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A DETAILED REVIEW ON NANOPARTICLES IN DRUG DELIVERY

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ABSTRACT

Nanoparticle-based drug administration has emerged as an important area of pharmaceutical research due to conventional dosage forms' poor water solubility, fast disintegration, low bioavailability, non-specific distribution, and dose-related toxicity. Nanoparticles can serve as carriers for an active pharmacological ingredient, increasing its apparent solubility, altering pharmacokinetics, and releasing the medicine in a controlled manner. Their small size and customizable surface features allow either passive or active targeting, as well as delivery via difficult-to-manage pathways. Recent work highlights polymeric nanoparticles, lipid nanoparticles, solid lipid nanoparticles, nanostructured lipid carriers, metallic nanoparticles, dendrimers, polymeric micelles, and Nano suspensions as essential medicinal delivery platforms..1,2,3,4 This study outlines the fundamental concept of nanoparticles in drug delivery, key nanoparticle systems, preparation methods, drug loading and release processes, targeting techniques, therapeutic uses, benefits, limitations, safety concerns, and future prospects. The 2018 literature is highlighted, with a focus on the transition of nanomedicine from proof-of-concept research to clinically relevant formulations. The review also highlights why particle size, surface charge, shape, composition, and protein-corona formation should be treated in tandem rather than as separate formulation factors.

KEYWORDS: Nanoparticles; Nano Medicine; Drug Delivery; Controlled Release; Targeted Delivery; Polymeric Nanoparticles; Lipid Nanoparticles; Nanocarriers; Bioavailability; Pharmaceutical Technology.

1. INTRODUCTION

Medicine delivery is more than simply administering a medicine into the body. The formulation must protect the medication, release the proper amount at the right time, reach the desired biological site, and maintain a useful concentration while avoiding unacceptable toxicity. Conventional dosage forms

can accomplish these duties for many drugs, but they are less effective when the drug is insoluble in water, unstable, rapidly metabolized, or unable to pass a biological barrier. Nanotechnology has sparked continued interest in pharmaceutics because nanoscale materials can exhibit physicochemical and biological features that differ from bigger counterparts.[5,6]Nanoparticles are typically defined as particulate systems with dimensions in the nanometer range, while the precise size range utilized in pharmaceutical literature varies depending on the system and intended application. According to Petra and colleagues' 2018 study, Nano medicine is a fast emerging discipline that uses nanoscale materials for diagnosis and regulated, site-specific administration of therapeutic medicines.[1]Rizvi and Saleh noted that nanoparticle systems can be tailored by varying particle size, surface characteristics, and material composition in order to achieve controlled release and tissue-specific delivery.[2] These ideas make nanoparticles especially relevant in modern pharmacy, as formulation design is increasingly related to pharmacokinetics, biopharmaceutics, and patient-centered care. Designed as a reservoir, matrix, surface-decorated carrier, or multipurpose platform. Drugs can be dissolved, adsorbed, trapped, encapsulated, or chemically bound to the carrier. Polyethylene glycol, antibodies, peptides, sugars, and other ligands can be used to modify the surface and affect circulation and cellular uptake.[7,8,9] At the same time, nanoparticles may introduce new problems, including aggregation, instability, manufacturing complexity, immunological interactions and uncertain long-term safety. Consequently, the successful development of a nanomedicine requires a balance between pharmaceutical performance and biological behavior.

2. Rationale for Nanoparticles in Drug Delivery

performance comparable to conventional tablets, capsules, or injections. Poor aqueous solubility can cause sluggish dissolution and variable absorption, whereas chemical or enzymatic instability can limit the quantity of active medication that reaches the bloodstream. Nanoparticle formulations have the potential to increase a drug's effective surface area while also improving dissolving and perceived solubility in certain systems. Nanocrystals and nanosuspensions are especially effective for poorly water-soluble medications since particle size reduction can speed up dissolution and, in some cases, improve oral exposure.[10,11]

Sensitive molecules can also be shielded by nanocarriers. Before they reach their site of action, proteins, peptides, nucleic acids, and some natural compounds may undergo degradation. The drug's interaction with biological membranes can be altered and exposure to degrading enzymes can be decreased by encapsulation or association with an appropriate carrier. Twelve One of the most compelling medicinal justifications for nanoparticle delivery is the capacity to combine protection with controlled release. Sensitive molecules can also be shielded by nanocarriers. Before they reach their site of action, proteins, peptides, nucleic acids, and some natural compounds may undergo degradation. The drug's interaction with biological membranes can be altered and exposure to degrading enzymes can be decreased by encapsulation or association with an appropriate

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3. Major Types of Nanoparticles Used in Drug Delivery

3.1 Polymeric nanoparticles

Polymeric nanoparticles are one of the most extensively investigated systems in pharmaceutical research. They can be made from biodegradable synthetic polymers such as poly(lactic-co-glycolic acid), polylactic acid, and polyethylene glycol-containing compounds, or from natural polymers like chitosan and alginate.15 Polymeric nanoparticles are usually referred to as nanospheres or nanocapsules. In a nanosphere, the medication is disseminated throughout or coupled with a polymeric matrix, whereas a nanocapsule typically has a core surrounded by a polymeric shell. The release profile can be changed by modifying the polymer composition, molecular weight, and surface characteristics.

3.2 Liposomes and lipid-based nanoparticles

Liposomes, which are made up of lipid bilayers that surround an aqueous compartment, can transport hydrophilic drugs in the aqueous phase and lipophilic molecules within the lipid bilayer. Their biocompatibility and versatility have made them an important nanomedicine platform.[16] Lipid

nanoparticles, solid lipid nanoparticles, and nanostructured lipid carriers can also be used to improve the delivery of poorly soluble drugs and to modify drug release.[17]

3.3 Polymeric micelles

Polymeric micelles are self-assembled structures composed of amphiphilic polymers. Their hydrophobic core can solubilize poorly water-soluble medicines, while the hydrophilic outer shell promotes dispersion in watery biological settings. This makes polymeric micelles appealing for improving the apparent solubility and bioavailability of hydrophobic drugs.[18] Their very small size also makes them helpful for intravenous distribution and for study into tumor accumulation.

3.4 Dendrimers

Dendrimers are three-dimensional macromolecules with a distinct architecture and several surface functional groups. These properties enable pharmaceuticals to be physically trapped or chemically bonded to the dendrimer surface. Dendrimer-based systems have been studied for controlled release, targeting, and distribution via a variety of channels, though toxicity and formulation complexity remain significant concerns.[19]

3.5 Metallic and magnetic nanoparticles

Gold, silver, iron oxide, and other inorganic nanoparticles have been studied for drug delivery, imaging, and theranostic purposes. Magnetic nanoparticles are especially fascinating because an external magnetic field might affect their location and contribute to magnetic hyperthermia. Gold nanoparticles can be functionalized with medicines or targeted molecules and used in imaging or photothermal applications.[20,21]

3.6 Nanocrystals and nanosuspensions

Unlike carrier-based nanoparticles, pharmaceutical nanocrystals can be composed primarily of the medication itself, stabilized by appropriate surfactants or polymers. Reducing crystal size improves surface area, which can improve the dissolving behavior of poorly water-soluble substances. This method has helped to advance the development of oral nanomedicines and is appealing since the carrier burden can be smaller than in some encapsulation-based systems.[10,22]

4. Methods of Preparation

The process utilized to create nanoparticles has an impact on particle size, polydispersity, shape, drug loading, encapsulation efficiency, and stability. Common methods include nanoprecipitation, solvent evaporation, emulsification, ionic gelation, high-pressure homogenization, ultrasonication, and self-assembly. Polymeric nanoparticles are often created via nanoprecipitation or emulsion-based processes, whereas lipid nanoparticles can be prepared using high-pressure homogenization or other lipid-processing procedures.[15,17]

In nanoprecipitation, a polymer and medicine are dissolved in a water-miscible organic solvent before being put into an aqueous phase containing stabilizer. Rapid diffusion of the organic solvent can result in the creation of nanoscale particles. Emulsification-solvent evaporation begins with an emulsion and

then evaporates the organic solvent to produce the final particles. Ionic gelation is very effective for polymers like chitosan because electrostatic interactions can produce particles in relatively mild settings.[23]Reproducibility, solvent removal, sterility, energy consumption, batch-to-batch consistency, and batch-to-batch consistency become critical during scale-up. A pharmaceutical formulation scientist must choose a method based on the drug's solubility, polymer properties, intended route, required scale, and sensitivity to heat or organic solvents.[24]

5. Drug Loading and Encapsulation

Drug loading can happen during nanoparticle formation or after they've been prepared. The drug can be dissolved in a polymer or lipid matrix, adsorbed to the particle surface, encapsulated in a core, or covalently linked via a cleavable bond. The preferred approach is determined by the drug's molecular weight, ionization, lipophilicity, chemical stability, and therapeutic dose.

Encapsulation efficiency and drug-loading capacity are two crucial formulation factors. High encapsulation efficiency lowers drug wastage during manufacture, whereas high drug loading can reduce the amount of carrier that needs to be delivered. However, optimizing drug loading should not compromise particle stability or release behavior. In practical formulation development, a balanced design is often more useful than maximizing a single parameter in isolation.[25]

6. Controlled and Stimulus-Responsive Drug Release

One of the primary advantages of nanoparticles is the ability to adjust how quickly the medicine becomes available. Diffusion, polymer erosion, matrix swelling, desorption, or carrier degradation are all possible methods of release.[26] Mathematical and mechanistic models can assist researchers determine whether release is mostly diffusion-controlled, degradation-controlled, or regulated by a mix of mechanisms.

More advanced systems respond to biological or environmental inputs. pH-sensitive carriers can release pharmaceuticals in acidic settings, whereas temperature-sensitive systems can change their structure when exposed to heat. Magnetic and light-responsive systems have also been studied for externally controlled release and therapeutic uses.[27,28] These techniques are intriguing because they can link drug release to a disease-associated microenvironment or a programmable external trigger.

7. Targeted Drug Delivery

Targeting may be passive or active. Passive targeting is based on the biological distribution of nanoparticles and, in some cases, aberrant vascular permeability. Active targeting entails introducing a ligand that recognizes a receptor or another molecular characteristic on the target cell. Examples of targeting ligands include antibodies, peptides, folic acid, and hyaluronic acid.[7,9] However, active targeting does not guaranty that nanoparticles will reach all target cells. The particles must first survive in bodily fluids, circulate properly, exit the bloodstream, enter the tissue, and connect with the target. The protein corona that develops around nanoparticles following contact to biological fluids

might change their apparent surface identity and affect absorption.[29]Therefore, targeting should be considered as a complete biological process rather than simply a ligand-binding event.

Applications in Pharmacy and Medicine

8.1 Cancer therapy

Cancer has been a major application area for nanoparticle medication delivery. Nanocarriers have been studied for the transport of cytotoxic medications, nucleic acids, imaging agents, and combinations of therapeutic agents. The goal is to increase drug exposure to the tumor while decreasing systemic effects. Liposomal and other nanocarrier formulations have shown that repurposing an existing medicine can alter its pharmacokinetic and safety profiles.[13,30]

8.2 Brain and central nervous system delivery

The blood-brain barrier restricts the admission of numerous therapeutic compounds into the central nervous system. Nanoparticles are being studied to increase transport across or around this barrier by changing surface features, using receptor-mediated routes, or administering intranasally. Chitosan and other mucoadhesive nanoparticles have gained attention for their ability to increase residence duration and promote medication transport through nasal routes.[31]

8.3 Oral drug delivery

Many patients prefer oral delivery, however it offers obstacles in terms of solubility, gastrointestinal degradation, mucus barriers, and first-pass metabolism. Nanoparticles and nanocrystals can help to overcome some of these restrictions by improving apparent solubility, protecting medicines, and altering interactions with the gastrointestinal tract.[10,22]

8.4 Ocular, pulmonary and topical delivery

Nanoparticles have also been explored for ocular delivery, pulmonary administration and topical therapy. Their small size and changeable surfaces can promote retention, cellular uptake or penetration, whereas mucoadhesive polymers can extend contact with biological surfaces.[32] The proper design, however, depends largely on the anatomical barrier and the target site of action.

8.5 Delivery of natural products and biologics

Many natural compounds have promising pharmacological properties but suffer from low solubility, instability, or rapid metabolism. Nanoparticle encapsulation has so been studied to improve their bioavailability and medicinal efficacy.[1,33] Peptides, proteins, and nucleic acids follow similar principles, with protection from degradation and regulated cellular delivery as important formulation aims.

9 Advantages of Nanoparticle Drug Delivery

- Improved dissolution and apparent solubility of poorly water-soluble drugs.
- Potential enhancement of oral or systemic bioavailability.
- Protection of sensitive drugs from chemical or enzymatic degradation.

• Controlled, sustained or stimulus-responsive drug release.
• Possibility of passive or active targeting.
• Potential reduction of systemic toxicity by modifying drug distribution.
• Ability to combine therapeutic and diagnostic functions in theranostic systems.[36]
• Opportunities for delivery of difficult molecules such as nucleic acids, peptides and proteins.

10. Limitations and Safety Concerns

Nanoparticles should not be seen as inherently superior to traditional dosage forms. Their performance is highly dependent on composition, size, surface charge, shape, aggregation state, and mode of administration. Simple in-vitro experiments may not anticipate how nanoparticles interact with plasma proteins, immune cells, cell membranes, and organs.[20,29]

Insufficient understanding of nanomaterial toxicity remains a major barrier to wider translation, according to the 2018 literature. Toxicity is a major concern, especially for inorganic materials and systems that persist in the body. Oxidative stress, inflammatory responses, organ accumulation, and unexpected interactions with biological membranes must all be considered. Even biodegradable materials must have their degradation products evaluated.[1] Manufacturing and regulatory challenges are equally important. Small changes in particle size, surface chemistry or process conditions can change biological performance. Therefore, quality-by-design principles, robust analytical characterization and appropriate specifications are essential. Regulatory agencies must also evaluate nanomedicines in a way that accounts for their unique physicochemical and biological characteristics.[24,34]

11. Evaluation and Characterization of Nanoparticles

A comprehensive nanoparticle characterization program typically comprises particle size, polydispersity index, zeta potential, shape, surface chemistry, drug content, encapsulation efficiency, in vitro drug release, physical stability, and chemical stability. Depending on the formulation, additional tests may include crystallinity, thermal behavior, residual solvent, sterility, endotoxin level, and biological compatibility.[35]

Particle size is particularly important because it affects biodistribution, cellular uptake, clearance, and stability. Surface charge influences interactions with membranes and proteins, whereas shape influences circulation and absorption. These parameters should be interpreted together.Dynamic light scattering is typically employed to determine hydrodynamic size and polydispersity, whereas electron microscopy offers information on shape. Zeta-potential measurements are used to quantify surface charge and colloidal stability.[12] Current andFuturePerspectives

The focus of nanoparticle medication delivery is shifting from basic carriers to multifunctional systems. Future formulations are likely to incorporate targeting, controlled release, imaging, and personalized therapy in a single platform. The 2018 literature also emphasized the significance of

converting promising laboratory systems into replicable pharmaceutical solutions rather than relying solely on proof-of-concept experiments[1,3]Another important direction is the development of safer and more sustainable materials. Natural polymers, biodegradable lipids and greener synthesis routes may reduce some environmental and biological concerns, although every new material still requires rigorous safety evaluation.[15] Advances in artificial intelligence, computational formulation design and high-throughput screening may further help researchers select materials and process conditions more efficiently.In the long term, the success of nanomedicine will depend on whether it can provide a meaningful clinical benefit over established dosage forms at an acceptable cost and with predictable quality. The strongest formulations will therefore be those that solve a clearly defined pharmaceutical problem rather than using nanotechnology simply because it is technically possible.

13. CONCLUSION

Nanoparticles have altered the way pharmacists and pharmaceutical scientists approach medicine delivery. Their main significance is from their capacity to influence drug behavior by controlling particle size, content, surface features, and release mechanisms. Polymeric nanoparticles, lipid systems, micelles, dendrimers, metallic nanoparticles, and nanocrystals all have unique advantages and limits. According to the 2018 literature, nanoparticle systems can increase solubility, bioavailability, stability, targeting, and controlled release, as well as facilitate the delivery of challenging medicinal compounds[1,2,3]At the same time, nanotechnology is not free from challenges. Toxicity, protein-corona formation, scale-up, reproducibility, stability, regulatory requirements and manufacturing cost must be addressed before a promising formulation can become a dependable medicine. For pharmacy practice and pharmaceutical research, the most useful approach is therefore a balanced one: select nanoparticles only when their properties provide a clear therapeutic or formulation advantage, and evaluate the complete product from material selection to clinical performance.

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