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Recent Development in Vaccine Delivery System: From Oral to Transdermal Route

[1]Ms Tanuja Auti, [2]Ms. Shrutika Bangar, [3] Dr. Neha Aher, [4]Dr. Ramteke K. H, [5]Dr. Datkhile S. V
[1,2,3]Student of Samarth Institute of Pharmacy, Belhe, Pune, Maharashtra.
[4,5]Professor, Department of Pharmaceutics, Samarth Institute of Pharma, Belhe, Pune, Maharashtra.
shrutikabangar7545@gmail.com

Abstract: *Nanotechnology has reignited the cancer battle with a new chapter, which includes the possibility of far more precise drug delivery with considerably fewer side effects than the conventional methods of treatment. Over the last few years, scientists have come up with a diverse array of nanotechnology-based drug delivery vehicles—polymeric nanoparticles, lipid carriers, inorganic nanomaterials, and biomimetic vesicles—that are capable of intelligent navigation in the body and selective binding to tumor cells*

These sophisticated nanosystems not only make a hollow protection of drugs against their degradation but also ensure that the drugs are given in the right place and at the right time, and sometimes, they respond to signals from the tumor microenvironment. A large number of these platforms can also link the treatment with the imaging, thus, allowing the doctors to see the treatment progress in real timeThis article reviews the latest scientific advances in targeted nanocarriers for cancer therapy, illustrates the working of these technologies and talks about the potential, as well as the challenges, of using them in daily clinical practice In fact, the rapid transformation of nanomedicine is a new source of hope for cancer treatments that are safer, more effective, and more personalized.

Keywords: Nanotechnology, Targeted drug delivery, Cancer therapy, Nanocarriers, Polymeric nanoparticles, Lipid-based nanoparticles, Inorganic nanomaterials, Biomimetic delivery systems, Tumor microenvironment, Theranostics, Stimuli-responsive nanoparticles, Controlled drug release, Precision medicine, Nanomedicine

I. INTRODUCTION

Cancer remains one of the most challenging diseases of our time, not only because of its complexity but also due to the limitations of conventional treatments. Chemotherapy, despite being a cornerstone of cancer therapy, often struggles to distinguish between healthy and malignant cells, leading to severe side effects and reduced quality of life for patients. In recent years, the scientific community has turned to nanotechnology as a powerful tool to overcome these barriers and rethink how anticancer drugs can be delivered more safely and effectively.

Nanotechnology-based drug delivery systems offer the advantage of working at a scale similar to biological molecules, allowing them to interact more precisely with cancer cells and the tumor microenvironment. These nanoscale carriers—ranging from polymeric nanoparticles and liposomes to inorganic nanomaterials and biomimetic vesicles—have the ability to protect therapeutic agents, prolong circulation time, and increase drug concentration specifically at tumor sites. Advances in ligand-mediated targeting, stimuli-responsive release mechanisms, and multifunctional theranostic platforms have further expanded the potential of nanomedicine, moving it beyond simple drug transport toward intelligent, adaptive treatment strategies.

As research accelerates, nanotechnology continues to reshape the landscape of cancer therapy by offering new ways to enhance treatment efficacy, reduce toxicity, and support personalized medicine. This review explores the latest developments in nanotechnology-based targeted drug delivery systems, highlights their design principles, and discusses the opportunities and challenges that lie ahead in translating these promising innovations into clinical practice.

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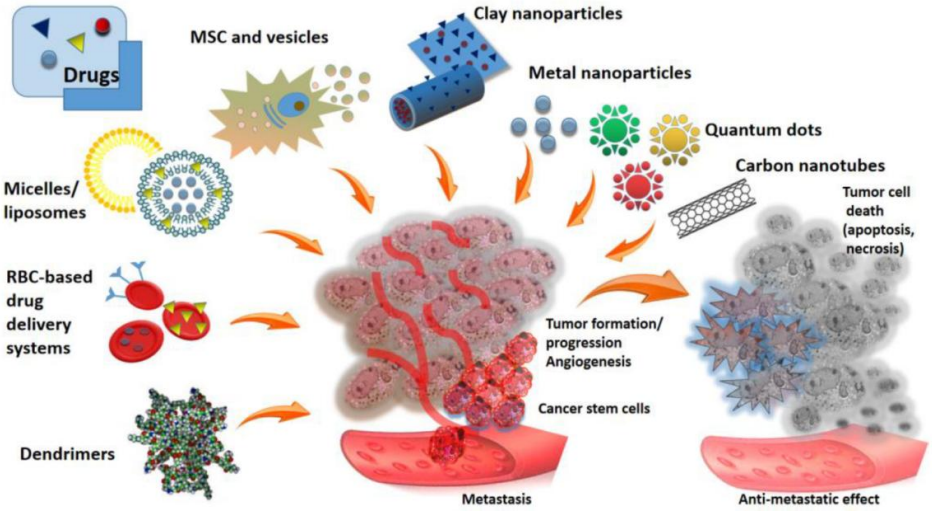

Fig : Drug Delivery Nano-Platforms for Advanced Cancer Therapy

Overview of Nanotechnology-Based Drug Delivery Systems

Nanotechnology-based drug delivery systems are a radical shift in how cancer treatments are conceptualized, delivered, and managed. These novel agents make use of nanoparticles—extremely small structures measured in billionths of a meter—to carry therapy directly to cancer cells and at the same time limit the damage to the healthy cells. Since nanoparticles are very small and their surfaces can be modified, they can stay for a longer time in the bloodstream, penetrate biological barriers more efficiently, and target tumors either by passive or active targeting.

Various cancer nanocarriers have been created to treat the different problems of cancer therapy. As an example, polymeric nanoparticles provide a durable and biodegradable platform which is capable of controlled and sustained drug release. Lipid-based carriers, comprising liposomes and solid lipid nanoparticles, are biocompatible and have major roles in clinical applications. In addition, inorganic nanomaterials, such as gold nanoparticles, silica, and magnetic nanoparticles, offer a bundle of unique optical and magnetic properties that facilitate imaging-guided therapy, hyperthermia, and combined treatments. More recently, biomimetic and cell-derived systems like exosomes and membrane-coated nanoparticles that are naturally immune to the immune system and are highly efficient in targeted delivery have been introduced.

The latest generation of nanocarriers are far from being mere drug containers—they can be designed in such a way that they can react to certain signals from within the tumor like low pH, high enzyme levels, or high glutathione concentrations. Certain devices could also be switched on by external stimuli such as light, heat, or magnetic fields, thereby allowing precise control over the exact time and place of drug release. There are also those that combine therapeutic and diagnostic capabilities, thus creating “theranostic” platforms which are able to treat as well as monitor in real-time.

To sum up, the implementation of nanotechnology-based drug delivery systems in cancer therapy has set new standards by improving drug stability, increasing tumor specificity, lessening the occurrence of adverse effects, and facilitating personalized treatment regimens. The main obstacles at present are large-scale production, safety evaluation, and regulatory approval, however, the quick advances in the field of nanomedicine indicate a rather bright future for cancer care that is more effective and patient-friendly.

Expanded & Deep Overview of Nanotechnology-Based Drug Delivery Systems

One of the major changes in the fashion of the transportation, release, and targeting of anticancer drugs in the body is the nanotechnology-based drug delivery systems. The main reason for their great success is that they are capable of

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functioning at the nanoscale- the very place where natural biological events such as protein interactions, receptor binding, and cellular uptake take place. By designing drug carriers at this level, scientists are able to determine the behavior of drugs in the body to a degree they could never before..

1. The Rationale Behind Nanotechnology in Cancer Therapy

Traditional chemotherapy distributes drugs systemically, causing widespread toxicity and exposing healthy tissues to harmful chemicals. Nanocarriers overcome these issues through:

- **Enhanced permeability and retention (EPR) effect**: Tumor tissues have leaky vasculature and poor lymphatic drainage, allowing nanoparticles (NPs) to passively accumulate.
- **Surface modification**: Nanoparticles can be coated with polyethylene glycol (PEG), proteins, or cell membranes to avoid immune clearance.
- **Targeted interaction**: Ligands such as antibodies, peptides, aptamers, or small molecules enable active targeting of overexpressed receptors on cancer cells.

These attributes reduce systemic toxicity while increasing therapeutic efficiency.

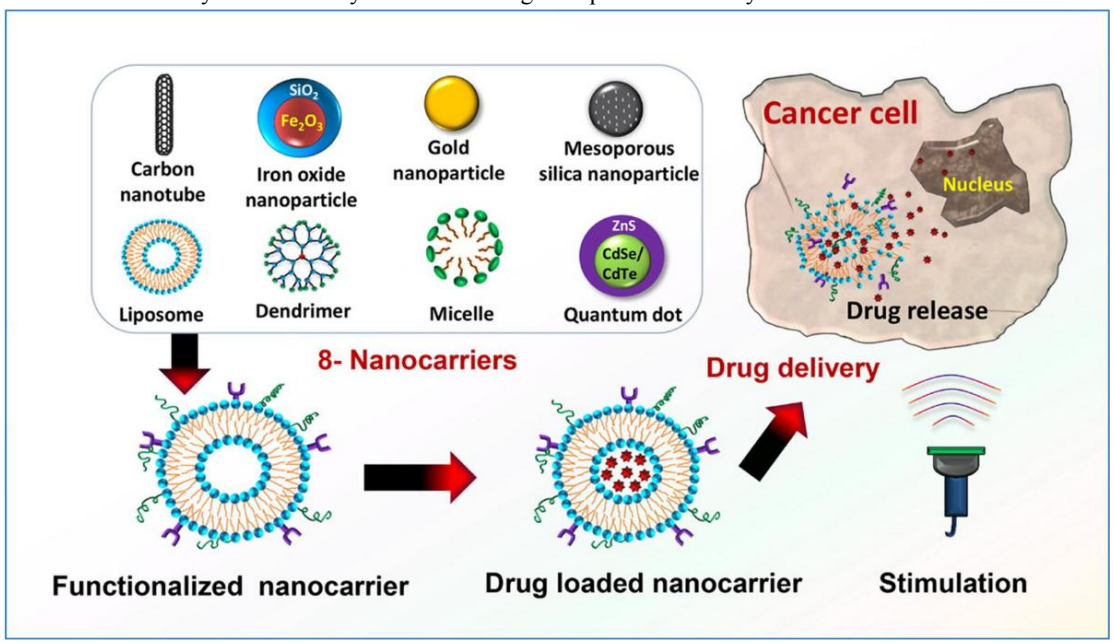

Fig- Nanoengineered approaches to improve the efficacy of targeted drug delivery for the treatment of malignancy

2. Major Categories of Nanocarriers and Their Deep Functional Roles

A. Polymeric Nanoparticles

These systems are created from biocompatible polymers like PLGA, PEG, chitosan, and poloxamers.

Deep advantages include:

- Tunable degradation and release rates
- High loading capacity for both hydrophilic and hydrophobic drugs
- Ability to carry multiple drugs for combination therapy
- Adjustable surface chemistry for targeting ligands

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Advanced polymeric nanoparticles can respond to **pH changes**, **enzymes**, or **redox conditions**, releasing drugs only in tumor-specific environments.

B. Lipid-Based Nanocarriers

Liposomes, micelles, nanostructured lipid carriers (NLCs), and solid lipid nanoparticles (SLNs) are widely used due to their natural biocompatibility.

Key strengths:

- Excellent membrane fusion and drug encapsulation
- Improved drug solubility
- Protection of unstable drugs such as mRNA, peptides, or siRNA
- Clinically approved formulations (e.g., Doxil)

New-generation lipid carriers combine hydrophobic and hydrophilic components, enabling co-delivery of chemotherapy and genetic material.

C. Inorganic Nanoparticles

Inorganic nanocarriers like **gold nanoparticles, silica nanoparticles, magnetic nanoparticles**, and **quantum dots** bring unique physical properties.

Deep functional roles:

- **Photothermal therapy (PTT):** Gold nanoparticles convert light into heat to kill cancer cells.
- **Photodynamic therapy (PDT):** Light-activated nanoparticles generate reactive oxygen species.
- **Magnetic hyperthermia:** Magnetic nanoparticles generate heat under alternating magnetic fields.
- **Real-time imaging:** MRI, CT, or fluorescence guidance.

These systems allow **theranostics**, combining therapy and diagnostics in a single platform.

D. Biomimetic and Cell-Membrane–Coated Nanocarriers

Biomimetic nanocarriers use natural membranes (e.g., cancer cell membrane, red blood cell membrane, platelet membrane) to cloak nanoparticles.

Deep advantages include:

- Immune evasion due to biological camouflage
- Longer circulation time
- "Homotypic targeting," where cancer-cell–coated nanoparticles preferentially bind to the same type of cancer cell
- Improved biocompatibility and biodistribution

Exosomes—the body's natural nanovesicles—are emerging as powerful carriers for genetic material and small drugs due to their innate targeting ability.

3. Mechanisms of Targeting and Release

Passive Targeting

Uses the EPR effect to accumulate nanoparticles in tumor tissue without specific ligands.

Active Targeting

Functionalized nanoparticles bind to cancer-specific receptors such as:

- HER2
- EGFR
- Folate receptor
- Transferrin receptor

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- Integrin αvβ3

This enhances uptake by tumor cells through receptor-mediated endocytosis.

Stimuli-Responsive (Smart) Release Systems

Nanocarriers can release drugs in response to:

- **Internal stimuli:**
  - Acidic pH in tumors
  - Elevated glutathione for redox-sensitive release
  - Overexpressed enzymes (e.g., MMPs)
- **External stimuli:**
  - Light (NIR-triggered release)
  - Magnetic fields
  - Ultrasound
  - Heat

These smart systems provide precise spatiotemporal control of therapy.

4. Biological Interactions

Nanocarriers must navigate complex biological environments including:

- Protein corona formation
- Recognition by the immune system
- Cellular uptake pathways (endocytosis, caveolae-mediated uptake)
- Endosomal escape, which is crucial for siRNA and mRNA delivery
- Intracellular trafficking and drug release into the cytosol or nucleus

Designing nanoparticles that can **survive circulation**, **avoid macrophage clearance**, and **penetrate deeply into tumor tissue** remains a major research focus.

Detailed Advantages of Nanotechnology-Based Drug Delivery Systems

Drug delivery systems based on nanotechnology have lessened the negative effects of cancer treatment, while simultaneously escalating their efficacy and selectivity. The foremost attractive feature of targeted drug delivery is feasible by such systems. Compared with standard chemotherapies, which comprise the whole body with free radicals along with tumor cells, nanoparticles can be set to be more likely to deposit at tumors. This happens as tumor blood vessels are composed of gaps and the tumor is poorly drained by the lymphatic system. Hence, nanoparticles will be more accumulated in a tumor by the enhanced permeability and retention (EPR) effect.Being able to attach cancer-specific ligands, e.g., peptides, antibodies, or small molecules, recognizing cancer cell receptors is another feature of nanoparticles. This active targeting can significantly increase the drug concentration at the tumor site leading to a reduction of the drug contact with normal cells and thus, the side effects will decrease and the therapeutic efficiency can increase.

The main idea behind the application of the nanocarriers is to improve the solubility of the drugs and make them more stable. Most of the times in the anticancer drug discovery, one comes across the problem that the drug has low solubility in water which limits absorption, distribution and thus therapeutic potential. By using nanocarriers these drugs can be protected against degradation and can be made more soluble. Moreover, drug release at premature stages is stopped, thus active molecules remain stable until they reach the tumor environment. Thus, nanotechnology permits the realization of such drugs that would otherwise be ineffective due to poor solubility or rapid metabolism.

Nanocarriers have the ability to offer very precise control over drug release which is in fact very significant in cancer treatment when timing and dosage affect substantially therapeutic success. The scientists have an option of letting the particles release their content when they react to a trigger. This trigger may be acidic pH in tumor, presence of

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glutathione, overexpression of certain enzymes or even an external stimulus like light or heat. The occurrence of controlled and sustained release gives a chance to reduce dosing frequency, prevents drug concentration spikes which may result in toxicity and also assures that therapeutic levels are kept for longer periods. Such programmable release profiles increase patient comfort and adherence while, at the same time, enhancing the effectiveness of treatment.

Another advantage that nanocarriers have is that they can break through the barrier of multidrug resistance (MDR), which is the major problem of cancer treatment. Typically cancer cells develop methods to remove drugs from their cytoplasm, thus making chemotherapy inefficient. Nanoparticles by means of endocytosis (which is a different pathway from channel proteins through which cancer cells expel drugs) can get into cells and hence, can avoid the defense mechanisms of cancer cells. When inside the cells, they liberate the drugs in the cytoplasm or nucleus in high concentrations to overwhelm the resistance pathways. There are some nanoparticles that can simultaneously delivdrugs and genetic materials such as siRNA to suppress the genes that are related to resistance and thus make the cancer cells more vulnerable to treatment.

Also, nanotechnology facilitates single-platform combination therapy which is quite challenging with conventional drug formulations. Polymeric nanoparticles may hold a variety of therapeutic agents like anticancer drugs, genes, immune response modulators, and photothermal agents thus, they may use the complementary mechanisms of action to eliminate cancer cells. This multi-functional way may generate synergistic effects leading to better overall treatment outcomes while each drug dose is decreased and toxicity returns to a low level. Such combined nanoplatforms mean a big step toward complete and personal cancer care.

Moreover, nanoparticles play a part in the lowering of systemic toxicity that is among major problems tied with chemotherapy. The reason is how nanocarriers concentrate their payloads at tumor sites and let loose the cargo in a controlled manner. Therefore, much lower drug doses get to healthy tissues. This may lessen significantly chemotherapy-related side effects of the kind hair loss, nausea, anemia, and organ damage, thus, the patient's quality of life during treatment improves considerably. The use of natural and biodegradable materials for making nanoparticles further ensures minimum risk to the patient since they are split into non-toxic residues after their therapeutic payload is delivered.

Another great advantage of nanotechnology is the possibility to merge therapy and diagnostics into one system, hence theranostics. For example, gold or magnetic nanoparticles can be used as both drug carriers and imaging agents, thus they enable real-time monitoring of drug distribution and treatment response through MRI, CT, or optical imaging. Having this dual role, they help doctors to see the effectiveness of the treatment, make dose adjustments accordingly, and locate early signs of relapse. This personalized feedback circle, which is not doable with conventional chemotherapy, is a milestone in precision oncology.

At last, they provide the ground for precision medicine by offering adjustment possibilities for nanoparticles. Examples of modifications include dimensions, forms, surface chemistries, and targeting ligands. Hence, they could be created to be perfectly compatible with the distinct features of an individual's tumor. This capability to customize the treatment according to the unique biological profiles of patients leads to far more precise, potent and patient-tailored therapies in cancer.

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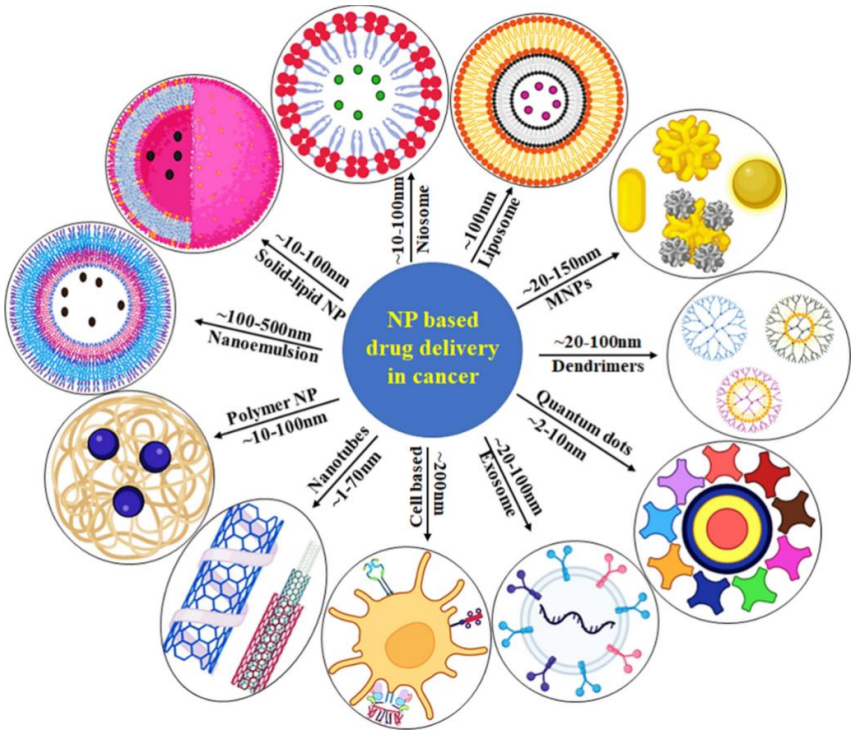

Fig- An updated landscape on nanotechnology-based drug delivery, immunotherapy, vaccinations, imaging, and biomarker detections for cancers

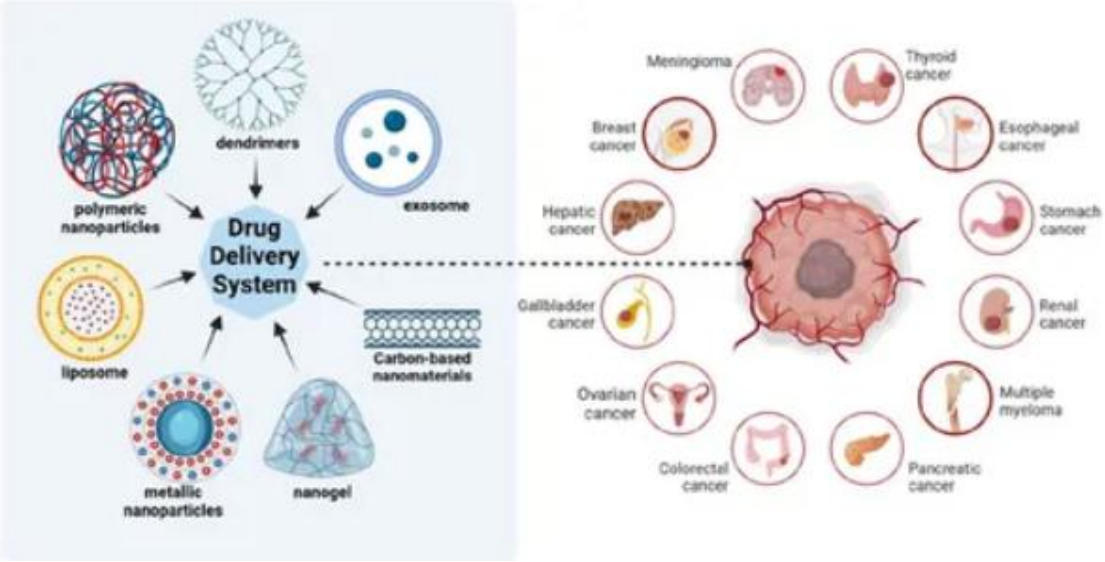

Fig- Harnessing nanotechnology for cancer treatment

II. DISCUSSION

Nanotechnology-based drug delivery systems have rapidly evolved, these changes have significantly reshaped the cancer therapy landscape, which in turn is now able to provide innovative solutions for many limitations of

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conventional treatments. With the field continually evolving, it is becoming more evident that nanocarriers do not merely enhance drug delivery but actually alter the way clinicians rethink cancer therapy. The assortment of nanomaterials—from polymeric nanoparticles, lipid-based carriers, inorganic systems to biomimetic platforms—reflects the different scientific disciplines that have come together to develop multifunctional drug delivery means. Although these are able to achieve great advances in therapeutic specificity, drug stability, and controlled release, they also bring to light the difficulties of clinical application of nanoscale innovations.

The central idea that can be drawn from the research of narrate is the significance of targeting precision. For a long time, the enhanced permeability and retention effect has been regarded as the main reason for nanoparticle accumulation in tumors, however, current research has shown that EPR only cannot guarantee tumor targeting that is both consistent and effective in all kinds of cancers. This understanding has led to the adoption of active targeting strategies utilizing ligands which attach to the receptors that are overexpressed on the surface of cancer cells. Nevertheless, the effectiveness of active targeting in receptor-mediated cellular uptake can be affected by factors such as low receptor expression and tumor heterogeneity. This emphasizes the need for a comprehensive understanding of tumor biology in order to come up with the design of the nanocarrier which is the next generation and can be biologically adaptive.

III. CONCLUSION

Nanotechnology-based drug delivery systems have essentially turned around the cancer therapy game by allowing precise targeting, controlled drug release, and lessening of side effects in comparison to the conventional treatments. Improvements in polymeric, lipid-based, inorganic, and biomimetic nanoparticles have made it possible to create intelligent, multifunctional platforms that not only combine therapy with diagnostics but also provide a way towards personalized medicine.

Although there are still issues like tumor heterogeneity, biological barriers, and difficulties in large-scale production, the research that is being done now, is helping to overcome these challenges by continually refining these systems and thus, making them closer to be used as a routine in clinics. In general, nanomedicine is a great potential that can result in cancer treatments that are safer, more effective, and patient-centered within a short period of time.

IV. RESULTS

The most recent research on nanotechnology-based drug delivery has shown great advancements in efficacy and safety for cancer treatments. Polymeric nanoparticles have achieved enhanced tumor accumulation and prolonged drug release, thereby increasing the cytotoxicity of cancer cells and at the same time lowering the general toxicity. Lipid-based carriers, e.g., liposomes and solid lipid nanoparticles, have been instrumental in improving the solubility of poorly water-soluble drugs and enhancing bioavailability, with a few formulations already approved for clinical use. In addition, inorganic nanoparticles, e.g., gold and magnetic nanoparticles, have facilitated combined therapies such as photothermal and photodynamic treatments, as well as real-time imaging, thus revealing the potential of theranostic applications. Furthermore, biomimetic and cell membrane-coated nanoparticles have shown better immune evasion and targeted delivery, thus achieving a more profound tumor penetration and higher therapeutic efficiency than that of the conventional nanocarriers. Stimuli-responsive nanocarriers that release drugs in response to pH, redox conditions, enzymes, or external triggers were found across these studies to deliver drugs more specifically to tumors, thus reducing off-target effects. The use of combination therapy with nanocarriers for co-delivering chemotherapeutic drugs and genetic material has demonstrated a synergistic effect, thus effectively managing the problem of multidrug resistance in different tumor models. To sum up, the combined findings of the recent studies speak in favor of nanotechnology-based drug delivery systems which not only enhance drug stability, targeting, and therapeutic outcomes but also provide the versatility to create personalized and multifunctional cancer therapies.

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V. FUTURE SCOPE

The next-generation medicine using nanotechnology-based drug delivery systems for cancer treatment has a bright future and is packed with potential to create intelligent, personalized, and multifunctional therapies. The latest advances in material science and bioengineering are likely to result in the production of nanoparticles that are capable of responding even more accurately to tumor-specific signals, getting a deeper penetration into tissues, and releasing drugs in a very controlled way.

Moreover, the use of artificial intelligence and machine learning can facilitate the predictive modeling for personalized nanoparticle design, thus helping in the targeting and therapeutic efficiency optimization of individual patients. Nanoparticles may act as a target for treatment while at the same time imaging and monitoring, and this concept may become prevalent enabling the clinicians to check the response to therapy and change the treatment accordingly in real-time.

Furthermore, the invention of scalable, cost-efficient, and reproducible production methods will be indispensable for the transformation of the innovations in the laboratory into the routine practices in clinics. In essence, the continuous effort in research is turning nanomedicine into a major factor for safer, more efficient, and highly personalized cancer therapy in the nearest future.

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