

# Original Article: Nanomaterials in Drug Delivery Systems: Challenges and Perspectives

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## ABSTRACT

Nanomaterials have emerged as a transformative technology in drug delivery systems, offering unique properties that enhance therapeutic efficacy and safety. Their small size, high surface area, and ability to be engineered for targeted delivery enable improved solubility, controlled release, and reduced side effects of pharmaceuticals. This paper discusses various types of nanomaterials used in drug delivery, including nanoparticles, liposomes, and dendrimers, highlighting their mechanisms of action and advantages over conventional delivery methods. Despite their potential, the integration of nanomaterials in clinical applications faces several challenges, including manufacturing scalability, regulatory hurdles, bio distribution unpredictability, and concerns regarding toxicity and biocompatibility. Additionally, complex interactions between nanomaterials and biological systems pose significant hurdles. The future of nanomaterials in drug delivery lies in innovative approaches, such as personalized medicine and biodegradable carriers, necessitating continued interdisciplinary research and collaboration. This review aims to provide insights into the current status and future perspectives of nanomaterials in drug delivery, emphasizing the importance of overcoming existing challenges to fully harness their potential in enhancing patient outcomes.

## Introduction

The use of large-sized materials in drug delivery poses major challenges such as in vivo instability, poor solubility, poor absorption in

the body, and possible adverse effects of drugs on non-target tissues [1]. Therefore, the use of novel drug delivery systems to target drugs to specific parts of the body can be an option that may solve these critical issues [2]. Hence,

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nanotechnology plays an important role in advanced medical/pharmaceutical formulations and controlled drug delivery. Nanotechnology using nanostructures and Nano phases has been shown to be applicable in various scientific fields, especially in Nano medicine-based drug delivery systems. Nanomaterials can be well defined as materials with sizes between 1 and 100 nm, which affects the frontiers of Nano medicine from biosensors, microfluidics [3], drug delivery, and microarray experiments to tissue engineering. Nanotechnology uses therapeutic agents at the nanoscale to develop Nano medicines.

The biomedical field including: Nano biotechnology, drug delivery, biosensors and tissue engineering is powered by nanoparticles. Since nanoparticles consist of materials designed at the atomic or molecular level, they are usually Nano spheres of small size. Hence, they can move more freely in the human body compared to larger materials. Nanoscale particles exhibit unique structural, chemical, mechanical, magnetic, electrical and biological properties [4].

Nano medicines have been well received in recent times. Because nanostructures can be used as delivery agents by encapsulating drugs or attaching therapeutic agents and delivering drugs to target tissues with controlled release. The first generation of nanoparticle-based therapeutics included lipid systems such as liposomes and micelles, which are now FDA-approved [4]. These liposomes and micelles can contain inorganic nanoparticles such as gold or magnetic nanoparticles. These features are increasing the use of inorganic nanoparticles with emphasis on drug delivery, imaging and therapeutic functions [5]. Nano drugs show higher oral bioavailability because they exhibit the typical absorption mechanisms of sorption endocytosis [6]. Nanostructures remain in the circulatory system for a long time

and allow for the release of the incorporated drugs according to the dose. Therefore, they cause less plasma fluctuations and reduce adverse effects [7].

These Nano-sized structures penetrate the tissue system, facilitate easy drug uptake by cells, allow efficient drug delivery and ensure action at the desired site. The uptake of nanostructures by cells is much higher than that of large particles with sizes between 1 and 10  $\mu\text{m}$ . Hence, they directly interact with diseased cells to treat diseased cells with improved efficacy and reduced or negligible side effects [8].

Nanotechnology therefore offers numerous benefits in the treatment of chronic human diseases through the delivery of drugs in a specific and targeted manner. However, insufficient knowledge about the toxicity of nanostructures is a major concern and undoubtedly warrants further research to improve efficacy with higher safety to enable safer practical implementation of these drugs. Therefore, careful design of these nanoparticles can be helpful in overcoming the problems associated with their use [9].

### **Nano-based drug delivery systems**

Recently, there have been many advances in the field of delivery systems to deliver therapeutic agents or active pharmaceutical ingredients to the target site for the treatment of various diseases. A number of drug delivery systems have been successfully used in recent times. However, there are still certain challenges that need to be addressed and an advanced technology needs to be developed for the successful delivery of drugs to their target sites [10].

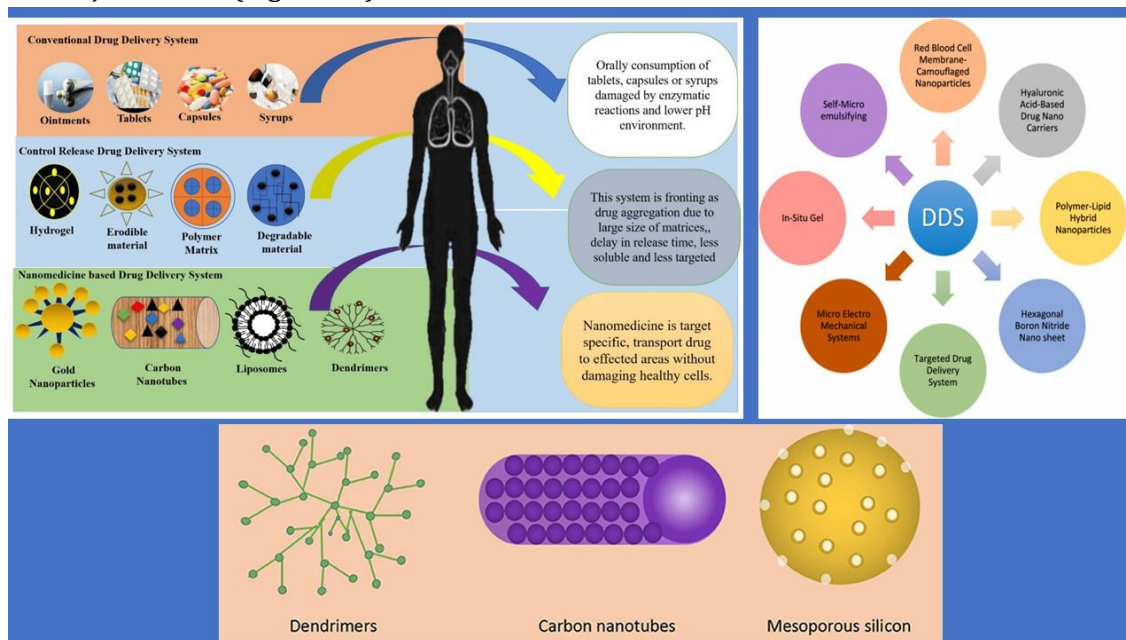
### **Nanoparticles used in drug delivery system**

There are several bio polymeric materials that are used in drug delivery systems. These

materials and their properties are discussed below [11].

**1- Chitosan:** Chitosan exhibits mucoadhesive properties and can be used to act at tight epithelial junctions (Figure 1). Therefore,

chitosan-based nanomaterials are widely used for sustained drug delivery systems for various types of epithelium including intestinal, nasal, ocular, and pulmonary [12].



**Figure 1.** Nanoparticles used in drug delivery system

**2- Alginate:** Another biopolymer material that has been used as a drug delivery agent is alginate. This biopolymer presents terminal carboxyl groups, which are classified as anionic copolymers and exhibit greater mucoadhesive strength compared to cationic and neutral polymers [13].

**3- Xanthan Gum:** Xanthan gum (XG) is a high molecular weight heteropolysaccharide produced by *Xanthomonas campestris*. It is a polynomic polysaccharide and has good bio adhesive properties. Because xanthan gum is considered non-toxic and non-irritating, it is widely used as a pharmaceutical supplement.

**4- Cellulose:** Cellulose and its derivatives are widely used in drug delivery systems mainly to modify the solubility and gelation of drugs, which leads to the control of its release profile. The presence of hydrogen bonds between cellulose nanocrystals and the drug led to its sustained release and subsequently

nanoparticles made with oxidized cellulose nanocrystals had lower release compared to nanoparticles made with cellulose nanocrystals [14].

**5- Liposomes:** They were discovered in 1960 by Alec Bingham. Liposomes are used in the pharmaceutical and cosmetic industry to transport a variety of molecules and are among the carrier systems for drug delivery. Liposomes are a formulation strategy to improve drug delivery. They are spherical vesicles composed of phospholipids and steroids, usually in the size range of 50 to 450 nm. Since their membrane structure is similar to that of cell membranes and since they facilitate the incorporation of drugs into them, they are considered better carriers for drug delivery [15]. They have also been shown to stabilize therapeutic compounds, improve their bio distribution, and are also biocompatible and biodegradable.

**6- Polymeric micelles:** Polymeric micelles are nanostructures made of amphiphilic block copolymers that self-assemble and form a core-shell structure in aqueous solution. The hydrophobic core can be loaded with hydrophobic drugs such as camptothecin, docetaxel, paclitaxel [16].

At the same time, the hydrophilic shell solubilizes the entire system in water and stabilizes the core. Polymeric micelles are less than 100 nm in size and usually have a narrow distribution, to prevent rapid renal excretion. Therefore, their accumulation in tumor tissues is possible through the EPR effect. In addition, their polymer shell inhibits non-specific interactions with biological components. These nanostructures have strong prospects for hydrophobic drug delivery. Because their inner core structure allows the adsorption of these types of drugs, leading to increased stability and bioavailability [17].

**7- Dendrimers:** Dendrimers are highly bifurcated, well-defined, three-dimensional structures. They are spherical in shape and their surface is easily functionalized in a controlled manner, making these structures excellent candidates as drug delivery agents. Dendrimers are limited in their clinical applications due to the presence of amine groups. These groups have a positive or cationic charge that makes them toxic. Hence, dendrimers are usually modified in order to reduce or eliminate this toxicity [18].

**8- Inorganic nanoparticles:** Inorganic nanoparticles include silver, gold, iron oxide, and silica nanoparticles. Only a few nanoparticles have been accepted for clinical use, while most of them are still in the clinical trial stage. Metal nanoparticles, silver and gold, have special properties such as SPR (surface plasmon resonance) that liposomes, dendrimers, micelles lack. They have shown several advantages such as good biocompatibility and versatility regarding

surface functionalization. In vivo transport and absorption mechanism Drugs can be conjugated to the surfaces of gold nanoparticles (AuNPs) through ionic or covalent bonding and physical adsorption, and can be delivered and their release controlled through biological stimuli or photo activation. Silver nanoparticles have shown antimicrobial activity, but very few studies have been conducted on drug delivery [19].

**9- Nanocrystals:** Nanocrystals are pure drug solid particles in the range of 1000 nm. These are 100% drug without any carrier molecules attached to them and are usually stabilized using polymeric steric stabilizers or surfactants. Nanocrystals have special properties that allow them to overcome problems such as increased saturation solubility, increased dissolution rate and increased adhesion to the surface/cell membrane [20].

**10- Metal nanoparticles:** In recent years, there has been an increased interest in the use of metal nanoparticles in various medical applications such as bio imaging, biosensors, targeted/sustained drug delivery, hyperthermia and photo ablation therapy. Furthermore, modification and functionalization of these nanoparticles with specific functional groups allows them to be attached to antibodies, drugs and other ligands, making these systems more promising in biomedical applications [21].

**11- Quantum dots:** Quantum dots are known as semiconductor nanocrystals with a diameter range between 2 and 10 nm, and their optical properties such as absorption and luminescence are size-dependent. Quantum dots have attracted much attention in the field of Nano medicine [22].

Because, unlike conventional organic dyes, quantum dots emit in the near-infrared region, which is a highly desirable property in the field of biomedical imaging due to their low

absorption by tissues and reduced light scattering. In addition, quantum dots of different sizes and compositions can be excited by the same light source, resulting in the emission of distinct colors over a wide spectral range. In this regard, quantum dots are very attractive for multispectral imaging. In the medical field, quantum dots have been widely studied as targeted drug delivery, sensors, and bio imaging [23].

### **Protein and Polysaccharide Nanoparticles**

Polysaccharides and proteins are collectively referred to as natural biopolymers and are extracted from biological sources such as plants, animals, microorganisms and marine sources. Protein-based nanoparticles are generally biodegradable, metabolizable and can be easily functionalized to bind specific drugs and other target ligands [24].

### **The Future of Nano medicine and Drug Delivery Systems**

The science of Nano medicine is currently one of the most exciting areas of research. By using a variety of nanoparticles to deliver precise amounts of drugs to damaged cells such as cancer cells without disrupting the physiology of normal cells, the use of Nano medicine and Nano drug delivery systems is certainly a growing trend [25].

The examples of nanoparticles shown in this communication are not uniform in size. Some of them are truly measured in nanometers, while others are measured in sub-micrometers. The application of metallic nanoparticles, including gold and silver, in both diagnostics and therapy is an area of research that could potentially lead to a wider application of Nano medicines in the future. One of the main interests in this direction involves gold nanoparticles, which appear to be well absorbed into soft tumor tissues and render the tumor susceptible to radiation [26].

Despite the widespread understanding of the future prospects of Nano medicine and Nano drug delivery systems, their actual impact on the healthcare system, even in cancer treatment/diagnosis, remains very limited. This is because this is a new field of science with only two decades of real research on the subject and many key fundamental properties are still unknown [27].

Basic markers of diseased tissues, including key biological markers that allow absolute targeting without altering the natural cellular process, are a major area of future research. Ultimately, the application of Nano medicine will advance with our increasing knowledge of diseases at the molecular level or the identification of markers comparable to the size of subcellular nanomaterials to open avenues for new diagnosis/therapy [28].

Hence, understanding the molecular signatures of disease will lead to future advances in Nano medicine applications. The concept of controlled release of specific drugs at confined sites, the technology to assess these events, the effect of the drug at the tissue/cellular level, as well as the theoretical mathematical models for prediction are still not complete. Several studies in the field of Nano medicine have focused on biomaterials and formulation studies, which seem to be the initial stages of biomedical applications [29].

Valuable data in potential application as therapeutic and diagnostic drug studies are obtained from animal studies and multidisciplinary research, which requires significant research time and resources. With the growing global trend for drug discovery and more accurate diagnosis, the future looks bright for a more intelligent and multi-pronged approach of Nano medicine technology and Nano drug delivery [30].

There is great enthusiasm with the view of simplifying the development of Nano robots that function in tissue recognition and repair

mechanisms with complete external control mechanisms [31].

However, like their benefits, the potential risk of Nano medicines to both humans and the environment in general requires long-term study. Hence, the appropriate impact analysis of the possible acute or chronic toxic effects of new nanomaterials on humans and the environment needs to be analyzed. As Nano medicines gain popularity, their cost-effectiveness is another area of research that requires further research input [32].

### Discussion

The discovery and production of drugs depends on new insights into a health area or information about a disease process. These can include testing a large number of molecular compounds to find beneficial effects on diseases, improving existing treatments that have adverse effects, or developing new technologies that may offer new and innovative ways to target specific areas of concern in the body [33].

What is certain is that a large number of drug candidates are registered in the early stages, gradually reducing to a small number that actually have the potential to achieve FDA approval for a particular disease. Another challenge in this area is cost. Developing a new molecular entity such as a small compound or a

new biological entity, such as antibodies or gene therapies, is expensive [34].

The cost of developing these drugs to market is estimated to be around \$2.6 billion. As expected, this is a major hurdle for many pharmaceutical companies, who may even underestimate the large amount of associated costs required to produce a new drug treatment during each stage of development. Increasingly, optimizing high-load drug formulations is also a challenge for researchers, to ensure that a significant amount of drug is available and well distributed at each dose. This is also related to the obstacle of properly optimizing the drug delivery system for each specific formulation [35].

### Nano medicine and Drug Development

These challenges are usually troublesome for researchers, but with the advancement of Nano medicine technology, promising solutions are likely to emerge for the pharmaceutical industry [36]. Enhancing the drug discovery process with Nano medicine technology, which uses particles and materials on the scale of 1 to 100 nanometers, could play an important role in pharmaceuticals (Figure 2). These particles are smaller than typical drug molecules and allow them to enter through pathways that are considered biological barriers to conventional drugs.

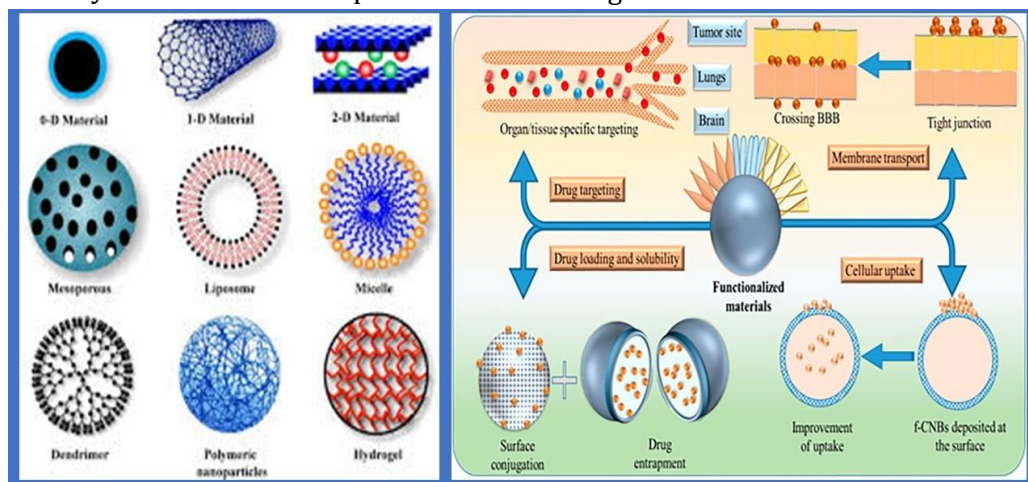


Figure 2. Nano medicine and Drug Development

Such sizes are crucial because crossing biological barriers, such as the blood-brain barrier, which prevents many conventional drugs from reaching the brain, could make it possible to treat a range of brain-related diseases and disorders [37].

An example of this is brain cancer such as glioblastoma multiforme, a common brain tumor with a poor prognosis. This brain cancer can be described as incurable, with a median survival of 15 months, and only 5.5 percent of patients survive five years after diagnosis. Increasing the ability to target brain-related diseases such as glioblastoma by incorporating Nano medicine into drug formulations could increase the number of drugs approved to treat intractable diseases [38].

Drug discovery could be boosted through this innovative approach. Because it may enable precise targeting of receptors, proteins and other biological molecules, increasing the efficiency of drug development and delivery [39].

This can also be enhanced due to the higher solubility and surface functionality of nanoparticles, which allow ligands to be attached to them, enabling higher levels of targeting.

### Future Outlook for Nano medicine and Drug Development

Since the 1970s, there have been approximately 60+ pharmaceutical applications involving nanomaterials that have been approved and have continued to gain attention over the years [40].

Nanomaterial-based drug formulations may involve different biological pathways than a conventional small molecule drug, and this may subsequently affect the safety, quality and even efficacy of the drug. This challenge requires further research into the intricacies of Nano formulations and how they affect the patient in vivo [41].

These challenges led to the use of the Medical Nanotechnology Risk Assessment Task Force to assess the potential impact of nanotechnology on drugs in 2014, with expertise from the FDA's Center for Drug Evaluation and Research (CDER). Such an expansion has allowed for the expansion of drug standards, with CDER introducing guidance for drugs and biologics that contain nanomaterials in 2017 [42]. Guidance for this innovative category could enable the production of higher volumes of drugs for diseases and disorders that have previously been challenging to treat, such as brain cancer.

### Nanotechnology for HIV Prevention

According to the National Nanotechnology Initiative, nanotechnology is recognized as a promising tool in the prevention and treatment of HIV. This technology can help improve the delivery of antiviral drugs [43], increase the effectiveness of treatment, and reduce toxicity. In recent years, various studies have focused primarily on the use of nanotechnology to improve therapeutic efficacy and target antiviral methods.

**1- The role of nanotechnology in improving the delivery of anti-HIV drugs:** Their ability to incorporate, protect, and absorb non-oral anti-HIV drugs, namely oligonucleotides, significantly improves the bioavailability of various molecules. The use of nanoparticle systems for the delivery of antiretroviral drugs can be particularly useful for targeted delivery, especially to cells directly involved in human immunodeficiency virus (HIV) [44].

**2- Novel applications of nanotechnology in the treatment of HIV infection:** The application of nanotechnology in medicine provides many possibilities and facilities in the treatment of HIV. Nanotechnology-based systems can influence drug delivery systems and improve drug properties. They can also

increase the efficacy of treatment and reduce drug toxicity [45].

**3- Nanoparticle systems as a tool for targeting CD4+ T cells:** In HIV infection, CD4+ T cells are important targets for the virus. This has stimulated a number of nanoparticle-based strategies to deliver modifying factors, such as antiviral siRNA or antiretroviral drugs, to CD4+ T cells to inhibit HIV replication. Lipid nanoparticles encapsulating the antiretroviral drug indinavir were targeted to CD4+ T cells using peptides that recognize the CD4 co-receptor. Pretreatment of CD4+ T cells with targeted lipid nanoparticles resulted in a reduction in the number of cells infected with non-targeted lipid nanoparticles in vitro [46].

**4- Nanotechnology and Gene Therapy:** Nanotechnology-based gene therapy is a method of treating HIV by introducing a gene into a cell that is associated with viral infection or replication. Other nucleic acid-based compounds can be used to interfere with viral replication [47].

**5- Effect of dendrimer siRNA on suppression of HIV virus replication:** The dendrimer siRNA complex showed the best efficiency in HIV-infected peripheral blood mononuclear cells without any cytotoxicity and protected the siRNA from degradation in RNase presentation [48].

**6- Safe gene transfer in HIV therapy:** Dendrimers were studied in mice and efficient transfer of siRNA across the blood-brain barrier was observed. Scientists at the University of California, Los Angeles have shown that cell-derived gene transfer is safe and active in HIV-infected individuals [49].

**7- Novel techniques in HIV gene therapy from siRNA to Zinc Finger Nucleases:** Specific delivery of 4 CD siRNAs results in RNA responses without side effects such as cell toxicity or immune stimulation. Antibody-based siRNA delivery has been shown to suppress HIV replication in primary T cells.

Another gene therapy approach is the persistent inactivation of 5CCR by zinc finger nucleases [50].

### Nanotechnology and Vaccines

Nanoparticles not only provide improved antigen delivery but also play a significant role in primary immunity [51]. The use of nanoparticles in vaccine formulation has the following advantages:

**1- Role of nanoparticles in antigen amplification:** Nanoparticles can amplify adsorbed antigens and act as an antigen themselves. They can also mimic the properties of pathogens such as viruses and induce adaptive and innate immune responses [52].

### Advantages of nanoparticles in vaccines

Due to their specific surface area and high performance, they are used as antigen carriers to enhance antigen processing and presentation [53]. These characteristics of nanoparticles have led to effective cell targeting and controlled release of antigens. Nanoparticles can increase the half-life of most vaccines [54].

### History of HIV vaccine research with nanoparticles

The first attempt to deliver HIV antigens using liposomes was reported nearly two decades ago. Since then, the influence of various features including liposome components, fabrication methods, HIV antigen, route of administration, and type of adjuvant has been investigated for the development of liposomal HIV vaccines, and research is still ongoing [55].

### Polymeric nanoparticles, an option for vaccine delivery

Polymeric nanoparticles have attracted much attention in vaccine delivery due to some attractive features including biocompatibility, predictability, biodegradability, stability, easy

modification, and surface and safety [56]. Polymer-based delivery systems have shown some advantages such as sustained release, protection of the encapsulated antigen from enzymatic degradation [57], targeted delivery, and adjuvant effects. Some polymer nanoparticles have been pursued for the production of mucosal vaccines for antigen delivery. Carbon nanoparticles are used as another compound for drugs and vaccines due to their high biocompatibility. They can also increase the level of IgG response [58].

## Nanomaterials for HIV Prevention and Treatment

### 1- Liposomes:

**A) Nano vesicular carriers:** Liposomes are vesicle carriers consisting of two phospholipid bilayers and an aqueous core. They are suitable as drug carriers [59].

**B) Structure and function of liposomes:** It is worth noting that the aqueous core is better for retaining hydrophilic drugs, while the two phospholipid bilayers retain hydrophobic and amphiphilic drugs. In addition, they are very useful for antiviral agents. Because it is taken up by the reticuloendothelial system and is rapidly removed from the bloodstream [60].

**C) History and research on liposomes:** Liposomes were the first to be developed and also have the longest research history among commercial Nano carriers. The size of liposomes can range from 80 nm to 10  $\mu\text{m}$ , depending on the preparation and composition [61].

**D) Properties and applications of liposomes:** Many studies provide a detailed description of liposome compositions, manufacturing methods, types of liposomes, their biophysical properties, properties and applications. The characteristic of liposomes for rapid identification of phagocytic cells of the liver and spleen and their accumulation in lysosomes has been used to enhance the

prevention and treatment of various infectious diseases [62].

**E) Liposomal formulations and pharmaceutical applications:** The first liposomal formulation introduced to the world pharmaceutical market was a liposome containing doxorubicin called RDoxil. The presence of polyethylene glycol (PEG) on the surface of this liposome increases the half-life of doxorubicin. Overall, it has been shown that fluorescently labeled cardiolipin liposomes are retained in the vaginal cavity of mice for approximately 24 hours after intrauterine administration, and the liposomal formulation has no adverse effects [63].

### Advantages of Nanotechnology in Anti-HIV Drug Delivery

In general, nanotechnology has many advantages in anti-HIV drug delivery. Some Nano medicine approaches are being used to treat patients with a wide range of conditions.

### The impact of nanoparticles in HIV treatment and prevention

According to published results from clinical and animal models, the impact of nanoparticles in HIV treatment and prevention can be understood with approaches such as drug delivery, gene therapy, and vaccines. The use of nanoparticles in HIV treatment and prevention can be likened to a double-edged sword [64].

### Challenges and limitations

In the future, clinical research based on nanoparticles should consider various issues, including the development of pharmacodynamics and pharmacokinetic models in different situations, the stability of nanoparticles, and the interaction with tissues and cells [65].

The use of this technology in the treatment process has limitations and challenges that need to be overcome, and further research is

needed in this area. Nanoparticles can also be used to treat AIDS-related diseases such as Burkitt syndrome. Finally, nanotechnology provides interesting opportunities for advanced therapeutic fields and HIV prevention [65].

### Conclusion

Initially, the use of nanotechnology was mainly based on increasing the solubility, absorption, bioavailability, and controlled release of drugs. Good examples of therapeutic application of nanotechnology are bebeerine, curcumin, ellagic acid, resveratrol, curcumin and quercetin. The efficacy of these natural products has been greatly improved through the use of Nano carriers formulated with polymeric nanoparticles of gold, silver, cadmium sulfide and titanium dioxide along with solid lipid nanoparticles, crystal nanoparticles, liposomes, micelles, superparamagnetic iron oxides and iron nanoparticles.

There has been a continuous demand for new natural biomaterials due to their biodegradable, biocompatible, readily available, renewable and low toxicity qualities. One of the great interests in the development of Nano medicine in recent years is related to the integration of therapy and diagnosis, an example of which is cancer as a disease model. Good examples are iron oxide nanoparticles encapsulated with oleic acid for diagnostic applications via near infrared. Since the 1990s, the list of nanotechnology-based products and clinical trials approved by the FDA has grown dramatically, including synthetic polymeric particles.

Liposome formulations, micellar nanoparticles, protein nanoparticles, nanocrystals, and many others are often combined with drugs or biologics. Although regulatory mechanisms for Nano drugs along with safety/toxicity assessment will be the subject of further

development in the future, Nano medicine has already revolutionized the way drugs are discovered and administered in biological systems.

In the last few decades, the vast potential of nanomaterials for biomedical and healthcare applications has been widely explored. Several case studies have shown that nanomaterials can offer solutions to current raw material challenges in the medical and health fields. This review describes different approaches to the synthesis of nanoparticles and nanostructured materials, and presents some emerging applications in biomedicine, healthcare, and agriculture and food.

This review focuses on types of nanomaterials such as spheres, Nano rods, nanotubes, Nano sheets, nanofibers, core-shell and mesoporous, which can be synthesized from various raw materials and their emerging applications in bio imaging, drug delivery and agro-foods. Depending on their morphology, nanomaterials can be used as formulation modifiers, humectants, Nano fillers, additives, membranes and films. Since toxicological evaluation depends on sizes and morphologies, precise regulation of dosage tests of efficient nanomaterials is required.

Challenges and prospects for industrial advancement of nanomaterials are related to the optimization of production and processing conditions. Nanotechnology, as a novel approach in HIV treatment, offers significant opportunities to improve the quality of life of patients and increase the efficacy of treatments. However, there are many challenges that need to be addressed, including nanoparticle stability, safety and production costs. With more investment in research and development, the potential of this technology can be effectively utilized and HIV treatment can be pushed to a new and more successful stage. Ultimately, combining nanotechnology with existing therapies could open up new

horizons in the fight against HIV and improve public health.

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