor microenvironment to increase local drug concentrations and decrease systemic toxicity. The EPR effect is widely employed for tumor-targeted drug delivery in liposomes, polymeric nanoparticles, and mesoporous silica nanoparticles. However, the value of passive targeting is often limited due to inter- and intratumoral variability in the EPR effect, necessitating the development of more specific targeting strategies. (Hsu et al., 2023) (Elumalai et al., 2024)

ACTIVE TARGETING :

Active targeting involves modifying the surface of nanoparticles with ligands that specifically bind to receptors that are over-expressed on cancer cells, inducing receptor-mediated endocytosis and improving intracellular drug delivery. Commonly used targeting ligands include monoclonal antibodies, peptides, aptamers, folic acid, hyaluronic acid, and transferrin. Common targets for receptors are folate receptors, transferrin receptors, epidermal growth factor receptors (EGFR), and human epidermal growth factor receptor 2 (HER2). Ligand–receptor interactions enable selective nanoparticle uptake and thus enhance treatment specificity and therapeutic efficacy. (Hong et al., 2023)

For example, folate-conjugated nanoparticles show increased cellular uptake in cancers that overexpress folate receptors, while transferrin-functionalized nanoparticles take advantage of the increased iron demand of rapidly dividing tumor cells. Active targeting reduces off-target effects and improves treatment outcomes compared with conventional chemotherapy. (Hong et al., 2023) (Hasan et al., 2024).

STIMULI-RESPONSIVE TARGETING :

Stimuli-responsive nanoparticles are designed to react to specific internal or external stimuli, allowing for controlled and site-specific delivery of therapeutic agents. Internal stimuli include tumor-associated conditions such as acidic pH, hypoxia, increased enzyme activity, oxidative stress, and altered redox potential. These physiological differences can be utilized for selective drug release in the tumor microenvironment. For example, pH-responsive nanoparticles are stable under physiological conditions and rapidly release the payload in acidic tumor tissues. External stimuli like temperature, ultrasound, magnetic fields, near-infrared irradiation, and laser exposure can also be used to trigger drug release with precise spatiotemporal control. Stimuli-responsive nanoparticles capable of on-demand drug release at the target site are promising strategies for precision oncology, maximizing therapeutic efficacy with minimized adverse effects. (Sanchez-Moreno et al., 2018) (Liu et al., n.d.)

TYPES OF NANOPARTICLES USED IN CANCER THERAPY :

A wide variety of nanoparticle platforms have been developed for drug delivery in cancer. Each type has its own structure, characteristics, and therapeutic benefits.

LIPOSOMES :

Liposomes are spherical vesicles formed by phospholipid bilayers able to encapsulate hydrophilic and hydrophobic therapeutic agents. Liposomes are among the best-studied and most successful nanoparticle systems in the clinic, owing to their:

- Very Good Biocompatibility
- Biodegradability
- Low toxicity
- Ability to prolong circulation time
- Increased tumor accumulation

Clinically approved liposomal formulations, such as Doxil® and Myocet®, have exhibited favorable pharmacokinetic profiles and diminished cardiotoxicity compared to conventional doxorubicin formulations. Liposomes have shown great efficiency against breast cancer, ovarian cancer, lung cancer and Kaposi's sarcoma. (Dayani, 2019)

POLYMERIC NANOPARTICLES :

Polymeric nanoparticles are prepared from biodegradable polymers such as Chitosan, PEG, PLGA, and PLA. These nanoparticles offer controlled drug delivery, improved stability, more protection from drugs, and capabilities for surface modification. Polymeric nanoparticles can be used to deliver small molecules, proteins, peptides, and nucleic acids. The controlled

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release characteristics of these materials provide extended therapeutic drug levels, thus increasing the efficacy of the treatment as well as patient compliance.(Elumalai et al., 2024)

DENDRIMERS :

Dendrimers are highly branched tree-like macromolecules with the following properties: a one-size-fits-all definition of building many functional groups on the surface. This unique structure allows for a high loading capacity of drugs and precise surface functionalization. Dendrimers have emerged as promising candidates in chemotherapy, gene delivery, imaging, and target therapy. The capacity to carry several therapeutic agents at the same time makes them attractive candidates for combination therapies.(Dayani, 2019)

MESOPOROUS SILICA NANOPARTICLES (MSNS) :

Mesoporous silica nanoparticles have high surface area, high pore space, tunable pore architectures, and excellent stability. These properties allow efficient drug loading and controlled release. MSNs have been extensively studied for chemo, gene therapy, combination treatment, and the treatment of colorectal cancer. Their surfaces are amenable to modification with targeting ligands to improve treatment specificity.(Hasan et al., 2024)

GOLD NANOPARTICLES :

Gold nanoparticles (AuNPs) have unique optical and electronic properties that make them promising for cancer therapy agents applications are delivery of drugs, photothermal treatments, imaging, and radiosensitisation. Gold nanoparticles facilitate local radiation absorption in tumor tissue and thus enhance radiation-induced DNA damage. The high atomic number is responsible for better radiation dose deposition and improved therapeutic results. Functionalization of gold nanoparticles with antibodies and peptides is also possible for targeted drug delivery. (Mesbahi, 2010)

MAGNETIC NANOPARTICLES :

Magnetic nanoparticles, in particular iron oxide nanoparticles, have been the subject of much attention because of their ability to respond to an external magnetic field. Benefits of using these are Magnetic targeting, drug-controlled release, and contrast enhancement in MRI of hyperthermia therapy. Magnetic hyperthermia is the technique of applying an alternating magnetic field to magnetic nanoparticles, which causes local heating that can kill cancer cells. This strategy can be used with chemotherapy to increase the effectiveness of the treatment. (Graham et al., 2025)

HYDROXYAPATITE NANOPARTICLES :

Hydroxyapatite nanoparticles (HANs) are biocompatible calcium phosphate materials having excellent biodegradability and low toxicity. Recent studies have shown their effectiveness in the therapy of colon cancer, drug entrapment, prolonged drug release, pH-dependent drug delivery. Because of their favourable Biological properties, they are promising candidates for future clinical applications in targeted cancer therapy. (Withrow et al., 2024)

LIPID NANOPARTICLES :

Nucleic acid delivery using Lipid Nanoparticles has emerged as one of the most significant platforms today. Key features of LNPs are: Biocompatibility, High efficiency of mRNA delivery, Transport of siRNAs, and genome editing uses. New innovations have made it possible to develop programmable lipids that can control biodistribution, intracellular trafficking, and the rate of release. Four Domains Model developed by Liu et al. (2025 - NP26) consists of Structure, Interface, Cargo, and Dispersal. These domains serve as guidelines for future development of LNPs for precision oncology. (Liu et al., n.d.)

HYBRID NANOPARTICLES :

The hybrid nanoparticles have the benefits of different materials packed in a single system. For instance, polymer-lipid hybrid nanoparticles, Metal-polymer hybrid nanoparticles, and theranostic nanoparticles. Benefits offered by hybrid systems include stability, targeting efficiency, Drug loading capacity, and dual functions (imaging and therapy). Multifunctional nanoparticles like those mentioned above are being considered for personalized cancer treatments. (Yao et al., 2020)

RECENT ADVANCES IN NANOPARTICLES-BASED CANCER THERAPY :

With the swift evolution of nanotechnology, the nanoparticles used as drug-delivery systems have evolved into more versatile tools that can perform functions beyond merely carrying drugs to target sites. Nanoparticles now have applications in

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diagnosis, imaging, targeted delivery of medicines, immunomodulation, and even gene delivery. Some of the recent advances in nanoparticles include smart nanoparticles, nanotheranostics, gene delivery systems, and programmable lipid nanoparticles.(Dutta et al., 2025) (Hsu et al., 2023)

NANOTHERANOSTICS :

Nanotheranostics is a term used to describe the combination of diagnostic and therapeutic capabilities into a single nanoparticle technology that helps detect diseases, deliver drugs, and monitor their therapeutic effects at the same time. The combination of imaging technologies such as fluorescent dyes, magnetic resonance imaging contrast agents, radioisotopes, gold nanoparticles, and quantum dots with the therapeutic molecules is what constitutes nanotheranostics. This helps personalize cancer therapies, especially breast, colorectal, lung, and brain cancers. (Al-Thani et al., 2024) (Wang et al., 2024)

SMART DRUG DELIVERY SYSTEMS :

Intelligent nanoparticles are designed in such a way that they can release drugs within the body based on triggers like pH, hypoxia, enzyme action, oxidative stress, and redox states. These triggers may be inside or outside the body, such as temperature, ultrasound, light, and magnetism. This helps in delivering a targeted drug to the diseased organ and reducing toxicity to the body. (Sanchez-Moreno et al., 2018) (Dutta et al., 2025)

GENE DELIVERY SYSTEMS :

Gene delivery vectors based on nanoparticles have been developed as promising carriers for the delivery of DNA, mRNA, siRNA, miRNA, and CRISPR-Cas9 elements inside cancer cells. Lipid-based nanoparticles, polymer nanoparticles, and dendrimers not only prevent nucleic acid degradation but also enable their entry into cells. This enables regulation of gene expression, gene silencing, and even restoration of normal tumor suppressor gene function. (Yao et al., 2020) (Liu et al., n.d.)

TUMOR MICROENVIRONMENT MODULATION :

The newer generation of nanoparticle approaches is directed towards overcoming the obstacles existing in the tumor microenvironment (TME), which include hypoxia, dense extracellular matrix, aberrant vasculature, and immunosuppressive conditions. The TME-responsive nanoparticles could help deliver drugs to the site of interest, deliver oxygen, recruit immune cells, and normalize the vasculature. (Hong et al., 2023)

TARGETING THE PI3K/AKT/M TOR SIGNALING PATHWAY :

The PI3K/AKT/mTOR signaling pathway is one of the major signaling pathways that regulates the growth, survival, and metastasis of cancer cells. The application of nanoparticles for the targeted delivery of drugs against this signaling pathway increases their bioavailability, stability, and specificity to the tumor cells. Some of the drugs against this pathway include PI3K inhibitors, AKT inhibitors, mTOR inhibitors, and siRNAs. (Rahman et al., 2025)

NANOPARTICLES IN OVERCOMING DRUG RESISTANCE :

MDR continues to be an essential challenge in cancer treatment due to mechanisms like drug efflux, increased DNA repair, drug metabolism alterations, defective apoptosis, hypoxia, and genetic mutations. Increased expression of ATP-binding cassette transporters, especially P-glycoprotein (P-gp), leads to reduced intracellular drug accumulation and plays a major role in the development of treatment resistance. Nanoparticle-based methods serve as promising tools for addressing MDR because they can overcome the effects of drug efflux, ensure controlled drug delivery, and allow the combination of chemotherapy drugs with small interfering RNA and immunomodulators. Additionally, nanoparticles can silence the genes responsible for MDR, thus overcoming the problem of treatment resistance. These methods have proven successful in treating several drug-resistant forms of cancer, including breast, colon, ovarian, and lung cancers. (Yao et al., 2020) (Dutta et al., 2025)

NANOPARTICLES IN COLORECTAL CANCER :

Nanoparticles have been developed to be used in drug delivery systems as novel treatments against colorectal cancer due to their ability to target the tumor site, increase accumulation of drugs in the tumors, and decrease systemic toxicity. Several types of nanoparticles, such as liposomes, polymers, mesoporous silica, and hydroxyapatite nanoparticles, have shown high levels of therapeutic potential. Furthermore, targeted nanoparticles that can target receptors such as folate and EGFR are more effective against colorectal cancer. (Hasan et al., 2024) (Withrow et al., 2024)

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CLINICAL APPLICATIONS AND APPROVED NANOMEDICINE :

Nanoparticle drug delivery systems have been successfully translated into clinical practice, resulting in the development of numerous nanodrugs characterized by advanced pharmacokinetics, increased tumor targeting, prolonged circulation time, and decreased toxicity relative to other forms of treatment. Anticancer drugs encapsulated into nanoparticles enhance the stability and delivery of drugs to cancerous cells. (El-Readi and Althubiti, 2019) (Giri et al., 2023)

APPROVED NANOMEDICINE :

Several nanoparticle drug formulations have received clinical approval for cancer therapy. Doxil® is the PEGylated liposomal form of doxorubicin that offers decreased cardiotoxicity along with increased tumor uptake and has been approved for ovarian, breast cancer, and Kaposi's sarcoma. Myocet® is a liposomal preparation of doxorubicin that is not pegylated and has low cardiac toxicity. Abraxane® is a formulation of albumin-bound paclitaxel nanoparticles. (Hasan et al., 2024)

NANOPARTICLES IN DIAGNOSTIC IMAGING :

Nanoparticles have contributed to advancements in cancer detection with better sensitivity and specificity in imaging techniques. These particles have special optical and magnetic characteristics that can be useful for MRI, CT, fluorescence imaging, and PET. Gold and magnetic nanoparticles have been proven to be very important due to their theranostic use in imaging and treatment. (Wang et al., 2024) (Al-Thani et al., 2024)

CLINICAL TRIALS AND EMERGING THERAPIES :

There are many types of nanoparticles being evaluated in different clinical trials for the management of breast cancer, lung cancer, colorectal cancer, ovarian cancer, pancreatic cancer, and brain cancer. The main emphasis of current research is on the use of intelligent nanoparticles, gene delivery systems, immunotherapy-related nanomedicines, cancer microenvironment targeting technologies, and combinatory therapies. (Elumalai et al., 2024)

CHALLENGES AND LIMITATIONS

Though considerable progress has been achieved in the area of nanoparticle-based drug delivery, some issues still pose difficulties and hinder their broad clinical use. First of all, biological barriers like protein corona formation, fast removal from circulation via the reticuloendothelial system (RES), and inability to penetrate tumors may impair the efficiency of drug delivery and efficacy (Elumalai et al., 2024). Safety aspects are also worth considering when talking about long-term toxicity, biodistribution, oxidative stress, inflammation, and immunogenicity. Metal-based nanoparticles, for example, should be studied extensively for toxicology. Moreover, large-scale production raises issues of reproducibility, stability, drug loading, and costs. Complex physicochemical characteristics and functionality of nanoparticle-based delivery systems require thorough study prior to clinical applications. (Hsu et al., 2023) (Rahman et al., 2025) (Khan et al., 2025)

FUTURE PERSPECTIVES :

The future development of cancer nanotechnology will likely depend on advances in personal medicine, the application of artificial intelligence, gene editing techniques, and multifunctional nanodelivery systems.

PERSONAL NANOMEDICINE :

Personal nanomedicine strives to create nanoparticles taking into account the molecular features of particular cancers. Personal nanoparticles may enhance Effectiveness, Targeted action, Safety, and therapeutic results. (Dutta et al., 2025)

AI-POWERED DESIGN OF NANOPARTICLES :

Nowadays, artificial intelligence and machine learning are actively used to improve the formulation and composition of nanoparticles, determine their biodistribution, adjust the drug-release profile, and reduce drug development expenses. Such approaches will make it possible to significantly increase the drug development success rate.

CRISPR TECHNOLOGY AND NANODELIVERY SYSTEMS :

A combination of nanodevices and the CRISPR-Cas9 technique is an effective way of implementing precision oncology. Nanoparticles can successfully deliver CRISPR elements without affecting non-tumor tissues. They can provide an opportunity to repair genetic disorders that cause cancer. (Liu et al., n.d.)

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DELIVERY SYSTEMS IN RESPONSE TO TUMOR MICROENVIRONMENT :

In the future, researchers will try to implement tumor microenvironment-responsive nanoparticles with such functionalities as Responsive drug delivery, Modulation of immune response, Remodeling extracellular matrix, Controlled drug release. (Hong et al., 2023)

GREEN NANOTECHNOLOGY:

Environmentally friendly processes for producing nanoparticles are becoming increasingly popular. Green nanotechnology focuses on minimizing hazardous materials, improving biocompatibility, ensuring environmental friendliness, and decreasing production costs. (Khan et al., 2025) (Dutta et al., 2025)

CONCLUSION

The development of nanoparticle drug delivery systems has led to an unprecedented revolution in cancer treatments. The novel physical and chemical features of nanoparticles allow for increased solubility, sustained circulation, efficient targeting, and controlled drug release with low toxicity. Nanoparticles such as liposomes, polymer nanoparticles, dendrimers, mesoporous silica nanoparticles, gold nanoparticles, magnetic nanoparticles, hydroxyapatite nanoparticles, and lipid nanoparticles have shown promising capabilities in therapeutic treatment.

In addition to advances in drug delivery systems, nanotheranostics, gene delivery technologies, modification of the tumor microenvironment, and pathway-based targeting have further broadened the scope of applications of nanotechnology in oncology. Additionally, the use of nanoparticles has allowed researchers to overcome multidrug resistance associated with cancer cells. However, some limitations include biological barriers, materials science, biotechnology, artificial intelligence, and precision medicine should address the aforementioned problems. Thus, innovations in personalized nanomedicine, programmable lipid nanoparticles, gene editing technology, and theranostics could facilitate the future application of nanoparticle drug delivery systems in cancer therapy.

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