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NANOTECHNOLOGY: A REVOLUTIONARY APPROACH IN DRUG DELIVERY SYSTEMS

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ABSTRACT

Nanotechnology, often referred to as *nanomedicine* in the healthcare context, is among the most prevalent and commercially developed technologies aimed at improving the standards of modern healthcare. Despite certain limitations, many pharmaceutical and medical device companies have already adopted medical nanotechnology in their products. In particular, nanotechnology enables the targeted delivery of drugs with enhanced safety profiles, such as chemotherapeutic agents used in cancer treatment, which traditionally carry a high risk of toxicity. It is important to note that living cells can be viewed as tiny molecular machines responsible for a multitude of biological processes, including cell signaling, metabolism, energy generation, and nutrient transport. Consequently, nanotechnology is regarded as a highly promising tool for therapeutic applications in biology and medicine. In this review, we discuss the significance of nanoscience and the various nanotechnology platforms currently being utilized in multiple areas of medicine. Additionally, we address future opportunities for the application of nanotechnology in improving human health. Over the past four decades, nanotechnology has advanced at a remarkable pace and continues to evolve without signs of slowing down.The application of nanotechnological innovations has revolutionized many aspects of daily life—from medical and pharmaceutical uses to their impact on the food industry. The effectiveness of certain treatments, such as anticancer therapies, has been improved, the intracellular delivery of hydrophobic drugs has been enhanced, and the shelf life of food products has been significantly extended through the use of nanoparticles. As a result, nanotechnology has profoundly influenced both the global economy and the overall quality of life worldwide. This review highlights the physicochemical characteristics of nanoparticles that contribute to their desirable as well as potentially toxic biological effects. Furthermore, it explores their applications across different biological fields, focusing on nanoparticle-based drugs and delivery systems in biomedicine, including nano-based therapeutics currently approved by the U.S. Food and Drug Administration [FDA]. The possible consequences of continuous exposure to nanoparticles resulting from the increased use of nanotechnology, along with potential mitigation strategies, are also discussed.

KEYWORDS: Nanotechnology, Nanoparticles, Drug Delivery Systems.

1. INTRODUCTION

A drug is a chemical substance that can cause changes in the cells, tissues, organs, or the whole body.[1] Some drugs can also kill harmful germs such as bacteria, viruses, or fungi.[2] The part of the drug that actually causes the effect in the body is called the active ingredient.[3] A drug also contains inactive ingredients, which are called excipients.[4] These have no effect on the body but are used to help make the drug—for example, as fillers, binders, or lubricants.[5] Most drugs work by attaching to specific parts of cells, such as receptors or enzymes, to block or change their activity.[6] For a drug to work well, it should stay active inside the body and only act on its target without affecting other parts of the body.[7]

In the past, most drugs were made from plants or other natural sources. Today, many drugs are made artificially in laboratories.[8] Drugs help treat many diseases and have greatly improved human health by protecting us from infections and epidemics.[9] However, modern drugs still face problems such as low effectiveness, poor absorption**,** toxicity**,** side effects, and biocompatibility issues**,** which can make them less useful or safe.[10] In recent years, nanomaterials—very tiny engineered particles—have been used to solve many of these problems.[11] In this review, we discuss how nanomaterials are used in drug delivery systems and how nanoparticles behave inside the body when combined with drugs.[12]

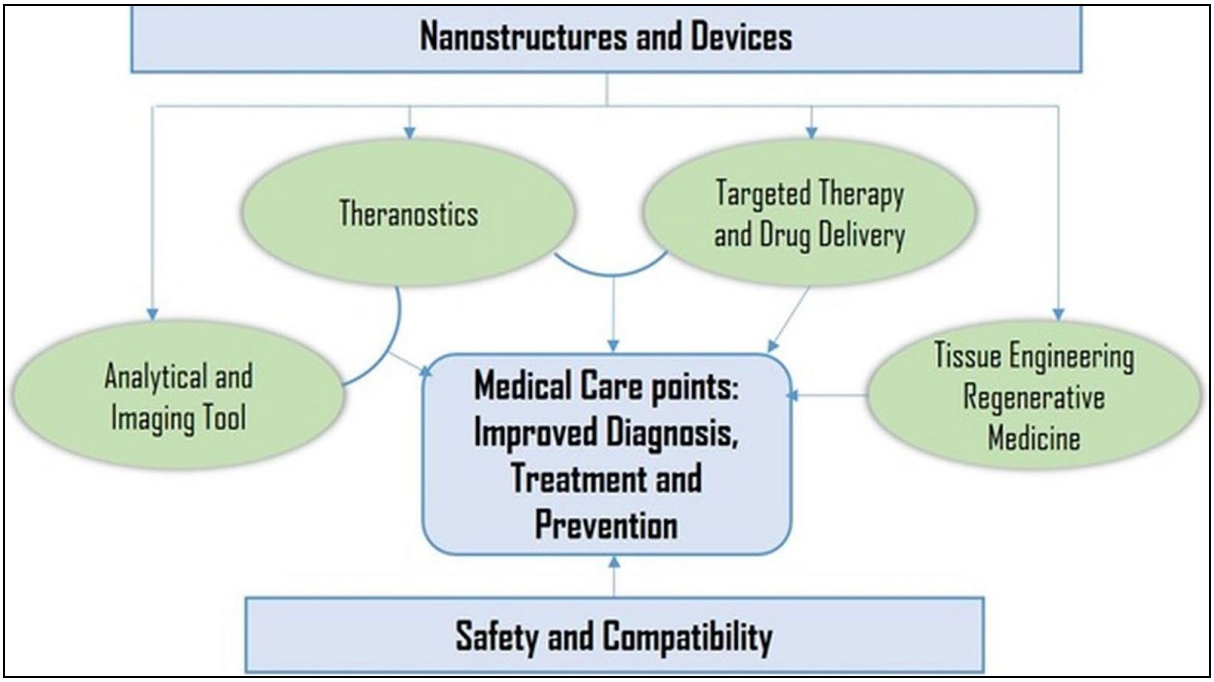

Fig. 1: Application and Goals of Nanomedicine in Different Sphere of Biomedical Research.

2. DRUG DEVLOPMENT AND DRUG DILIVERY

In traditional drug development and delivery, medicines are usually taken by mouth or injected into the bloodstream. After entering the body, the blood helps to carry the drug to different organs.[13] However, only a small amount of the active ingredient actually reaches the part of the body where it is needed. Sometimes, the drug also affects other organs that are not the target, which can cause unwanted side effects.[14] Developing new drugs is also a long, difficult, and expensive process for pharmaceutical companies.[15]

One major problem in drug development is that many drugs do not dissolve easily in water. When a drug has low solubility, the body cannot absorb it properly, which reduces its effectiveness.[15,16] Another problem is low bioavailability, which means only a small amount of the drug enters the bloodstream. Drugs given through injections go directly into the blood and have full bioavailability, but drugs taken by mouth are partly lost during digestion, so less of the drug is available to work.[13,14]

Sometimes, drugs also have low efficacy, meaning they do not produce a strong enough effect. For a drug to work well, it needs to attach tightly to its target in the body, such as a specific cell or enzyme. If it does not bind well, the treatment becomes less effective and may take longer to work. Another issue is fast excretion. When the body removes a drug too quickly through the kidneys, there is not enough time for it to reach the target organ and have the desired effect.[13]

In some diseases like cancer, it is important for the drug to build up in certain areas, such as tumor cells, in higher amounts than in normal cells.[18] However, many drugs do not stay in these target areas long enough or at the right concentration, which reduces their effectiveness in treatments like chemotherapy. All these challenges make drug development and delivery a complex process that scientists continue to work on improving.[15,16,18]

3. DRUG DESIGNING AND DRUG DELIVERY PROCESSAND MECHANISM

With the progress of nanomedicine and the development of drug design and delivery systems, many new treatment methods have been proposed, and traditional diagnostic methods have been improved to make drugs more specific and accurate.[19,20] Researchers are exploring new ways to give drugs so that they act only in targeted areas, reducing side effects and increasing how well the body absorbs them.[20,21] Drug design has become important for discovering new drugs based on biological targets, and advances in computer technology and lab methods for studying proteins and peptides have supported this development.[22] Natural products can also inspire new drugs with useful properties.[23]

Drug delivery systems have become increasingly important because they can control how drugs are released in the body.[24] Nanocarriers, for example, have unique chemical, physical, and structural features and can interact with drugs in different ways, affecting how the drugs are released.[25] The composition of nanocarriers and the way drugs are incorporated, such as in a core-shell or matrix system, also influence drug release.[25] Different mechanisms, like diffusion, chemical reactions, and stimuli-controlled release, can determine how the drug moves from the carrier to the body.[24,26] Researchers are also working to improve how nanocarriers target specific areas and reduce immune reactions using coatings or chemical modifications such as polymers, natural polysaccharides, antibodies, cell membranes, peptides, and surfactants.[25,27]

In cases where drugs cannot naturally reach their target or cross barriers like the blood-brain barrier, ligand-modified nanocarriers can help deliver drugs to the right place.[22,28] For example, hyaluronic acid has been used on nanocarriers to improve treatment against various cancer cells, help deliver drugs to the eye, and reduce immune reactions.[22,27,28] However, designing these systems is complex, and their interaction with cells and uptake mechanisms are 1still not fully understood.[29] Nanoparticles can enter cells through different pathways, but the exact processes can vary depending on their properties.[29]

Stimuli-responsive nanocarriers can release drugs in response to external factors like heat, light, ultrasound, magnetism, pH, or ionic strength, which helps improve targeting and dosage control.[27,30] Magnetic nanoparticles and polymeric or lipid carriers, as well as hybrid nanoparticles, have been developed for controlled release and combined therapy and imaging.[26,30] Hybrid nanocarriers combine different properties in one system, making them promising for both treatment and diagnosis.[27,31] Despite these advances, the exact mechanisms of action and potential toxicity of these systems are not fully known, which provides opportunities for further research.[31] Studies are also increasing on creating nanocarriers using environmentally friendly methods, such as plant extracts and natural materials.[32]

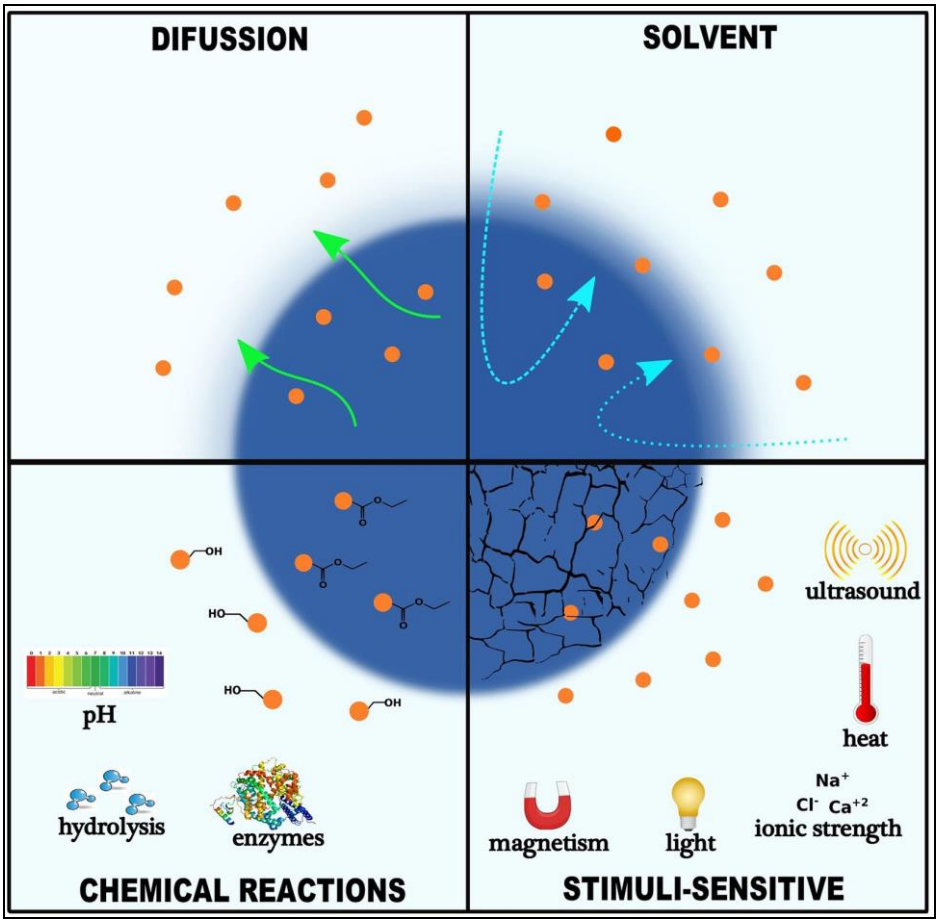

Fig. 2: Mechanisms for Controlled Release of Drugs Using Different Types of Nanocarriers.

4. DRUG DELIVERY SYSTEM [DDS]

To overcome the problems seen in traditional drug formulations—such as poor absorption, low bioavailability, and unwanted side effects—the concept of a drug delivery system [DDS**]** was introduced to make drug treatment more efficient and targeted.[44,45]

A drug delivery system refers to the design and method used to introduce a pharmaceutical compound into the body in a controlled way to safely achieve its desired therapeutic effect.[46] It involves combining the active drug with a carrier or formulation that helps deliver it effectively to the site of action while minimizing damage to healthy tissues.[44,48] In simple terms, a drug delivery system increases the concentration of medicine in the part of the body that needs it most, while keeping the levels lower in other areas to reduce side effects.[44,45,47] Such systems can also control how fast

or how long the drug is released in the body, which helps maintain a steady concentration of the medicine, reduces dosing frequency, and improves patient comfort and treatment outcomes.[44,47,48]

5. NANOTECNOLOGY IN DRUG DELIVERY SYSTEM

Nanotechnology is the science and technology of creating and using materials that are specially designed at a very small scale called the nanoscale.[33,34] It involves working with materials that are measured in nanometers.[34,35] The word “nano” comes from Greek and means “dwarf.” One nanometer is one-billionth of a meter, which is about the size of three atoms placed side by side.[34,35] Nanotechnology usually deals with materials smaller than one micron, or a few hundred nanometers in size.[34,35] Because it focuses on such small structures, nanotechnology connects with many fields of science such as chemistry, biology, physics, and engineering.[33,34,36]

Researchers use nanotechnology to develop new kinds of drug delivery systems called nano drug delivery system.[37,38] These systems are designed to carry drugs directly to the part of the body where they are needed.[37,38] The goal is to deliver a specific amount of medicine slowly and steadily to the diseased area, keeping the right level of the drug in the blood and tissues while avoiding harm to healthy parts of the body.[37,38,39]

Developing these systems requires teamwork among chemists, biologists, and engineers to make them as efficient as possible.[37,38]

Modern drug delivery research focuses on two main goals. The first is targeted delivery, which means making sure the drug only works in the area that needs treatment, such as cancer tissue.The second is sustained release, which allows the drug to be released slowly over time in a controlled way.[38,39,40] For targeted delivery to work well, the drug carrier must be able to avoid the body’s defense systems and reach the intended site of action. This helps concentrate the medicine where it is needed most.[37,38]

The main aim of a targeted drug delivery system is to keep the drug working for a longer time, focus it on the right area, and protect it from being destroyed or causing side effects. Unlike traditional delivery methods, where drugs are simply absorbed across cell membranes, targeted systems release drugs directly at the site of disease. This reduces how often a patient needs to take the medicine, keeps the drug’s effect more stable, and lowers the chance of side effects. Because of these advantages, targeted delivery is believed to make treatments more effective and safer.[38,39,40]

Scientists are now focusing on targeted drug delivery for chronic diseases such as diabetes, heart disease, and especially cancer.[38,39,40] These systems are designed based on the nature of the drug, its side effects, how it enters the body, and where it needs to act.[38,39] There is an optimal concentration range in which a drug works best—too much can be toxic, and too little may not help at all.[37,38] Because many drugs still have low bioavailability, researchers are working on new ways to make sure more of the drug reaches the target cells.[37,39]

This new approach combines different scientific areas, including molecular biology, polymer science, pharmacy, bio-conjugate chemistry, and nanotechnology.[33,38,40] These advanced methods help reduce drug loss and degradation, prevent side effects, improve bioavailability, and increase the amount of drug that reaches the required site.[37,38,40] In recent years, scientists have developed many types of modern drug delivery systems, some of which are still being tested.[38,39,40] These include soluble polymers, microparticles, microcapsules, lipoproteins, liposomes, micelles, dendrimers, hydrogels, and carbon nanotubes. These tiny carriers are designed to work in specific conditions, such as

changes in pH or temperature, and can be directed to certain areas of the body by attaching special antibodies to them.[38-40]

Drug targeting can be divided into two main types: passive and active targeting. In passive targeting, the drug naturally builds up at the target site. In active targeting, the surface of the drug carrier is modified with molecules called ligands that specifically bind to receptors on target cells.[38,39,40] Because ligand–receptor binding is very selective, active targeting provides higher accuracy and better results in reaching the desired area.[39,40]

Every drug has an ideal concentration range where it works best—too much can be harmful, and too little may not work at all.[37,38] Because many drugs are not absorbed well by the body, scientists are working to improve how much of the drug reaches the target cells.[37,39]

This new approach combines ideas from different scientific areas such as molecular biology, chemistry, pharmacy, and nanotechnology.[33,38,40] These advanced techniques help reduce drug loss, prevent side effects, improve absorption, and make sure more of the drug reaches the right place in the body.[37,38,40] In recent years, many new types of drug delivery systems have been developed, and some are still being tested. These include polymers, microparticles, liposomes, micelles, hydrogels, and carbon nanotubes.[37,38,40] These carriers can respond to changes in the body, such as pH or temperature, and can be guided to specific areas by attaching special molecules to them.[37,38,39]

There are two main ways drugs can be targeted. In passive targeting, the drug naturally collects in the diseased area. In active targeting, the drug carrier is coated with special molecules that attach only to certain cells. Because these molecules recognize specific cell receptors, active targeting is more accurate and helps the drug reach the exact area that needs treatment.[38,39]

Table 1: Toxicity of Few Nanoparticles.

Nanoparticles	Test Organ/Species	Toxic Effect [Simplified Description]	References
ZnO nanoparticles	Human lung cancer cells [LTEP-a-2]	Caused cell damage [cytotoxicity] in lung cancer cells	[49][50][51]
TiO_2 nanoparticles	Human blood immune cells [mononuclear cells]	Reduced enzyme [IDO] activity and interferon [IFN-γ] production	[52][53]
Silver nanoparticles	Human colon cancer cells	Caused oxidative stress and cell damage	[54][55][56]
Nickel oxide nanoparticles	Human lung cells [BEAS-2B and A549]	Caused inflammation and DNA damage in lung cells	[57]
Fullerenol nanoparticles	Human lung fibroblast cells	Caused cell damage and genetic changes [DNA damage]	[58][59]
ZnO nanoparticles	Human white blood cells [neutrophils]	Slowed down the normal process of cell death in neutrophils	[60]
Silver nanoparticles	Human umbilical vein cells [HUVECs]	Caused injury and malfunction in blood vessel cells	[61]
Bare TiO_2, ZnO, MgO, Ag, Au nanoparticles and their triglyceride-coated forms	Mouse skin cells [Balb/c]	Caused cell damage [cytotoxicity]	[62]
Metal oxide nanoparticles [ZnO, CeO_2, TiO_2, Al_2O_3]	Human blood lymphocytes	Changed gene expression and affected immune cell activity	[63]
TiO_2 nanoparticles	Human stomach cells	Caused oxidative stress and DNA damage	[64-74]

6. MECHANISM OF TOXICITY CAUSED BY NANOPARTICALS

The chemical and physical reactivity of nanoparticles can lead to the creation of free radicals, also known as reactive oxygen species [ROS], such as superoxide and hydroxyl radicals.[41,43] These can form either directly or indirectly when nanoparticles activate certain enzymes in the body, causing oxidative stress.[41,42,44] Oxidative stress happens when the balance between harmful free radicals and the body's ability to remove them is disturbed, leading to damage in cells and tissues.[42,43,44]

There are several ways in which nanoparticles can cause oxidative stress.[42,43] First, the particles themselves can produce oxidants or trigger cells to make more ROS as a defense response.[42,43,44] Second, nanoparticles made from transition metals, or those contaminated with metal catalysts during production, can also generate ROS.[44] Third, some nanoparticles have relatively stable free radicals on their surfaces, which can react with biological molecules.[42,44] Fourth, nanoparticles that have been chemically modified may contain redox-active groups that can easily transfer electrons and produce ROS.[43,44] Fifth, smaller nanoparticles can enter cells more easily through passive uptake than larger ones, making them more likely to interact with cell components.[41,42] Because of this, small nanoparticles often cause stronger toxic effects and more noticeable cellular responses than larger particles.[41,42,43]

DISCUSSION

Drug delivery systems represent a crucial aspect of pharmacology, as they are responsible for the physical introduction of therapeutic agents into the body. These systems are engineered technologies designed for targeted delivery or controlled release of drugs. Localized administration, as opposed to systemic delivery, is often preferred because it can minimize side effects and reduce toxicity while enhancing therapeutic efficacy.

However, modern drug delivery systems still face several challenges, including issues related to bioavailability, biocompatibility, toxicity, efficacy, and controlled release. To address these limitations, nanomaterials have been explored for their exceptional biological and physicochemical properties. Their biocompatibility, biodegradability, and ability to provide controlled and targeted drug release have made them attractive as potential drug carriers.

Nevertheless, the use of nanomaterials also raises safety concerns. Identifying and understanding their toxicological properties is essential for designing novel, biodegradable, and efficient drug delivery formulations that minimize risks to human health and the environment. Therefore, knowledge of the molecular mechanisms and biological pathways involved is critical in modern drug development. Due to their nanoscale size, these materials can easily penetrate biological systems and potentially interfere with normal cellular functions. Despite these concerns, the application of nanomaterials in drug delivery remains a promising approach, and current research continues to focus on harnessing their unique properties to overcome existing pharmaceutical challenges.

CONCLUSIONS

Drug discovery and delivery represent a critical interface between biochemistry and medicine. This review discusses the advantages and limitations of current drug delivery systems and highlights the role of nanotechnology in addressing these challenges. Nanomaterials are often preferred as drug delivery vehicles due to their biodegradable and biocompatible nature, as well as their ability to provide targeted and sustained drug release. However, these materials are not entirely safe and may exert toxic effects on healthy cells. Therefore, careful assessment of nanoparticle toxicity

is essential for biomedical applications, particularly in novel drug delivery systems, gene delivery, and therapeutic interventions.

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