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Nanoparticles in drug delivery: Comprehensive insights into recent advances and its applications

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Abstract
Nanoparticles have risen as one of the most transformative stages in advanced medicate conveyance, advertising strides bioavailability, supported discharge, and focused on restorative activity. Later progresses in nanotechnology, particularly in lipid nanoparticles, polymeric carriers, inorganic frameworks, and biomimetic plans, have moved the worldview from conventional details to exactness pharmaceutical. This article audits key improvements in nanoparticle-based sedate conveyance from 2020 to 2025centering on their applications in oncology, irresistible maladies, neurological disarranges, quality treatment and personalized pharmaceutical. Challenges such as harmfulness, large-scale fabricating and administrative endorsement are moreover talked about, nearby future viewpoints for clinical translation. Recent headways in nanoparticle surface alteration have moved forward both dynamic and inactive focusing on methods, permitting for focused on conveyance that minimizes systemic poisonous quality and increment helpful viability. Multifunctional nanoparticles are being made to consolidate medicate conveyance with diagnostics (theranostics), giving real-time perception of treatment results. Besides, advances microfluidic, large-scale generation and the administrative rules is speeding up the clinical execution of nanoparticle-based frameworks. In any case, impediments hold on, such as delayed harmfulness, end forms, consistency in mass generation, and administrative challenges.

Keywords: Lipid nanoparticles, polymeric nanoparticles, exosomes, biomimetic coatings, stimuli-responsive nanomedicine, mrna delivery, sirna, epr effect, anti-peg antibodies, blood–brain barrier

Introduction

Nanomedicine has transformed drug delivery with site specific transport, controlled release, and improved pharmacokinetics. Also, we see that conventional drug formulations do have issues like poor solubility, rapid clearance, and systemic toxicity which in turn play a great role in reducing their therapeutic outcomes. But nanoparticles (NPs) which have a tunable size (1to 100 nm), surface modifications and are multi-functional put forth an attractive alternative to that. Also, during the COVID-19 pandemic we saw the authorization of mRNA vaccines to use lipid nanoparticles which brought to the fore the clinical importance of nanotechnology and at the same time also increased interest in the broad application of these tech. Also, it is to be noted that nanoparticles in general which fall in the size range of 1 100 nanometers have unique structural and functional properties that make them a better choice as a delivery platform as compared to traditional systems [1].

In recent times we have seen great improvement in the design of nanostructured vehicles which put forward or attach therapeutic agents in ways that greatly improve performance and at the same time reduce toxicity. For example, we have reported success with nanoparticles which deliver formulated drugs in cancer therapy, antiviral treatment which includes HIV and COVID-19, and chronic inflammatory diseases [2, 3, 4].

Types of Nanoparticles in Drug Delivery

1. Lipid Nanoparticles (LNPs)

Lipid nanoparticles have picked up conspicuousness for nucleic acid conveyance. They typify mRNA, siRNA, and DNA, protecting them from enzymatic corruption while enhancing cellular take-up. Their victory in COVID-19 vaccines illustrated their versatility and security. Beyond vaccines, lipid nanoparticles are under examination for rare hereditary disorders and cancer therapy. Lipid nanoparticles (LNPs) speak to one of the most advanced and flexible nanocarrier frameworks currently utilized in pharmaceutical investigation and clinical practice. These nanoscale congregations are fundamentally composed of ionizable or cationic lipids, cholesterol, phospholipids, and polyethylene glycol (PEG)–lipid conjugates, which together frame a steady structure competent of encapsulating and ensuring helpful specialists. The unique combination of biocompatibility, biodegradability, and high encapsulation effectiveness has situated LNPs as the leading stage for the conveyance of nucleic acids, peptides, and little molecules [5, 6].

2. Polymeric Nanoparticles

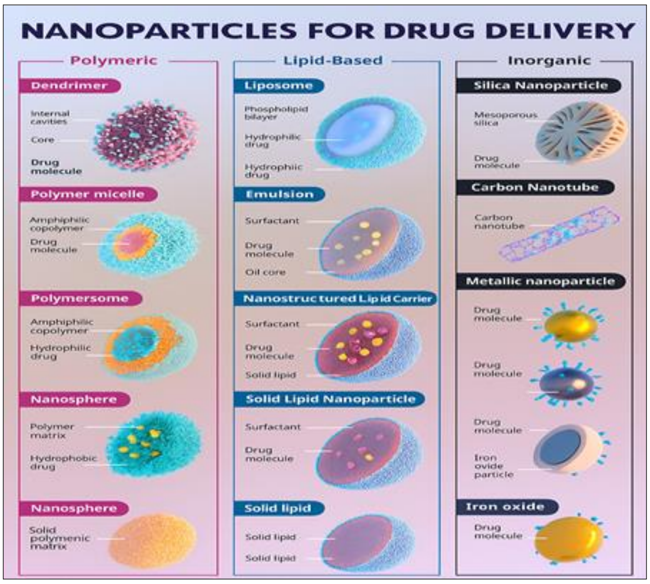
Polymer nanoparticles (PNNs) are at the forefront of what is researched in therapeutic delivery systems. They are colloid particles that range in size from 10 to 1000 nanometers, and we see natural and synthetic polymers used in them. These polymers we see are put in, attached to, or linked with a great variety of bioactive materials. What we see in these polymers is a solid structure that is very stable in terms of drug load and also is a platform that allows for controlled release of the drug and also for tuning the surface chemistry as we see fit. This in turn we see to improve drug bioavailability and the performance of the therapy [7, 8].

3. Inorganic Nanoparticles

Inorganic nanoparticles (INPs) have been widely used in drug delivery and bioapplications because of their physicochemical characteristics, structural stability, and multi-functionalities. In contrast to the organic vehicles, inorganic NPs are usually composed of metallic, metal oxide, or silica materials and can be more readily modulated in the nanometer range. Further, due to their tunable size, geometry, surface charge, and optical properties, these multifunctional nanoparticles could be used not only for therapeutic delivery but also for imaging, biosensing, or theranostics—the integration of diagnosis and treatment on one platform [9, 10].

4. Biomimetic Nanoparticles

Biomimetic and hybrid nanoparticles have become a new way of drug delivery systems that aim to combine the advantages of synthetic nanocarriers and natural biological entities. The idea behind these nanostructures is to replicate not only the structural but also the functional and compositional aspects of the biologically derived components such as cell membranes, proteins, and extracellular vesicles. In essence, biomimetic and hybrid nanoparticles operate as the synthetic particles acquire the physicochemical properties from the nanosized biologically derived materials, which already possess biocompatibility and immune evasion properties. As a result, these nanoparticles have been demonstrated to be an excellent choice in areas of targeted therapy, sustained release, and systemic circulation improvement [11, 12].



Applications of Nanoparticle

1. Drug Delivery Systems

Targeted drug delivery is one of the main uses of nanoparticles, is done to increase the therapeutic effect and decrease side effects. Their very small size allows them to go through natural barriers in the body like cell membranes and the blood–brain barrier, thus making delivery at the desired site possible. Through the use of ligands, antibodies, or peptides on the surface of nanoparticles, these can be made to identify the receptors that are the most highly expressed on the cells that are sick (e.g., cancer cells). Nanoparticles are the ideal carriers for drugs, as they allow for the controlled and sustained release of the drugs; thus, pharmacokinetics and bioavailability are improved. Such are lipid nanoparticles for mRNA vaccines and polymeric nanoparticles for anticancer drug delivery [13].

2. Cancer Diagnosis and Therapy

Nanoparticles make possible the detection of tumors at the early stages through advanced imaging techniques like MRI, CT, and fluorescence imaging. Nanoparticles that are functionalized can be used as imaging contrast agents that facilitate imaging sensitivity and resolution. In therapy, they are instrumental in photothermal therapy (PTT) as well as photodynamic therapy (PDT), which are the therapies where nanoparticles change light energy into heat or reactive oxygen species that lead to the death of cancer cells. Multifunctional theranostic nanoparticles are a combination of diagnosis and therapy merged into one platform for personalized cancer management [14].

3. Biomedical Imaging and Biosensing

Gold, silver, and iron oxide nanoparticles are some of the metal-based nanoparticles that have been extensively used in biomedical imaging because of their potent optical and magnetic properties. They enhance the visualization in imaging methods like magnetic resonance imaging (MRI) and computed tomography (CT). In biosensing, nanoparticles are linked with the biological molecules (e.g., enzymes or antibodies) for the detection of biomarkers, toxins, and pathogens that have high sensitivity [15].

4. Gene Drug Delivery and Genetic Engineering

Nanoparticles serve as non-viral vectors that are safe and efficient in delivering DNA and RNA into target cells. They put up a protective shield for the genetic materials against enzymatic degradation and also make the materials more attractive to the cells.Positive lipid nanoparticles have demonstrated that they can be very successful in the development of mRNA vaccines, for instance, the ones that are used for COVID-19 vaccines.These types of carriers make possible gene silencing and gene editing technologies such as CRISPR/Cas9 that can be used for therapeutic gene modulation [16].

5. Antimicrobial and Antiviral Applications

Among the metallic nanoparticles, there are silver, copper oxide, and zinc oxide nanoparticles that have the ability to produce reactive oxygen species (ROS) and rupture microbial membranes, and that is why they exhibit strong antimicrobial activity. The nanoparticles are introduced into the materials that are used for dressing of wounds, coatings, and disinfectants so that infection can be prevented [17].

6. Environmental Remediation

Nanoparticles are catalysts and adsorbents that have been used for purifying water, filtering air, and detoxifying soil. Environmental pollutants are being degraded with the help of titanium dioxide (TiO_2) and iron oxide nanomaterials that are also getting rid of heavy metals from wastewater. They have very high reactivity at a nanoscale, which makes possible the efficient degradation of pollutants even when the conditions are mild, and that is why they are very good alternatives that are sustainable to the conventional methods [18].

7. Energy Storage and Conversion

With the help of nanoparticles, batteries, fuel cells, and solar cells become high performance as a result of improved conductivity and surface reactivity. Nanoparticle-based electrodes in lithium-ion batteries enable faster ion transport, and the battery can keep a higher capacity for a long time. Metal oxide and quantum dot nanoparticles are also put to use in photovoltaic instruments to absorb lighter and enhance the energy conversion efficiency [12, 19].

8. Agricultural and Food Industry
Nanoparticles are one of the winning factors of precision farming through which they can effectuate better pesticide delivery, nutrient release, and crop protection. Nano-fertilizers and nano-pesticides are very good at providing controlled release and making plants take up more, and that is why the environment is less polluted [20].

9. Cosmetics industry and Personal Care
Nanoparticles like titanium dioxide (TiO_2) and zinc oxide (ZnO) in cosmetic products act as sunscreens that effectively protect from UV rays. They contribute to the texture, absorption, and stability of the creams and lotions.
Transdermal delivery of active substances is made possible with the help of lipid-based nanoparticles (such as solid lipid nanoparticles); thus, the ingredient goes deep into the skin, and the effect stays for a long time [20].

10. Electronics and Sensor Technology
Nanoparticles are helpful in miniaturization and the production of effective electronics through their very good electrical, magnetic, and optical behaviors. Carbon nanotubes and graphene nanoparticles are some of the works that have been done on them to come up with flexible electronics, sensors, and transistors [21].

11. Nanomedicine
The concept of nanotechnology in pharmaceuticals was first introduced by Dr. Richard P. Feynman in the late 1950s while he was describing the development of atomic machines with nuclear accuracy for use in construction and medicine. He discussed the viability of using atomic machines to operate inside the body or ones that can be permanently implanted to support damaged organs [22].

12. Hyperthermia
Hyperthermia treatment is a treatment strategy where body tissues are warmed to temperatures between 41 and 45 degrees Celsius. This handle harms and murders cancer cells whereas causing small hurt to sound tissues. In later years, nanoparticles have become an exceptionally promising device for conveying focused on and controlled hyperthermia. This is because of their little estimate, huge surface range, and capacity to turn outside vitality into warm, making them valuable in cutting edge cancer treatments [23].

Side Effects of Nanoparticle in Drug Delivery
Indeed, in spite of the fact that nanoparticles offer extraordinary benefits in treatment, they moreover have extraordinary security issues. Since they are truly little, they can come into near contact with cells, proteins, and interior cells, which might lead to startling issues in the body. Cytotoxicity A few nanoparticles make destructive substances called responsive oxygen species (ROS) interior cells. This causes stretching on the cells, harm to DNA, hurt to the energy-making parts of the cell, and can lead to cell passing. This is frequently seen with metallic nanoparticles such as silver, titanium dioxide, and quantum dots [24].

Challenges and Limitations in Drug Delivery System
Despite the major breakthroughs, systems based on nanoparticles still encounter problems such as the following: The toxicity and immunogenicity of some nanomaterials. Difficulty in scaling up for a large-scale production.Regulatory hurdles due to limited standardization and the long approval timelines.Concerns with the stability, especially for nucleic acid, are loaded systems.
It is necessary to deal with these problems if the clinical translation is to be a success [24].
Whereas nanoparticles have a colossal potential to make strides in restorative adequacy, focusing the down-to-earth utilization of nanoparticles in sedate conveyance is restricted by numerous challenges. These challenges result from physicochemical flimsiness, fabricating challenges, natural obstructions, and security concerns that prevent their interpretation from the lab to the clinic [25, 26].

Future of Nanoparticles in Drug Delivery System
Today the main topics of research are hybrid nanoparticles, artificial intelligence (AI)-guided design, and combination therapies integrating nanomedicine with immunotherapy. The creation of biodegradable, non-toxic, and patient-specific nanoparticles is likely to lead to the rapid clinical use of the same in oncology, neurology, and chronic disease management.
The future of nanoparticles in medicate conveyance frameworks is exceptionally bright to alter the drugs of the show. With diligent advances in nanotechnology, fabric science, and chemistry, nanoparticles are anticipated to break through the display obstructions to focus on conveyance, soundness, and security, in this way coming about in more successful and personalized therapies.Centered on and Personalized Medicine Delivery: Next-generation nanoparticle frameworks will be built for exactness, focusing on and empowering site-specific sedate conveyance to infected tissues or cells with the slightest systemic side impacts [27, 28].

Result and Discussion
The present review confirms that nanoparticles represent one of the most advanced, efficient, and promising platforms in modern drug-delivery systems. The study shows that lipid nanoparticles, polymeric carriers, inorganic nanoparticles, and biomimetic systems significantly enhance drug solubility, stability, and bioavailability compared to conventional formulations. They also enable targeted delivery, controlled release, and reduced systemic toxicity, which greatly improves therapeutic outcomes in diseases such as cancer, neurological disorders, infections, and genetic conditions.The project findings also indicate that recent breakthroughs such as surface modification, stimuli-responsive nanocarriers, mRNA delivery systems, and hybrid biomimetic nanoparticles have accelerated clinical applications, especially after the success of COVID-19 LNP-based vaccines. In addition, multifunctional nanoparticles have provided new opportunities for theranostics, allowing both diagnosis and therapy on a single platform.

Conclusion
Nanoscale drug delivery has been one of the major therapeutic revolutions of the last decades, as it enables drugs to be targeted, controlled, and safely transported in the organism. Nanocarriers, in comparison to traditional drug delivery methods, have the ability to increase the drug bioavailability, protect the drug from the harsh environment, and finally discharge the drug at the exact location, thus

lowering the side effects and increasing the efficiency of the therapy. Their efficacy is mainly due to the wide range of potential materials and structures, for instance, lipid, polymeric, inorganic, and biomimetic nanoparticles, which can be used in a wide range of medical applications.

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