Journal of Pharmaceutical Research and Integrated Medical Sciences (JPRIMS)
ISSN: 3049-1681, Vol. 02, Issue No. 02, 2025 (pp. 76-92)

REVIEW ARTICLE https://aktpublication.com/index.php/jprims/index

Nanomedicine In Cancer Therapy: Advances, Challenges, And Future Direction

[1]*Pratibha Sahu [2]Harshalata Kanwar

[1]Shri Rawatpura Sarkar Institute of Pharmacy Kumhari, Durg, Chhattisgarh, India

[2]KIPS, Shri Shankaracharya Professional University, Bhilai, Chhattisgarh, India, 491001

***Corresponding Author E-mail: pharmapratibha23@gmail.com**

Cancer is a major global cause of death that requires new approaches to treatment outside the use of traditional chemotherapy, radiotherapy, and surgery. Nanomedicine, based on the application of nanoparticles (NPs) to targeted drug delivery, offers an exciting area of research for increased therapeutic benefits while reducing side effects. In this review, developments in nanotechnology-based drug delivery systems (DDSs) are discussed, focusing on their value in transcending multidrug resistance (MDR), improving bioavailability, and increasing the specificity of treatment. Several NP-based systems, such as liposomes, polymeric NPs, metal NPs, and quantum dots, are analyzed with respect to cancer therapy. Additionally, this paper addresses issues with clinical translation, including biocompatibility, toxicity, and regulatory issues. At last, upcoming trends and directions of future studies to optimize NP-based cancer treatments are presented.

Key Words:

Nanomedicine, Cancer Therapy, Targeted Drug Delivery, Nanoparticles, Drug Delivery Systems, Regulatory Challenges, Future Trends.

Article History:

Received Jan 25,2025

Accepted Feb 16,2025

Published Feb 28,2025

1. INTRODUCTION

Cancer continues to be one of the most difficult diseases due to its complexity, non - genetic and its resistance to traditional treatments. Common cancer treatments, including chemotherapy and radiation, tend to cause significant side effects due to non - selective and interfere with healthy and malignant cells[1]. This creates a convincing need for more targeted and effective treatments. Nanomedicine, a relatively new subject that brings nanotechnology into medicine, is capable of transforming cancer treatment by improving the use of drugs, increasing the effectiveness of treatment and minimizing side effects.

Nanomedicine uses nanoparticles such as liposome, dendrimers, polymer nanoparticles and metal -based nanoparticles to provide a selective treatment agent for cancer cells with healthy fabric saving[2]. Nanoparticles are designed to have physical characteristics that

are different from conventional formulas on improving solubility, stability and prolonged drug release. They are also made to be functionalized with ligands to achieve specific delivery to specific cancer cell receptors for improving selectivity in therapy. This selective therapy reduces toxicity and increases therapeutic effect while overcoming one of the significant limitations of traditional chemotherapy.

In spite of the encouraging developments in nanomedicine for cancer treatment, a number of challenges exist, such as biocompatibility, large-scale production, regulatory clearance, and possible toxicity issues. The behavior of nanoparticles in biological systems is multifaceted, and their long-term impact on human health is under exploration. Furthermore, the cost and scalability of nanoparticle-based treatments are major impediments to their extensive clinical application[3]. In the future, the nanomedicine of cancer treatment will aim to make treatment more efficient, multifunctional, and tailored to individual patients. Novel technologies, including stimuli-responsive nanoparticles, immuno-nanomedicine, and theragnostic strategies integrating therapy and diagnosis, are very promising[4]. As nanotechnology, artificial intelligence, and personalized medicine continue to advance, nanomedicine will be at the center of the future of cancer therapy, with safer, more effective, and better individualized therapeutic options available to the patient.

1.1. Background and Context

Cancer is a significant worldwide health issue, causing one in six deaths globally. Conventional therapies such as chemotherapy, radiotherapy, and surgery are limited by their severe side effects, non-specific drug delivery, and recurrence risk. These limitations underscore the necessity for more targeted and efficient therapies[5].

Nanomedicine provides a revolutionary strategy through the application of nanoparticles in targeted drug delivery, optimizing therapeutic efficacy while reducing toxicity. Passive targeting (EPR effect) and active targeting (ligand-receptor interactions) are methods that enhance drug concentration at tumor sites. Theranostic nanoparticles also provide the possibility of diagnosis and treatment simultaneously, opening the door to personalized cancer therapy. With progressing research, nanomedicine is poised to break through the limitations of traditional treatments and advance patient outcomes.

1.2. Objectives of the Review

The objectives of this review are:

- To assess nanoparticle-based drug delivery systems' potential to improve cancer therapy efficacy and reduce toxicity.
- To analyze obstacles to nanomedicine clinical translation, such as biocompatibility, toxicity, and regulatory limitations.
- To investigate nanomedicine trends and future directions for individualized, multifunctional cancer treatments.

1.3. Importance of the Topic

Nanomedicine has also become a promising strategy to overcome the limitations of regular cancer treatment. Traditional chemotherapy and radiation therapy often cause systematic toxicity, leading to side effects that reduce the quality of life of the

patient. On the other hand, nanotechnology therapies allow the use of targeted drugs, minimize damage to healthy cells and improve the specificity of treatment[6]. Nanomedicine also allows the design of multifunctional nanoparticles with the ability to diagnose and treat simultaneously, often called therapy.

Knowledge of progress in nanomedicine is essential for scientists and clinicians to maximize treatment regimens, increase drug bioavailability, and enhance patient survival. Additionally, with the rise of personalized medicine, nanomedicine offers a platform for individualized cancer therapies depending on individual genetic and molecular characteristics[7]. With the growing worldwide burden of cancer, ongoing research and investment in nanomedicine can revolutionize oncology and significantly enhance patient outcomes.

2. NANOPARTICLE-BASED DRUG DELIVERY SYSTEMS IN CANCER THERAPY

Nanoparticle-based drug delivery systems have risen to prominence as a revolutionary technology in cancer therapy that facilitates the accurate targeting of drugs, lowers systemic toxicity, and improves the efficacy of therapies[8]. Unlike typical chemotherapy, with its resultant non-specific distribution and side effects, NPs promote sustained and controlled drug release together with the targeting of drug sites via passive and active mechanisms to accumulate at sites of tumors. The application of multiple classes of nanoparticles such as liposomal, polymeric, metallic, and quantum dot-based systems has transformed oncology through improved drug bioavailability, extended circulation half-life, and imaging-guided therapy integration.

2.1. Liposomal and Polymeric Nanoparticles

Liposomal Nanoparticles

Liposomal nanoparticles are lipid bilayer vesicles in spherical form that entrap hydrophilic and hydrophobic drugs in a biocompatible and biodegradable drug delivery system[9]. Liposomes have a structure similar to natural membranes, which allows for effective drug loading and slow release. Liposomes can be designed to have longer circulation time and greater tumor targeting by altering their lipid composition and surface characteristics.

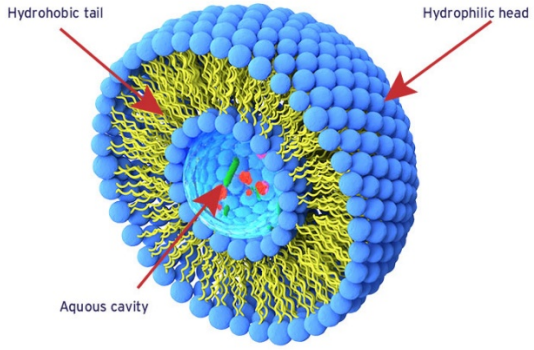

Figure 1: Liposomal Nanoparticles[10]

One of the principal innovations in liposomal drug delivery is PEGylation, in which polyethylene glycol (PEG) chains are linked onto the liposome surface. PEGylation inhibits MPS clearance, thus prolonging the half-life of the drug in circulation and enhancing its tumor accumulation. One of the most effective nanomedicine-based chemotherapy agents is Doxil, a PEGylated liposomal doxorubicin formulation, which possesses lower cardiotoxicity and better tumor penetration than free doxorubicin[11].

Though having several benefits, liposomes have limitations in terms of stability, high cost of production, and drug leakage prior to reaching the target location. Optimization of lipid composition, surface modification, and scalable manufacturing methods are the main areas of research to enhance their clinical utility.

Polymeric Nanoparticles (PNPs)

Polymeric nanoparticles (PNPs) refer to colloidal drug carriers constructed from biodegradable and biocompatible polymers including polylactic-co-glycolic acid (PLGA), chitosan, and polycaprolactone (PCL).

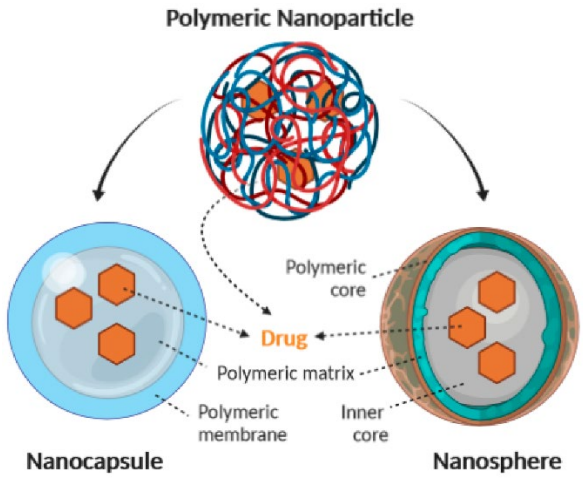

Figure 2: Polymeric Nanoparticles (PNPs)[12]

They are in two main forms:

- Nanospheres, in which the drug is uniformly dispersed in the polymer matrix.
- Nano capsules, in which the drug is encapsulated in the polymer compartment.

PNP has some advantages compared to traditional medicinal preparations, such as releasing drugs and prolonging drugs[13], improving the stability of the drug and protecting enzyme degradation. Surface function with coordinates (for example, antibodies, adaptation) also facilitates the positive targeting of cancer cells, improving the effectiveness of treatment with the target effects reduction. However, limitations such as complex synthesis, challenges and changes of lots with lots of large -scale production restrictions. Scientists discover new polymer formulas and hybrid nanoparticles to overcome these challenges and improve their clinical translation.

2.2. Metallic Nanoparticles and Quantum Dots

Metallic Nanoparticles (MNPs)

Metallic nanoparticles (MNP) have also been identified as a potential agent in cancer treatment as a function of their optical, magnetic and heat characteristics. Their ability to perform in the use of drugs, visual therapy and targeted therapy has created ideal candidates for these applications. Nanoparticles of gold, silver and iron oxide are part of the metal nanoparticles that have been searched mostly for cancer applications[14].

a) Gold Nanoparticles (AuNPs): Photothermal Therapy and Drug Delivery

Gold nanoparticles (AuNPs) is the most useful because they have biological compatibility, stability and above thermal light. AunP facilitates photothermal therapy (PTT), a cancer treatment. Using this method, AunP is deposited in tumor tissue by enhanced permeability and retention (EPR). When exposed to laser irradiation near-infrared (NIR), these nanoparticles produce local temperature, selectively destroying cancer cells without harming nearby healthy tissues[15]. This reduces the damage of

collateral for standard treatments such as radiation and chemotherapy

Besides, AuNPs can be functionalized with anticancer drugs, targeting ligands, and imaging agents, such that drug delivery, tumor imaging, and monitoring of treatment could be achieved concurrently. This double functionality increases precision medicine strategies and makes AuNPs very promising for personalized cancer therapy.

b) Silver Nanoparticles (AgNPs): Anticancer and Cytotoxic Effects

Silver nanoparticles (AgNPs) possess strong anticancer and antimicrobial activities. AgNPs have been reported to trigger the generation of reactive oxygen species (ROS), which creates oxidative stress, mitochondrial impairment, and apoptosis in cancer cells. The capacity of AgNPs to cause cell homeostasis disruption and DNA damage makes them effective to be used in cancer therapy.

Nevertheless, their cytotoxicity, bioaccumulation, and potential long-term consequences on normal tissue have been the cause of concerns[16]. Research indicates that AgNPs can induce oxidative stress in cancer cells as well as normal cells, resulting in systemic toxicity. Hence, additional studies need to be carried out to standardize their dosage, surface coating, and biocompatibility to make them clinically safe.

c) Iron Oxide Nanoparticles (IONPs): Magnetic Hyperthermia and Imaging

Iron oxide nanoparticles (IONPs) are generally applied in magnetic hyperthermia therapy (MHT) and magnetic resonance imaging (MRI). The superparamagnetic nanoparticles cause localized heat in response to alternating magnetic field, resulting in apoptosis of cancer cells selectively. The approach allows cancer treatment to be minimally invasive, especially in the case of deep-seated tumors where photothermal therapy would not be useful.

In addition, IONPs also serve as contrast agents in MRI for real-time imaging of tumors, accurate tumor localization, and monitoring of the course of therapy. The ability of IONPs to function in both diagnostics and treatment is highly beneficial in theranostics, an emerging field where therapy and diagnostics are integrated in a single platform[17]. Nevertheless, potential issues in their long-term retention, potential induction of oxidative stress, and immune reactions need to be overcome prior to widespread clinical applications.

Although metallic nanoparticles have vast promise in targeted cancer therapy, toxicity, bioaccumulation, and long-term safety concerns are still substantial. Careful preclinical and clinical safety testing must be performed to maximize their biocompatibility and therapeutic index prior to broad medical use.

- **Quantum Dots (QDs) in Cancer Therapy**

The semiconductor Nano crystals are called quantum dots (QD) with higher optical properties, including adjustable emission spectrum, high intensity photography and vibrant fluorescent. They are ideal to monitor drugs, tumors and respond to real -time monitoring therapy due to these characteristics.

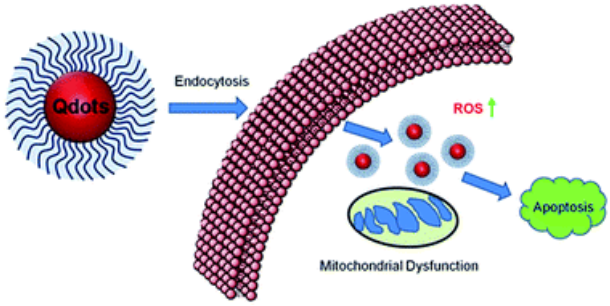

Figure 3: Therapeutic effect of quantum dots for cancer treatment[18]

- **Applications of QDs in Cancer Imaging and Drug Delivery**

QD with fluorescent emission depends on the size, causing them to adapt to the high -resolution multi -channel images of tumor cells. The ability to monitor biological molecules, image cell interaction and monitor drug distribution in real time providing useful information on tumor development and treatment[19].

In addition, the decision can be functional with anti -cancer, peptides and antibodies, facilitating the use of target drugs and increasing the specificity of the tumor. The function of improving the bioavailability of the drug and reducing the impact does not include goals, which makes valuable QDs in personalized medical strategies.

- **Challenges and Safety Concerns of QDs**

Although they are the advantage, most traditional decisions have heavy factors such as cadmium (Cd), lead (Pb) or Selenium (Se), capable of cytotoxic and ecological risk. Evidence shows that excessive contact with them can cause oxidation stress, DNA damage and inflammation and therefore, causing serious problems related to biological compatibility.

Researchers work to develop non -toxic alternatives such as carbon -based QS and decreases that can biodegrades and are modified on the surface to overcome these problems. These advances are aimed at improving their safety records while retaining their usefulness to images and treatment.

2.3. Comparative Study of Drug Delivery Systems

Each system based on nanoparticles has distinct strengths and weaknesses in cancer treatment. A comparison is presented below:

Table 1: Comparison of Nanoparticle-Based Drug Delivery Systems[20]

Nanoparticle Type	Advantages	Limitations
Liposomes	High biocompatibility, effective drug encapsulation, prolonged circulation (PEGylation)	Stability issues, high production cost, potential drug leakage
Polymeric NPs	Controlled and sustained drug release, biodegradable, customizable surface modifications	Complex synthesis, regulatory hurdles, scalability challenges

Metallic NPs	Dual imaging and therapy (theragnostic potential), photothermal and magnetic properties	Potential toxicity, uncertain long-term effects, accumulation concerns
Quantum Dots	High fluorescence stability, precise tumor imaging, real-time drug tracking	Cytotoxicity concerns (heavy metals), expensive production, biocompatibility challenges

Through increased drug targeting, reduced systemic toxicity, and imaging in real-time, nanoparticle drug delivery technologies have transformed the treatment of cancer[21]. Though metal nanoparticles and quantum dots provide more advanced therapeutic and imaging functions, liposomes and polymeric nanoparticles are more beneficial to drug stability and controlled release. Nevertheless, for effective clinical translation, toxicity, stability, cost, and regulatory approval are the problems to be solved. To achieve optimal cancer therapy and improve patient outcomes, the future research needs to focus on developing safer, multi-functional, and personalized nanomedicine technologies.

3. MECHANISMS AND APPLICATIONS OF NANOMEDICINE IN CANCER THERAPY

Through the enhancement of drug targeting, enhancing therapeutic effectiveness, and conjugating diagnostics and therapy, nanomedicine offers revolutionary approaches to cancer therapy. Nanoparticles (NPs) are proving to be an effective oncology treatment because of their ability to reduce injury to normal cells while selectively concentrating within diseased tissues[22]. The underlying mechanisms and various applications of NPs in cancer therapy are discussed in this section, with a special focus on combination therapies, targeted delivery of drugs, theranostics, and landmark studies highlighting their therapeutic potential.

3.1. Targeted Drug Delivery Mechanisms

The efficiency of drug delivery using nanoparticles depends on two major targeting approaches: passive targeting and active targeting. These mechanisms enhance drug deposition in tumor tissues while minimizing systemic toxicity.

1) Passive Targeting: Enhanced Permeability and Retention (EPR) Effect

For elevated NP accumulation within the tumor site, passive targeting leverages the unique characteristics of the tumor vasculature. The enhanced permeability and retention (EPR) effect is a state in solid tumors, described by disordered, leaky blood vessels with poor lymphatic drainage.

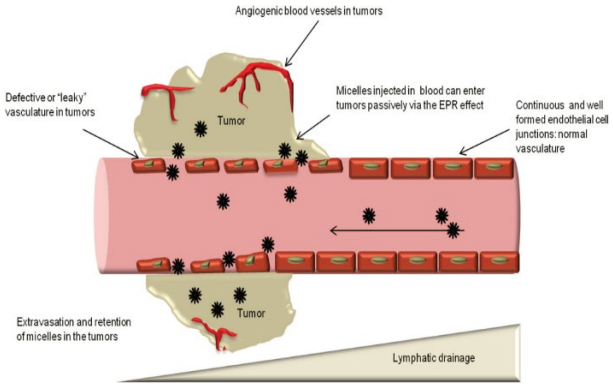

Figure 4: Enhanced Permeability and Retention (EPR) Effect[23]

This allows for nanoparticles to extravasate and accumulate within the tumor microenvironment, which enhances the local drug concentration and facilitates prolonged retention.

- The EPR effect is exploited by liposomal drugs, like Doxil (doxorubicin encapsulated in PEGylated liposomes), to enhance penetration into tumors.
- For more efficient passive targeting, polymeric nanoparticles, such as PLGA-based carriers, have controlled release and prolonged circulation.

Nonetheless, EPR effect might be compromised due to interstitial pressure and heterogeneity of the tumor vasculature, precluding its predictable application. Towards enhancing passive accumulation of NPs, interventions such as tumor microenvironment modulation (e.g., tumor vasculature normalizing with anti-angiogenic compounds) are also being explored.

2) Active Targeting: Ligand-Functionalized Nanoparticles

For more accuracy and reducing off-target impacts, active targeting involves modifying nanoparticles with specific ligands (e.g., antibodies, peptides, or aptamers) that recognize and attach to receptors specifically found on cancer cells[24]. Frequently targeted receptors include:

Folic acid-conjugated nanoparticles targeting the Folate Receptor (FR), overexpressed in lung, breast, and ovarian cancers.

- HER2-antibody-conjugated nanoparticles specifically target the overexpressed human epidermal growth factor receptor 2 (HER2) in breast cancer.
- Transferrin-coated nanoparticles are used to deliver against the Transferrin Receptor (TfR), found over a broad range of cancers in order to stimulate fast cell proliferation.
- HER2-targeted gold nanoparticles for breast cancer treatment with increased tumor cell uptake and photothermal activity are one example of active targeting.
- Folate-functionalized polymeric nanoparticles that improve drug uptake in tumors with expressed folate receptors.

Active targeting not only improves therapy and tumor specificity but requires significant customization to ensure biocompatibility, stability of the nanoparticle, and binding affinity for successful clinical applications.

3.2. Combination Therapies and Theragnostic

Combination Therapies: Overcoming Multidrug Resistance (MDR)

The most important challenge to cancer therapy is the development of multidrug resistance (MDR) in cancer cells, which decreases the efficacy of standard chemotherapy. The mechanisms of MDR involve enhanced drug efflux, by which cancer cells expel drugs before they can have an effect, changed drug metabolism[25], which inactivates chemotherapeutic drugs, and improved DNA repair mechanisms, enabling cancer cells to withstand and recover from drug-induced damage. These reasons call for innovative strategies for increasing therapeutic effect, of which combination therapies involving nanoparticles are especially important.

Through the use of nanoparticles (NPs) as drug carriers, combination therapies provide

for the co-delivery of multiple therapeutic drugs, circumventing MDR and enhancing therapeutic outcomes. The merits of nanoparticle-based combination therapy are improved drug bioavailability, extended circulation half-life, targeted delivery, and control over the ratio of drugs. These characteristics synergistically inhibit tumor growth with reduced toxicity to normal tissues.

Key Examples of Nanoparticle-Based Combination Therapies:

1. **Liposomal Co-Delivery Systems**: Liposomes are vesicular biocompatible drug carriers that can encapsulate hydrophilic and hydrophobic drugs, enhancing their solubility and bioavailability.

Example: Doxorubicin + Paclitaxel liposomes allow two chemotherapeutic drugs to be released simultaneously, which results in increased tumor inhibition by distinct mechanisms. Doxorubicin inserts into DNA and inhibits topoisomerase II, arresting cell division, whereas Paclitaxel stabilizes microtubules, triggering apoptosis[26].

2. **Polymeric Nanoparticles for Chemotherapy and Gene-Silencing:** Polymeric nanoparticles (PNPs) are biocompatible carriers with ability to entrap small interfering RNA (siRNA) as well as chemotherapy agents.
   - RNA molecules have the capacity to silence the genes that contribute to MDR, e.g., P-glycoprotein (P-gp) efflux pump-related drug resistance.
   - Polymeric nanoparticles improve the efficacy of treatment by delivering siRNA concurrently with chemotherapy drugs, thereby prolonging the stay of the chemotherapeutic drugs within the cancer cells.
3. **Gold Nanoparticles (AuNPs) in Chemo-Photothermal Combination Therapy:** Gold nanoparticles (AuNPs) are a good platform for chemo-photothermal therapy (CPTT), where they are used to functionalize chemotherapy drugs and photosensitizers[27].
   - Gold nanoparticles, when exposed to near-infrared (NIR) light, emit heat, which causes localized hyperthermia to increase the cytotoxicity of chemotherapeutic drugs.
   - The combination of these processes enhances cancer cell apoptosis, especially those with resistant forms to conventional chemotherapy.

By combining these strategies, combination therapies synergistically suppress tumor growth, bypass resistance mechanisms, and enhance patient survival. Yet more research is needed to maximize dosage, biodistribution, and long-term safety before widespread clinical use.

Theranostic Nanoparticles: Integrated Therapy and Diagnostics

Theragnostic is a cutting-edge technology that integrates therapeutic and diagnostic capabilities into one nanoparticle system, providing a real-time and personalized solution for cancer treatment. This approach is especially valuable in precision oncology, where therapies are optimized according to the response of the individual patient and the characteristics of the tumor.

Theranostic nanoparticles enable:

- Real-time visualization of tumor growth and drug distribution.
- Targeted drug delivery to minimize off-target effects.
- Ongoing monitoring of response to treatment, enabling prompt modification of therapy.

Key Examples of Theranostic Nanoparticles:

- **Quantum Dots (QDs) for Real-Time Tumor Imaging:** Quantum dots (QD) are semiconductor Nano crystals on high images with long -term fluorescence, which makes them perfect for real -time tumor images and drug monitoring[28]. They can be combined with anti -cancer drugs to allow accurate location and targeted therapy, thus increasing the effectiveness of treatment.
- **Magnetic Hyperthermia Therapy and MRI with Iron Oxide Nanoparticles (IONPs):** By creating local thermal reactions when exposed to alternative magnetic fields, superparamagnetic iron oxide nanoparticles (SPIONs), as well as a MRI to detect high -resolution tumors. Simultaneous diagnosis and treatment improved cancer control.
- **Gold Nanoparticles (AuNPs) for Multimodal theragnostic:** Gold nanoparticles with function, with anti -cancer and fluorescent dyes, allowing images of tumors, optical electronics and optical Liberation of the drug. The ability to absorb near-infrared (NIR) can target specific cancer cells to destroy, while monitoring real -time of the treatment of adaptive treatments.

3.3. Summary of Key Research Studies

A number of studies have shown the potential of various drug delivery systems based on nanoparticles in cancer treatment. Some of the most significant findings are presented below:

Table 2: Reference Table

Reference	Study Focus	Nanoparticle Type	Findings
Bor et al. (2019)[29]	Liposomal Drug Delivery	Liposomal Nanoparticles	Improved drug-carrier ratios and enhanced tumor targeting efficiency, leading to increased treatment effectiveness.
Wicki et al. (2015)[30]	Polymeric Drug Carriers	Polymeric Nanoparticles	Demonstrated enhanced bioavailability, prolonged circulation, and reduced toxicity in breast cancer therapy.
Youn & Bae (2018)[31]	Photothermal Therapy	Metallic Nanoparticles	Gold nanoparticles enabled photothermal therapy, significantly increasing tumor cell apoptosis while minimizing damage to normal tissues.

Shi et al. (2017)[32]	Tumor Imaging & Drug Tracking	Quantum Dots (QDs)	Achieved high-resolution fluorescence imaging and effective targeted therapy, highlighting QDs' potential for real-time drug tracking.
Blanco et al. (2011)[33]	Multifunctional Nanocarriers	Hybrid Nanoparticles	Integrated multiple functionalities, such as targeted drug delivery and imaging, enhancing the precision of cancer treatment.
Kim & Jeong (2017)[34]	High-Load Drug Delivery	Dendrimers	Provided high drug-loading capacity, improved solubility, and targeted delivery to cancer cells.
Navya et al. (2019)[35]	Carbon-Based Therapeutics	Carbon-based Nanoparticles	Utilized for targeted therapy and diagnostics, offering high biocompatibility and efficient drug delivery.

These researches support the diversity and promise of nanomedicine in enriching drug delivery, evading multidrug resistance (MDR), merging imaging with therapy, and enhancing overall treatment efficacy.

4. DISCUSSION

4.1. Interpretation and Analysis of Findings

Through improving drug delivery precision, reducing systemic toxicity, and fighting multidrug resistance (MDR), nanomedicine-based drugs have proved to be of great potential in enhancing the outcome of cancer treatment. The critical examination of a number of medication delivery approaches involving nanoparticles proves their groundbreaking impacts on oncology.

Liposomal nanoparticles have been shown to increase drug solubility and bioavailability. PEGylation extends systemic circulation, enhancing tumor targeting by reducing the MPS's rapid clearance. Stability problems, premature drug leakage, and elevated production costs are often challenging to liposomal formulations, necessitating lipid composition, scalability, and manufacturing technology adaptation[36].

The controlled and sustained drug release offered by polymeric nanoparticles enhances the therapeutic efficacy and allows functionalization with ligands that bind to specific cancer cells. These particles can be engineered using biodegradable polymers such as chitosan, polylactic-co-glycolic acid (PLGA), and polycaprolactone (PCL) in order to enhance their biocompatibility. Their general clinical application is limited by their ease of synthesis, potential for immunogenicity, and regulatory concerns. For boosting their translational value, efforts are under way to optimize polymeric structures and introduce novel hybrid systems.

Metal nanoparticles, such as iron oxide nanoparticles (IONPs) and gold nanoparticles (AuNPs), are beneficial for hyperthermia therapy and image-guided treatment. For example, AuNPs allow for photothermal therapy (PTT), where the targeted destruction of tumor cells occurs due to the generation of heat by localized exposure to NIR light. On the other hand, IONPs are useful for magnetic hyperthermia therapy and serve as magnetic resonance imaging (MRI) contrast agents. Despite these advantages[37], cytotoxicity, bioaccumulation, and long-term safety issues call for rigorous in vivo studies alongside custom surface engineering to mitigate any harmful effects.

Owing to their exceptional optical features, quantum dots (QDs) are used in theragnostic and cancer imaging. They allow for the real-time monitoring of drug delivery and response through their stable fluorescence. Conventional QDs usually incorporate heavy metals like lead (Pb) and cadmium (Cd), and toxicity as well as biocompatibility concerns are a cause for concern. In order to enhance their clinical feasibility, non-toxic, biodegradable QDs such as carbon and silicon-based QDs are being explored on a constant basis.

4.2. Implications and Significance

- **Personalized Cancer Treatment:** Customized NP delivery can enhance clinical outcomes by reaching targeted cancer biomarkers, reducing side effects, and increasing drug efficacy.
- **Combination Therapies:** NP systems are able to co-deliver more than one therapeutic agent, allowing synergistic effects that enhance cancer treatment effectiveness and counteract MDR mechanisms.
- **Theragnostic:** Convergence of therapy and diagnostics through NPs enables the monitoring of treatment response in real time, allowing for prompt adjustment of therapeutic protocols and increased patient monitoring[38].
- **Reduced Systemic Toxicity:** Nanomedicine allows targeted drug delivery, decreasing damage to non-targeted healthy tissues and enhancing the quality of life for patients.
- **Imaging-Guided Therapy Advances:** NP-based imaging contrast agents optimize imaging modalities such as MRI, facilitating tumor localization and treatment planning.

4.3. Gaps and Future Research Directions

Despite notable progress, some essential gaps exist in nanomedicine:

- **Long-Term Toxicity and Safety Studies:** Additional in vivo and clinical studies are required to assess long-term biocompatibility and possible side effects of nanoparticle-based treatments[39].
- **Wider Clinical Trials:** More extensive and representative clinical trials are needed to confirm NP effectiveness for diverse cancer types and patient populations.
- **Strategies for Cost Reduction:** The creation of scalable, affordable nanoparticle manufacturing methods is essential to facilitate widespread clinical use and affordability.

- **Development of Smart Nanocarriers:** Future studies should focus on nanoparticles with real-time monitoring capabilities[40], stimulus-sensitive drug release systems, and improved biodegradability in order to enhance treatment specificity and safety.
- **Regulatory Standardization:** There should be clear guidelines and standardized testing protocols to enable the clinical translation of therapies based on nanomedicine and ensure their efficacy and safety.

These gaps will be bridged by interdisciplinary research and technology, and this will speed up the integration of nanomedicine into standard clinical practice, allowing for more effective and targeted approaches to cancer treatment.

5. CONCLUSION

5.1. Summary of Insights

A revolutionary progress in cancer treatment, Nanomedicine provides unprecedented accuracy levels in the use of drugs, as well as reducing systemic toxicity. The application of nanoparticles, such as metal nanoparticles, polymer nanoparticles, liposomes and quantum scores, significantly improved targeted therapy, ability to dissolve drugs and biological use. The release of controlled drugs, increasing the penetration into the tumor and increasing traffic time are some clear advantages that these Nanoarray systems provide. However, some challenges still despite these progresses, such as obstacles as prescribed, expensive production, immunity and toxicity. In order to successfully make Nanomedicine from the laboratory to the clinic, the next research must respond to these main concerns. In addition, there is also room to improve anti - cancer -based cancer -based therapies with a combination of artificial intelligence (AI) and machine learning (ml) in design and optimization of nanoparticles.

5.2. Importance of the Review

This review shows the potential of Nanomedicine to revolutionize cancer, highlighting its ability to increase the effectiveness of treatment while reducing side effects. Knowledge of different platforms of Nanocarriers is of great value to researchers, clinical doctors and pharmaceutical industry to design cancer effectively, safely and personalize more effectively. By building optimal nanoparticles, treatment protocols can be personalized for patients, which leads to better treatment results. In addition, this study emphasized the importance of multidisciplinary cooperation between scientists in nanotechnology, cancer doctors, management agencies and industrial partners to promote clinical translation and continue Nano nano therapy with faster speed. Cancer therapy with better results for patients and the survival rate becomes a reality by consolidating nanotechnology with immunotherapy, providing personalized drugs and real images.

5.3. Final Recommendations

To fill the gap between laboratory experiments and clinical utility, a number of strategic actions need to be taken:

- **Better Regulatory Policies:** Harmonized and standardized policies globally are needed for nanomedicine therapy approval. Regulatory agencies need to establish processes for assessing nanoparticle toxicity, long-term biocompatibility, and efficacy across various patient populations.

Enhancing these regulations will speed up approvals for nanoparticle-based cancer treatment and ensure safety.

- **Multifunctional Nanocarriers:** Create theragnostic hybrid nanoparticles with therapeutic and diagnostic capabilities. Multifunctional devices monitor drug distribution, treatment response, and tumor response in real time, allowing therapy to be adjusted. This can improve cancer therapy accuracy and efficiency.
- **AI-Based Drug Design:** AI/ML for optimization and nanoparticle design can transform cancer nanomedicine. AI predictive modeling can create nanoparticles of appropriate size, charge, and surface modification for minimum side effects targeting. AI can hasten drug screening, decrease research costs, and maximize clinical trial efficiency.
- **Scalable and Cost-Effective Production:** Synthesis of nanoparticles is challenging due to complex production processes and prohibitive expenses. Research must design scalable, cost-effective manufacturing techniques in order to ensure consistency and quality of nanoparticle preparation. It will make nanomedicine-derived medicines affordable and accessible to the masses.
    - **Long-term Safety and Efficacy Studies:** To provide nanoparticle efficacy and safety, long-term metabolism and biodistribution studies in the human body should be conducted. Accumulation, clearance, and toxicity of the nanoparticles should be resolved for approval by regulatory authorities and patient safety.

REFERENCES

1. Gupta, S., Gupta, P. K., Dharanivasan, G., & Verma, R. S. (2017). Current prospects and challenges of nanomedicine delivery in prostate cancer therapy. *Nanomedicine*, *12*(23), 2675-2692.
2. Mandal, S. D., Mandal, S., Pathak, Y. V., & Patel, J. K. (2021). Current Challenges and Future Directions in Nanomedicine. In *Emerging Technologies for Nanoparticle Manufacturing* (pp. 575-583). Cham: Springer International Publishing.
3. Narayan, S. (2021). Challenges and future opportunities of nanomedicine in cancer therapy. In *Nanomedicine for Cancer Diagnosis and Therapy* (pp. 221-249). Singapore: Springer Singapore.
4. Singh, V. K., Saini, A., & Chandra, R. (2017). The implications and future perspectives of nanomedicine for cancer stem cell targeted therapies. *Frontiers in Molecular Biosciences*, *4*, 52.
5. Nirmala, M. J., Kizhuveetil, U., Johnson, A., Balaji, G., Nagarajan, R., & Muthuvijayan, V. (2023). Cancer nanomedicine: a review of nano-therapeutics and challenges ahead. *RSC advances*, *13*(13), 8606-8629.
6. Zhang, P., Xiao, Y., Sun, X., Lin, X., Koo, S., Yaremenko, A. V., ... & Tao, W. (2023). Cancer nanomedicine toward clinical translation: Obstacles, opportunities, and future prospects. *Med*, *4*(3), 147-167.
7. Bregoli, L., Movia, D., Gavigan-Imedio, J. D., Lysaght, J., Reynolds, J., & Prina-Mello, A. (2016). Nanomedicine applied to

translational oncology: A future perspective on cancer treatment. *Nanomedicine: Nanotechnology, Biology and Medicine*, *12*(1), 81-103.

8. Kim, K., & Khang, D. (2020). Past, present, and future of anticancer nanomedicine. *International Journal of Nanomedicine*, 5719-5743.
9. Bhat, R., Himasvi, M. M., Varshini, N., & Shabaraya, A. R. (2024). Emerging Frontiers and Future Directions in Nanomedicine: A Comprehensive Review. *International Journal of Current Research in Physiology and Pharmacology*, 25-32.
10. Gavas, S., Quazi, S., & Karpiński, T. M. (2021). Nanoparticles for cancer therapy: current progress and challenges. *Nanoscale research letters*, *16*(1), 173.
11. Mirza, Z., & Karim, S. (2021, February). Nanoparticles-based drug delivery and gene therapy for breast cancer: Recent advancements and future challenges. In *Seminars in cancer biology* (Vol. 69, pp. 226-237). Academic Press.
12. Xu, M., Han, X., Xiong, H., Gao, Y., Xu, B., Zhu, G., & Li, J. (2023). Cancer nanomedicine: emerging strategies and therapeutic potentials. *Molecules*, *28*(13), 5145.
13. de Lázaro, I., & Mooney, D. J. (2021). Obstacles and opportunities in a forward vision for cancer nanomedicine. *Nature materials*, *20*(11), 1469-1479.
14. Abdel-Mageed, H. M., AbuelEzz, N. Z., Radwan, R. A., & Mohamed, S. A. (2021). Nanoparticles in nanomedicine: a comprehensive updated review on current status, challenges and emerging opportunities. *Journal of microencapsulation*, *38*(6), 414-436.
15. Pautler, M., & Brenner, S. (2010). Nanomedicine: promises and challenges for the future of public health. *International journal of nanomedicine*, 803-809.
16. Dong, Y., Wu, X., Chen, X., Zhou, P., Xu, F., & Liang, W. (2021). Nanotechnology shaping stem cell therapy: Recent advances, application, challenges, and future outlook. *Biomedicine & Pharmacotherapy*, *137*, 111236.
17. Wei, G., Wang, Y., Yang, G., Wang, Y., & Ju, R. (2021). Recent progress in nanomedicine for enhanced cancer chemotherapy. *Theranostics*, *11*(13), 6370.
18. Xie, X., Zhang, Y., Li, F., Lv, T., Li, Z., Chen, H., ... & Gao, Y. (2019). Challenges and opportunities from basic cancer biology for nanomedicine for targeted drug delivery. *Current cancer drug targets*, *19*(4), 257-276.
19. Greene, M. K., Johnston, M. C., & Scott, C. J. (2021). Nanomedicine in pancreatic cancer: current status and future opportunities for overcoming therapy resistance. *Cancers*, *13*(24), 6175.
20. Wang, Y., Santos, A., Evdokiou, A., & Losic, D. (2015). An overview of nanotoxicity and nanomedicine research: principles, progress and implications for cancer therapy. *Journal of Materials Chemistry B*, *3*(36), 7153-7172.
21. Kumar, V., Choudhary, A. K., Kumar, P., & Sharma, S. (2019).

Nanotechnology: nanomedicine, nanotoxicity and future challenges. *Nanoscience & Nanotechnology-Asia*, *9*(1), 64-78.
22. Liu, J., Zhang, R., & Xu, Z. P. (2019). Nanoparticle-based nanomedicines to promote cancer immunotherapy: recent advances and future directions. *Small*, *15*(32), 1900262.
23. Cheng, Z., Li, M., Dey, R., & Chen, Y. (2021). Nanomaterials for cancer therapy: current progress and perspectives. *Journal of hematology & oncology*, *14*, 1-27.
24. Tran, S., DeGiovanni, P. J., Piel, B., & Rai, P. (2017). Cancer nanomedicine: a review of recent success in drug delivery. *Clinical and translational medicine*, *6*, 1-21.
25. Jadhav, A. (2024). Nanomedicine: Current Trends, Applications, and Future Prospects. *Journal of Drug Delivery and Biotherapeutics*, *1*(03), 32-36.
26. Ediriwickrema, A., & Saltzman, W. M. (2015). Nanotherapy for cancer: targeting and multifunctionality in the future of cancer therapies. *ACS biomaterials science & engineering*, *1*(2), 64-78.
27. Rosenblum, D., & Peer, D. (2014). Omics-based nanomedicine: the future of personalized oncology. *Cancer letters*, *352*(1), 126-136.
28. Anchordoquy, T. J., Barenholz, Y., Boraschi, D., Chorny, M., Decuzzi, P., Dobrovolskaia, M. A., ... & Simberg, D. (2017). Mechanisms and barriers in cancer nanomedicine: addressing challenges, looking for solutions.
29. Bor, G., Mat Azmi, I. D., & Yaghmur, A. (2019). Nanomedicines for cancer therapy: Current status, challenges and future prospects. *Therapeutic delivery*, *10*(2), 113-132.
30. Wicki, A., Witzigmann, D., Balasubramanian, V., & Huwyler, J. (2015). Nanomedicine in cancer therapy: challenges, opportunities, and clinical applications. *Journal of controlled release*, *200*, 138-157.
31. Youn, Y. S., & Bae, Y. H. (2018). Perspectives on the past, present, and future of cancer nanomedicine. *Advanced drug delivery reviews*, *130*, 3-11.
32. Shi, J., Kantoff, P. W., Wooster, R., & Farokhzad, O. C. (2017). Cancer nanomedicine: progress, challenges and opportunities. *Nature reviews cancer*, *17*(1), 20-37.
33. Blanco, E., Hsiao, A., Mann, A. P., Landry, M. G., Meric-Bernstam, F., & Ferrari, M. (2011). Nanomedicine in cancer therapy: innovative trends and prospects. *Cancer science*, *102*(7), 1247-1252.
34. Kim, E. M., & Jeong, H. J. (2017). Current status and future direction of nanomedicine: focus on advanced biological and medical applications. *Nuclear medicine and molecular imaging*, *51*, 106-117.
35. Navya, P. N., Kaphle, A., Srinivas, S. P., Bhargava, S. K., Rotello, V. M., & Daima, H. K. (2019). Current trends and challenges in cancer management and therapy using designer nanomaterials. *Nano convergence*, *6*(1), 23.
36. Shapira, A., Livney, Y. D., Broxterman, H. J., & Assaraf, Y. G. (2011). Nanomedicine for targeted

cancer therapy: towards the overcoming of drug resistance. *Drug resistance updates*, *14*(3), 150-163.

37. Zhao, B., Chen, S., Hong, Y., Jia, L., Zhou, Y., He, X., ... & Gao, D. (2022). Research progress of conjugated nanomedicine for cancer treatment. *Pharmaceutics*, *14*(7), 1522.
38. Rajendran, S., Sundararajan, P., Awasthi, A., & Rajendran, S. (2023). Nanorobotics in Medicine: A Systematic Review of Advances, Challenges, and Future Prospects. *arXiv preprint arXiv:2309.10881*.
39. Germain, M., Caputo, F., Metcalfe, S., Tosi, G., Spring, K., Åslund, A. K., ... & Schmid, R. (2020). Delivering the power of nanomedicine to patients today. *Journal of Controlled Release*, *326*, 164-171.
40. Ezike, T. C., Okpala, U. S., Onoja, U. L., Nwike, C. P., Ezeako, E. C., Okpara, O. J., ... & Nwanguma, B. C. (2023). Advances in drug delivery systems, challenges and future directions. *Heliyon*, *9*(6).