BAGHDAD JOURNAL OF BIOCHEMISTRY AND APPLIED BIOLOGICAL SCIENCES
2025, VOL. 5, NO. 3, 162-180, e-ISSN: 2706-9915, p-ISSN: 2706-9907
https://doi.org/10.47419/bjbabs.v5i3.295

REVIEW ARTICLE

# Applications of Nanotechnology in Drug Delivery Systems

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## ABSTRACT

Nanotechnology offers a revolutionary approach to drug delivery systems, with nanoparticles playing a central role. These particles, typically sized between 1 and 100 nanometers, possess unique properties that enhance medication effectiveness and reduce side effects. This article explores the key applications of nanotechnology in drug delivery. The ability to deliver drugs directly to target sites is a significant advantage. Nanoparticles can be engineered to navigate biological barriers and reach specific cells or tissues, minimizing damage to healthy areas. This targeted approach is particularly valuable in cancer treatment, where it can significantly reduce the cytotoxicity of chemotherapeutic drugs. Nanotechnology improves the solubility and bioavailability of poorly soluble drugs. By encapsulating drugs within nanoparticles, their absorption and therapeutic effect are significantly enhanced.

**Keywords** Drug, Drug delivery, Healthcare, Nanoparticles, Nanotechnology

**Received** 26-03-2024
**Revised** 14-06-2024
**Accepted** 19-06-2024
**Published** 30-09-2024

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**DOI** https://doi.org/10.47419/bjbabs.v5i3.295

**Pages: 162-180**



## INTRODUCTION

The manipulation and production of materials and devices at the size of individual atoms or small groups of atoms is known as nanotechnology. The prefix ”nano” comes from the Greek word ”dwarf,” nano, which means billionths of a meter. Materials constructed at this scale frequently display unique chemical and physical properties because of quantum mechanical processes. Zinc oxide nanocrystals are used to make invisible sunscreens that block ultraviolet light, and silver nanocrystals are embedded in bandages to kill bacteria and prevent infection. Billions of microscopic ”nanowhiskers,” each measuring about 10 nanometers in length, have been molecularly hooked onto natural and synthetic fibers to impart stain resistance to clothing and other fabrics[1]. The field of nanotechnology is

extremely multidisciplinary, encompassing the study of physics, chemistry, biology, materials science, and all branches of engineering. Many people use the term ”nanotechnology” as shorthand to describe both the science and the technology of this new sector. Strictly speaking, nanoscience is the study of fundamental aspects of atomic and near-atomic scale physical, chemical, and biological phenomena. Within the restricted definition of nanotechnology, these qualities are deliberately altered to produce materials and functional systems with special powers[2]. Nanomedicine uses technologies at the nanoscale and nano-enabled techniques to prevent, diagnose, monitor and treat diseases. Nanotechnologies hold significant potential in medicine, enhancing imaging techniques, drug delivery systems, tissue engineering, implants, and pharmaceutical therapeutics, and advancing treatments for various diseases. Nanoparticle-based drug delivery systems have emerged as a promising approach in modern medicine. These systems utilize nanoparticles to deliver therapeutic agents with enhanced precision and efficacy[3,4]. Recent research highlights the significant advancements and potential applications of nanomedicines and nano-based drug delivery systems. Nanotechnology offers multiple benefits in treating chronic human diseases by enabling site-specific and target-oriented delivery of medications through engineering with specific surface properties, coatings, or functional groups that allow them to recognize and interact with target sites in the body. For example, surface modifications can be made to nanoparticles to facilitate binding to receptors or biomarkers present on the surface of target cells or tissues. Adjustments in nanostructures' size, shapes such as spherical nanoparticles, nanorings, nanorods, cubes, and surface properties can enhance the bioactivity of nanomaterials, while green nanoparticles are explored to reduce medication side effects. Various types of nanoparticles, including polymeric, lipid-based, inorganic, and metallic nanoparticles, are extensively studied for drug delivery purposes as shown in fig 1[5].

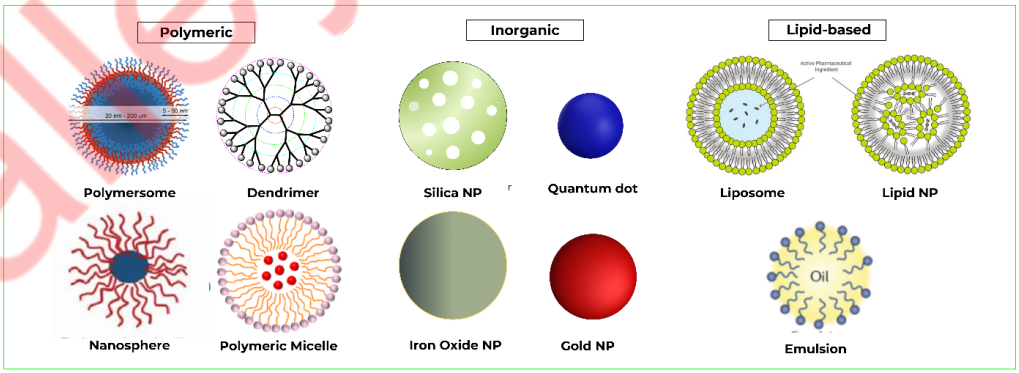


**Figure 1** Types of Nanoparticles[5].

These nanoparticles can improve drug bioavailability, solubility, and targeting, leading to enhanced therapeutic effects. The development of precision nanoparticles for drug delivery aims to overcome biological barriers and enhance therapeutic efficacy. By engineering nanoparticles in a more personalized manner, the field is moving towards precision medicine, tailoring drug delivery systems to individual patient needs[6–8]. The article aim

to explore the applications of nanotechnology in drug delivery systems and the study discusses how nanoparticles can be utilized to deliver drugs controllably to cure diseases. It highlights the importance of nanotechnological applications in drug delivery due to their high specificity, which can reduce the toxic side effects of drugs on normal cells.

## NANOPARTICLE IN DRUG DELIVERY SYSTEM

Nanomaterials are one of the most important materials used in very important processes for drug delivery at a specific site. Nanoparticles have the ability to eliminate tumor growth without causing any collateral damage by delivering them to the tumor site with high specificity. Therefore, nanoparticles have been of great help in the development of drug delivery system and it has experienced tremendous growth due the innovations currently recorded in the field[9]. Originally, they were created as vaccination and anticancer medication carriers.[10] Then, by altering drug biodistribution and toxicodynamics, nanoscale size ranges may greatly improve medication delivery. This can make in vivo distribution of a variety of medications with significant delivery of products a comparatively simple process[11]. Nanoparticles can effectively target and treat tumors while minimizing collateral damage through enhanced permeability and retention (EPR) effect. Nanoparticles can passively accumulate in solid tumors due to the leaky vasculature and poor lymphatic drainage in the tumor microenvironment. This allows nanoparticles to preferentially accumulate in tumors compared to healthy tissues. Nanoparticles can be surface-functionalized with targeting ligands like antibodies, peptides, or small molecules that bind to receptors overexpressed on tumor cells. This active targeting enhances tumor accumulation and cellular uptake of nanoparticles[12]. Also, through stimuli-responsive drug release, nanoparticles can be designed to release their cytotoxic cargo only in the tumor microenvironment in response to specific triggers like acidic pH, hypoxia, or enzymes. This minimizes systemic exposure and toxicity to healthy tissues. Nanoparticles can help overcome multidrug resistance mechanisms in tumors, such as drug efflux pumps and defective apoptotic pathways. This enhances the efficacy of chemotherapeutics[13].

Examples of nanoparticles used for tumor targeting include liposomes, polymeric nanoparticles, inorganic nanoparticles, and hybrid nanoparticles. These nanoparticles can encapsulate various therapeutic agents like chemotherapeutics, nucleic acids, and immunotherapeutics. Biological distribution refers to the in vivo fate and biodistribution of nanoparticles, which is influenced by factors like size, surface properties, and targeting ligands. Dynamic distribution involves the changes in nanoparticle distribution over time in response to biological stimuli. The biological and dynamic distribution of nanoparticles is crucial for optimizing their tumor targeting and therapeutic efficacy[14].

## TYPES OF NANOPARTICLE DRUG DELIVERY SYSTEM

### Inorganic Nanoparticle

Nanoparticles are used for several purposes in the field of biomedicine. Nanoparticles with unique features, such as silica nanoparticles, quantum dots metal nanoparticles, and lanthanide nanoparticles, can be used for a variety of bio-analysis applications. Metal nanoparticles such as quantum dots and lanthanide nanoparticles have distinct features that may be used in a variety of bio-analysis applications and apoptosis as shown in fig 2. A nanoparticle is important not only for indicating medication distribution, but also for confirming target delivery. Nanomedicine must be tracked from the systemic to the subcellular level.

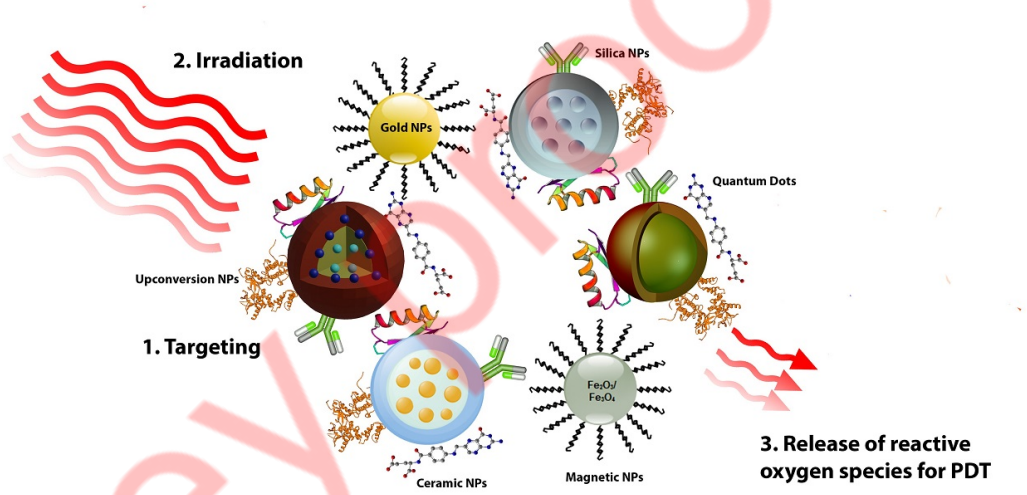


**Figure 2** Nanoparticles mechanism for applied active targeted cancer[15].

There are many fluorescent markers available; however, nanoparticles offer the benefit of improving fluorescent markers not only for medical imaging and diagnostic applications, but also for in vivo imaging of cancers and other disorders[16]. As example, generated $Fe_3O_4$ nanocrystals on uniform dye doped mesoporous silica nanoparticles to be employed as a contrast agent in magnetic resonance imaging with doxorubicin loaded in the pores. This device has a lot of potential as magnetic resonance and fluorescence imaging probes, and doxorubicin was successfully administered to tumor locations while maintaining its anticancer effectiveness.

Histidine is found in magnetic silica nanoparticles coated with cyan protein which are used in drug delivery systems and fluorescence imaging or as drug carriers and are also widely used in biological research[16]. Iron oxide and gold nanoparticles are the most widely used among the nanoparticles[17]. Gold, copper, and silver nanoparticles are characterized

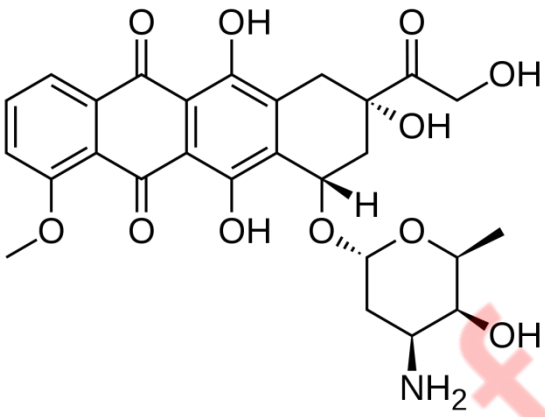


**Figure 3** Structure of doxorubicin[16].

by the presence of surface plasmons, so they absorb light in the visible region, allowing the analysis of size-dependent light absorption using surface plasmon resonance (SPR). Many unique features of gold nanoparticles and nanorods have been investigated for possible applications in biomolecular detection[15]. Gold nanoparticles, as approved by the FDA, offer specific benefits over other metallic particles in terms of biocompatibility and their ability not to cause cell damage might potentially be used as a preferred carrier for drug administration. Amino acids and proteins can be coupled using these nanoparticles[18]. More significant is the fabrication of gold nanoparticles and their functionalization with organic molecules in order to interact with any physiological system. Gold nanoparticles can be synthesized using various methods, including chemical reduction, photochemical methods, and green synthesis approaches. One common method involves the reduction of gold ions in the presence of a stabilizing agent, such as citrate or sodium borohydride, leading to the formation of colloidal gold nanoparticles. These nanoparticles typically range in size from a few to hundreds of nanometers in diameter and exhibit unique optical, electronic, and surface properties due to their small size and high surface area-to-volume ratio. After synthesis, gold nanoparticles can be functionalized or coated with organic molecules, such as ligands, polymers, peptides, or antibodies, to impart specific properties or functionalities. These functionalized nanoparticles are a viable drug delivery option as well as indicators for treatment resistance in cancer cells[19].

## Polymeric Nanoparticle

Biocompatible and biodegradable materials, as well as a range of natural (gelatin, albumin) and synthetic polymers, are used for the production polymeric nanoparticle (polylactides, polyalkylcyanoacrylates[20]. Metals and semiconductor nanoparticles depend mainly on polymers as a host material. These nanoparticles are used as drug carriers, delivering active compounds to their designated targets[21]. In nano-composites, polymers are filled with distributed nano-fillers (less than 100 nm). The drug's adsorption capability is affected

by polymer hydrophobicity, nanoparticle area, and monomer concentration[22]. Drugs can be introduced to the polymerization process and entrapped inside the nanoparticle polymer network. Polymers such as albumin and liposomes can all be used to make nano capsules[23]. There are several polymers that can be used to make nanoparticles. Synthetic polymers include polylactide–polyglycolide copolymers, polyacrylates, and polycaprolactones, among others, whereas natural polymers include albumin, gelatin, alginate, collagen, and chitosan[24]. Polylactides and poly (DL-lactide-co-glycolide) polymers are largely researched for drug delivery because of their ability to undergo hydrolysis upon implantation and create biologically suitable fragments[25]. It is obvious that chemical conjugation of medicines with different polymers affords potential to boost their activity. Amphiphilic N-(2-hydroxy)-propyl-3-trimethylammonium- chitosancholic acid polymers can be created by covalently attaching cholic acid and glycidyl trimethyl ammonium chloride to chitosan, which then self-assembled into nanoparticles in phosphate-buffered saline. Doxorubicin might be coupled in these nanoparticles, which would then be easily up taken and released into the cytoplasm by breast cancer (MCF-7) cells[26].

## Nanocomposites

Nanocomposites (NC) are multiphase materials with nanoscale additions in one of the phases. The merging of each component gives rise to the unexpected features of nanocomposites. They can be classified into three types based on their matrix, they include; ceramic matrix nanocomposite CMNC, polymer matrix nanocomposites PMNC and metal matrix nanocomposites MMNC. In comparison to pure or traditional composite materials, NC have gained attention in recent years due to their excellent thermal, mechanical, fire-retardant, and solvent resistance properties[27]. It is well recognized that the particle size and its distribution, surface characteristics, geometric shape, dispersion state all can have a significant impact on the properties of composite. As a result of the current commercial availability of nanoparticles, polymer nanocomposites are becoming more popular. Mechanical properties such as modulus and strength, water, gases, and hydrocarbon permeability, dimensional, thermal stability, chemical resistance, flame retardancy, and optical properties, dielectric, magnetic, electrical properties are all significantly improved in these composites[28]. In terms of mechanical, thermal, electrical, and barrier properties, nanocomposites have an edge over conventional composites. They can also greatly reduce flammability while maintaining the polymer matrix's transparency. These attractive properties are one of the reasons for their application for industrial uses.

## Lipid Based Nanoparticle

Nanoparticles such as liposomes, solid lipidnanoparticles (SLNs), and nanostructured lipid carriers (NLCs) have demonstrated tremendous clinical success in delivering both hydrophobic and hydrophilic therapeutics[29]. The first FDA-approved nanodrug, Doxil, is a doxorubicin (DOX)- loaded PEGylated liposome for treating breast cancer, ovarian can-

cer, and other solid tumors. The loaded PEGylated means that liposomes are encapsulated with doxorubicin and surface-modified with PEG chains[30]. Compared to free DOX, the PEGylated liposomal doxorubicin Doxil has a lot of benefits including reduction of cardiotoxicity, prolonged retention time in human plasma, and passively targeted delivery to tumors by taking advantage of the enhanced permeability and retention (EPR) effect[31] The clinical approval of Doxil in 1995 represents a big milestone for cancer nanomedicine and lipid-based drug delivery systems. On the other hand, lipid nanoparticles (LNPs) have also been recognized as an ideal carrier for nucleic acids like DNA, mRNA, and siRNA due to their outstanding biocompatibility, biodegradability, and entrapment efficiency. ONPATTRO (Patisiran) is the first approved double-stranded small interfering RNA delivering LNP[32]. Actually, LNPs containing cationic lipids or pH responsive lipids have been employed for nucleic acids encapsulation and delivery since 1980s. However, cationic lipids cause undesirable toxicity. In contrast, ionizable cationic lipids, having positive charges at lower pH (pH< 6.0) but neutral at physiological pH, are favorable for formulating LNP systems. siRNA is entrapped inside LNPs consisting of ionizable cationic lipids (DLin-MC3-DMA), phospholipid (1,2-Distearoyl-sn-glycero-3 phosphocholine [DSPC]), cholesterol, and polyethylene glycol-modified lipids (PEG2000-CDMG). During systematic circulation, the PEG2000-C-DMG coating is replaced by Apolipoprotein E (Apo E) recruited by cholesterol, which directs them to the liver and then be endocytosed by hepatocytes[33]. Upon entering the endosome, DLin-MC3-DMA in the LNPs becomes positively charged because of the acidic endosome condition disrupting the endosomal membranes, thus releasing the RNA cargo into the cytoplasm to achieve its function[34]. More recently mRNA COVID-19 vaccines developed by BioNTech/Pfizer and Moderna have been issued emergency use authorizations, and both of them use LNPs as mRNA carriers. The LNP not only protects mRNA from degradation, but also enables their uptake by host cells and delivery of mRNA inside transparency the cytosol, where the mRNA sequence is translated into the Spike protein. The continuous success of these LNPs for various disease treatments has demonstrated their enormous potential as the next-generation drug delivery systems[35].

## APPLICATIONS OF NANOTECHNOLOGY IN DRUG

## TARGETED DRUG DELIVERY FOR CANCER THERAPY

Targeted drug delivery for cancer therapy involves the selective delivery of therapeutic agents to tumor cells while minimizing exposure to healthy tissues. One of the ways to improve the survival rate of cancer patients is the targeted delivery of anticancer drugs. Advances in biomedical science and biotechnology have led to the discovery and development of effective drug carriers such as liposomes, dendrimers, and gold and magnetic nanoparticles[36]. This approach aims to enhance the efficacy of chemotherapy while reducing systemic toxicity and side effects. Targeted delivery strategies can precisely and effectively deliver most drugs to tumor cells or tissues instead of normal cells or tissues[37].Such delivery strategies can be achieved using nanotechnology. Typically, nanoparticle-based

drug delivery has attracted increasing attention because nanoparticles can accumulate at tumor sites through the EPR effect[38].

## Nanoparticle-based delivery systems

Nanoparticles, such as liposomes, polymeric nanoparticles, and inorganic nanoparticles, can be engineered to encapsulate chemotherapy drugs. These nanoparticles can passively accumulate in tumors through the enhanced permeability and retention (EPR) effect, which occurs due to leaky blood vessels and poor lymphatic drainage in tumors. Additionally, nanoparticles can be functionalized with targeting ligands (e.g., antibodies, peptides) to actively target specific tumor markers, further enhancing specificity and efficacy. Liposomes are round vesicles comprising of one or more lipid bilayers. A liposome incorporates an empty structure that is usually filled with a dissolvable and can convey an assortment of substances. Its hydrophobic film permits it to combine with cell layers and transport its substance inside cells. Liposomes are most regularly composed of phospholipids and cholesterol, but may also incorporate other lipids to improve endocytosis and tissue compatibility. Liposomes, as a well-established medicate vesicle, have been broadly utilized in drug delivery. Consequently, lipids can be wrapped on the surface of Nano drugs[39]. The biophysical properties of lipid films play a noteworthy impact on drug delivery. Besides, the various properties such as lipid structural domain formation, mobility, multivalent binding, leakage, and fusion, are all used for drug delivery. Also, polymers are macromolecules comprising of numerous repeating units called monomers. Homopolymers are shaped from indistinguishable monomer units, and copolymers are composed of two or more distinctive monomer units, regularly in a characterized arrangement, configuration, and structure. Polymers are chemically adaptable atomic stages in their measure and structure[40]. Peptides can be designed to specifically target receptors or biomarkers on cancer cells. Peptide ligands can be conjugated to drug carriers or nanoparticles to enable targeted delivery to tumors. Additionally, cell-penetrating peptides (CPPs) can facilitate intracellular delivery of drugs, bypassing cellular barriers and improving therapeutic efficacy. Such as peptide-based targeted nanoparticles. Peptides are formed through the condensation of amino acids through amide bonds. The diversity of amino acids and the multiple arrangements of amino acid sequences give rise to a large number of peptides with a wide range of biological functions. Most peptides are part of protein structure that are hydrolyzed from proteins into peptides and still maintain the properties of proteins[41]. These give peptides good biocompatibility and potential for biodegradability, as well as chemical modifiability.

## Nanomedicines for intracellular targeting

Nanomedicines, such as polymeric micelles and dendrimers, can be designed to deliver drugs directly to intracellular targets involved in cancer progression. These Nano carriers can penetrate cellular membranes and release their cargo inside cancer cells, allowing for targeted inhibition of specific signaling pathways or molecular targets. Micelles

are known for their hydrophilic surface and hydrophobic core; these tens of nanometer-sized particles are frequently employed as carriers of hydrophobic medications. They can enter the bloodstream through the skin or respiratory tract just like liposomes do. The use of amphiphilic block copolymers, which spontaneously form micellar structures, in the administration of cytostatic medicines, has garnered significant attention in recent years[42]. Amphiphilic block copolymers are usually assembled from two or three blocks, with PEG being the most common hydrophilic block in the copolymer structure. Other hydrophilic block-forming polymers include chitosan, polyvinylpyrrolidone, and poly (N-isopropyl acrylamide). Furthermore, dendrimers are three-dimensional, highly branching, and monomolecular; monodisperse macromolecules with rotational symmetry that frequently adopt a spherical form, such as poly (propylene imine), (PPI), poly (L-lysine) (PPL) and triazene-based dendrinemers. In general, dendrimers have a hydrophobic core from which they branch, ending in terminal functional groups responsible for their solubility in water[43]. These dendrimers can retain hydrophobic drugs and increase their concentration in water. Biocompatibility, easy excretion from the body, and a significantly improved EPR effect are the most remarkable advantages of dendrimers. Nevertheless, one major disadvantage of dendrimers is that, because of the physiological stability of cationic groups on their surfaces, they are harmful to normal cells. Dendrimer cytotoxicity is typically resolved by using biocompatible polymers, such PEG, to change the surface of the particles.[44–47].

## Inorganic nanoparticles and drug delivery systems

Nanoparticles made of materials like gold, silica, or iron oxide can be functionalized with targeting ligands and loaded with drugs for targeted delivery to tumors. Smart based systems are designed to respond to specific stimuli present in the tumor microenvironment, such as pH, temperature, or enzymatic activity such as calcium phospahte. They can release drugs in a controlled manner, improving drug accumulation and retention in tumors. Metal oxide nanoparticles have attracted much attention because of their unique physical properties. Their widespread applications span across optics, electronics, drug delivery, and biomedical imaging, which reflect their versatility and potential for various cutting-edge technologies[48]. Calcium phosphate (CaP)-based nanoparticles are crystalline formations of predominantly carbonate apatite capable of transporting a drug both on their surface and within their structure[49]. Minerals based on CaPs are the main inorganic components of the bones and teeth of vertebrates and humans. CaP-based nanoparticles have several peculiar properties that make them attractive for delivering anticancer drugs. CaPs are fully biodegradable, release non-toxic calcium and phosphate ions upon degradation, and decompose faster than other inorganic nanoparticles (zeolites, mesoporous silica particles, carbon nanoparticles, and quantum dots). Moreover, CaP-based nanoparticles have pH-sensitive solubility; they are insoluble at the physiological pH of 7.4 blood plasma but quickly dissolve in acidic biological media (pH < 5), for example, in endosomes and lysosomes, where they rapidly release encapsulated substances[50].

## ENHANCED BIOAVAILABILITY AND CONTROLLED RELEASE OF DRUGS

Bioavailability is a major fraction of administered drug absorbed into the systemic circulation. Drugs with high hepatic metabolism and faster excretion have low bioavailability. The therapeutic dose is present at the target set and results in low efficacy. Furthermore for low bioavailable drugs, high dosage is needed[51]. The focus of control release of drug is to minimize the frequency of drug administration with the aim of achieving the required therapeutic concentration for a specific time. It is therefore necessary to develop a release system in which the rate of maintenance dose is equal to the rate of drug output[52]. According to a research by[53] oral administering of drugs is the most widely used approach in the clinical treatment of various diseases. Originally before the absorption of an administered drug into the bloodstream, it must first be dissolved, changing its form and then finally penetrating into the bloodstream.

However, most drugs have very poor water solubility and limited absorption capacity, thereby resulting to poor oral bioavailability. The low aqueous solubility of many active ingredients can be enhanced by solid dispersion, salt formation, pH adjustment and the use of nanotechnology in drug delivery. The new technologies associated with drug delivery are delivery of poorly water-soluble drugs, longer and non-invasive technology, delivering protein /nucleic acid to targeted site using nano particles[54]. Nanocarriers are micro-sized particles with a large specific surface area due to which they offer improved bioavailability of the drug where and when needed. This nano particles offer efficient navigation in the environment protecting it from untimely degradation. Flexibility is the major focus for Nanocarriers in drug administration. In essence, Intra cellular release of drug can be achieved with Nanocarriers. These Nanocarriers have the ability to increase the concentration of the tissue without causing toxicity to the cell. According to[55] nano particles are used to deliver drug to the needed site where penetration and passage is difficult as a result of their anatomical barriers. Furthermore, Nanocarriers are best for drug delivery as they can break through barriers by trans cellular and paracellular pathways. Inorganic nano particle have also been widely studied because of their drug delivery potential as a result of their unique properties. They have the ability to encapsulate drugs and allows for control release of the drug, improving their therapeutic performance and reducing its side effect without causing any toxicity itself[56].

## 3 THERANOSTIC NANOPARTICLES FOR SIMULTANEOUS IMAGING AND THERAPY

Nanoparticles with the ability to perform imaging, diagnostics, and therapy concurrently are gaining popularity in cancer theranostics[57]. Theranostic nanoparticles have emerged as a promising approach for simultaneous imaging and therapy in cancer treatment. These nanoparticles integrate diagnostic and therapeutic functions, offering a multifaceted strat-

egy for precision medicine[58]. The development of theranostic nanoagents has been at the forefront of research, aiming to provide cost-effective solutions that combine therapy and diagnosis[59]. Theranostics Nanoparticles (TNPs) provide chances to integrate both passive and active targeting, environmentally-triggered drug delivery, molecular imaging, and additional therapeutic capabilities into a single platform[60]. Optimal theranostic nanoparticles should swiftly and selectively accumulate in targeted areas, accurately report biochemical and morphological disease features, effectively administer required drug dosages without harming healthy tissues, undergo rapid clearance from the body within hours, biodegrade into non-toxic byproducts, and demonstrate safety for human use[61].[62] reported that many theranostic nanoparticles, spanning both organic and inorganic varieties, have been developed for cancer treatment over the past decade. However, it is noteworthy that none of these nanoparticles have successfully met all the aforementioned criteria.

Theranostic nanoparticles can bring about a significant change in disease management. In recent years, there has been a surge of interest in developing different types of theranostic nanoparticles that can be used for both cancer imaging and therapy. To ensure accurate diagnosis and effective treatment, it is crucial to target these nanoparticles to the tumor site efficiently. One approach to achieve this is by injecting therapeutic agents onto existing imaging nanoparticles such as quantum dots, iron oxide nanoparticles (IONPs), and gold nanocages, utilizing their inherent properties for targeted drug delivery. Another approach is to tag imaging contrast agents onto therapeutic nanoparticles, enhancing their imaging capabilities and facilitating precise visualization of biodistribution. Encapsulating imaging and therapeutic agents within biocompatible nanoplatforms such as polymeric nanoparticles and ferritin nanocages provide controlled release kinetics and prolonged circulation times, optimizing therapeutic efficacy[63].[64] reported that various imaging probes, including nuclear imaging agents, MRI contrast agents (T1 and T2 agents), and fluorescent markers like inorganic quantum dots and organic dyes, can be attached to therapeutic delivery vehicles or agents to enable imaging. This imaging can provide valuable information about the delivery kinetics, trafficking pathway, and therapeutic efficacy of the agents.

The efficacy of Peptide-functionalized silicon nanoparticles (SiNPs-RGD) in labeling angiogenic blood vessels and suppressing neovascularization in mouse corneas highlights its potential as a novel theranostic agent for the simultaneous diagnosis and treatment of ocular neovascular diseases. SiNPs-RGD, which exhibit minimal toxicity and strong binding affinity to human retinal microvascular endothelial cells, demonstrate potent anti-angiogenic properties in various assays[65]. The study underscores the importance of exploring innovative strategies in advancing the multifunctional biomedical applications of nanotechnology[66] introduced a novel polyvalent theranostic nanocarrier, SPIONs@FA-PAMAM-CDF, capable of high MR contrast and enhanced anticancer activity, achieved by loading superparamagnetic iron oxide nanoparticles (SPIONs) with folic acid-poly amidoamine dendrimers (FA-PAMAM) decorated with 3,4-difluoro benzylidene-curcumin (CDF), showing potential for simultaneous imaging and therapy in folate receptor overexpressing cancers. There has been significant interest in developing theranostic

nanoparticles for targeted imaging and therapy in various diseases, including cancer. Another example is DHP, a novel theranostic nanoparticle responsive to glutathione (GSH), designed for dual-modal imaging and combination therapy. DHP comprises disulfide-bond-linked hydroxyethyl starch paclitaxel conjugate (HES-SS-PTX) and a near-infrared (NIR) cyanine fluorophore DiR, synthesized via a simple one-step dialysis method. Remarkably, DHP serves as an in vivo fluorescent and photoacoustic imaging probe while also demonstrating potent antitumor effects through chemo-photothermal combination therapy[67].

Mesoporous silica nanoparticles (MSNs) armed with aptamers (Aps) has also been reported as effective targeted drug delivery systems (DDSs) for cancer therapy. When decorated with Aps, it has proven to target specific sites actively, minimizing off-target effects and maximizing therapeutic efficacy with lower drug doses. The advancement of Aptamer-conjugated mesoporous silica nanoparticles (MSNs) for cancer treatment and imaging faces key challenges that require further research and innovation. These include improving the stability of aptamers as targeting agents, addressing safety concerns related to MSNs' physical properties, overcoming the slow biodegradability of inorganic materials in MSNs, and developing targeted gene delivery systems with precise control over drug release[68]. Furthermore, theranostic nanoparticles have been explored to enhance the therapeutic response of image-guided radiation therapy for oral cancer. Incorporating X-ray and MR contrast-bearing nanoparticles can improve radiation beam therapy's sensitivity and imaging quality, leading to enhanced efficacy of solid tumor radiation therapy[69]. However, despite their considerable potential, challenges remain in bringing these nanomedicines into clinical practice. Production complexity and safety issues must be addressed to advance their application in further diagnosis and treatment[70]. Nevertheless, the promise of theranostic nanomedicines lies in their ability to offer simultaneous noninvasive diagnosis and treatment of diseases, making them a valuable tool in personalized medicine[71].

## 4 APPLICATIONS IN PERSONALIZED MEDICINE AND PRECISION THERAPEUTICS

Personalized therapeutics, also known as precision therapeutics, is an emerging trend in healthcare, particularly in cancer treatment, that holds great promise in improving patient outcomes before, during, and after disease. These nanoparticles offer a dual functionality of diagnosis and therapy within a single platform, making them valuable tools in tailoring treatments to individual patients. By combining therapeutic operations with personalized theranostic nanostructures, personalized medicine can be significantly advanced, providing new advantages in treatment approaches. Theranostic nanolights, such as Aggregation-Induced Emission (AIE) dots, have shown great potential in increasing treatment efficacy while minimizing damage to healthy tissues. These nanolights employ localized photons to activate imaging and therapeutic functions, including photodynamic or photothermal therapy, offering a noninvasive approach to nanomedicine. Additionally, aggregation-enhanced

theranostic systems have been developed to meet the demands of personalized and precision medicine by enabling simultaneous diagnostic imaging and phototherapy interventions[72].

Nanostructures like quantum dots, iron oxide nanoparticles (IONPs), carbon nanotubes (CNTs), and gold/silica nanoparticles possess distinct surface properties that can be finely adjusted according to needs. This enables them to execute specific actions upon reaching their intended destination, enhancing and advancing personalized medicine[73]. Recent research has highlighted the potential of theranostic nanoparticles for cancer nanomedicine, as they offer a multifunctional platform that integrates both diagnostic and therapeutic functions, providing opportunities for precision medicine[74]. Unlike conventional therapies that target anatomical origins, precision medicine targets specific oncogenes responsible for driving cancer progression. A novel strategy called microRNA replacement therapy utilizes nanocarriers to regulate these oncogenes, representing a significant advancement in cancer precision therapeutics. Furthermore, nano-mediated oncogenic regulation's effectiveness is evaluated using genetically characterized patient-derived xenograft models[75]. Personalized theranostic medicine has been shown to have a higher success rate than conventional medicine systems. The unique properties of theranostic-based medicine allow for a more comprehensive understanding of the patient's health status and real-time response to therapeutic interventions, leading to better treatment outcomes[76].

## Conclusion

Nanoparticle-based drug delivery systems have shown significant advancements in recent years, enhancing the efficacy of drug formulations and reducing side effects. The nanoparticle size, surface characteristics, and material composition have enabled the development of smart systems that can encapsulate therapeutic agents, provide controlled release therapy, and target specific tissues. Moreover, the use of nanotechnology in drug delivery systems has led to improved bioavailability, enhanced solubility, and the ability to cross biological barriers like the blood-brain barrier. These advancements have paved the way for more effective drug delivery methods, reduced toxicity, and increased patient compliance. The article underscores nanoparticle in drug delivery system, targeted drug delivery for cancer therapy, enhanced bioavailability and controlled release of drugs and theranostic nanoparticles for simultaneous imaging and therapy. The continuous development and refinement of nano-based drug delivery systems hold great promise for the future of medicine, offering innovative solutions to improve treatment outcomes and patient well-being.

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