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Recent Advances and Biomedical Applications of Nanoparticles as Drug Delivery Systems: A Comprehensive Review

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ABSTRACT: Nanotechnology has improved the solubility, bioavailability, and controlled release of poorly soluble drugs and reduced off-target toxicity by precision targeting in medicine, food preservation, and industry for 40 years. This research studied polymeric, liposomal, and mesoporous nanoparticles (NPs) of structural features, fabrication methods, biological interactions, and therapeutic uses for drug transport efficiency and long-term safety. The experimental and clinical data on particle size, shape, surface chemistry, encapsulation techniques, drug transport kinetics, biodistribution, and cytotoxic responses both in vitro and in vivo for the conventional formulations. After 48 hours, poly(isohexylcyanoacrylate) nanocarriers delivered 56% of the injected dose to the liver and 1.6% to tumors, whereas liposomal doxorubicin (Doxil) increased tumor formation and lowered systemic toxicity by reduced macrophage clearance and cytotoxicity, PEG-coated NPs boosted tumor uptake and circulation. Silver or zinc oxide NPs prevented microbial degradation in strawberries, asparagus, and chicken, whereas mesoporous silica carriers stabilized hydrophobic agents and controlled payload release. The AuNPs and high-aspect-ratio particles generated oxidative stress and mitochondrial damage, affecting cytotoxicity. Thus, NPs increase therapeutic index but need surface property and release profile adjustment to address immune recognition, organ accumulation, and chronic toxicity.

Keywords: NPs; Drug delivery; Nanotechnology; Medicine

1. INTRODUCTION

Drug delivery determines how efficiently an active compound reaches its target tissue, influences therapeutic success, and limits side effects by controlling dose and release rate. Researchers have developed nanoparticles to improve solubility, prolong circulation, and enhance tissue selectivity, while previous trials showed higher tumor uptake and reduced systemic toxicity when drugs were encapsulated (1).

Nanoparticles are characterized as particulate dispersions or solid particles of between 10 and 1000 nanometers in size. The medicine is dissolved, bound encased, or affixed to a nanoparticle matrix. Nanoparticles, tiny particles, or small capsules may be produced based on the procedure of preparation used. Nanocapsules are systems whereby the drug is enclosed inside a cavity encased by a distinctive polymer membrane. Recently, biodegradable polymeric nanoparticles, especially those coated via hydrophilic polymers like poly(ethylene glycol) (PEG), referred to as long-circulating particles, have been utilized as prospective drug delivery systems due to their capacity for extended

circulation, targeted organ delivery, and transport of DNA in gene therapy, as well as their efficacy in delivering proteins, peptides, and genes (2).

The primary objectives in developing nanoparticles as a mechanism of administration are to regulate particle size, surface characteristics, and the release of pharmacologically active substances to ensure specific to the site drug activity at the therapeutically appropriate rate and dosage regimen (3). Despite being useful as carriers with distinct advantages, such as safeguarding pharmaceuticals from breakdown, focusing on specific sites of action, and minimizing toxicity or side effects, the industrial use of liposomes is constrained by intrinsic issues, including rapid leakage of water-soluble drugs, and inadequate storage stability. Conversely, polymeric nanoparticles have distinct benefits compared to liposomes. For example, they enhance the strength of pharmaceuticals and proteins while exhibiting beneficial controlled release characteristics (4).

Oral, nasal, parenteral, and intra-ocular delivery are covered. Ancient nanotechnology impacted drug delivery and the pharmaceutical business. Nanoparticles, typically below 0.1 μm or 100 nm, are often utilized in drug delivery. Drugs are dissolved, encapsulated, or bonded to nanoparticles. Nanoparticles impact absorption and biodistribution, making them effective drug carriers. The hydrophobic core facilitates drug loading, while the hydrophilic surface prevents opsonization and enhances mobility throughout the system. Various nanodevices have been documented in the nanotechnology domain, including carbon nanotubes, quantum dots, and polymeric micelles (5).

Mesoporous nanoparticles are gaining prominence for their established medication delivery and targeting capabilities (6). Kresge et al. have historically delineated a method for integrating sol-gel chemistry with liquid-crystalline templating to fabricate ordered porous molecular sieves, distinguished by periodic configurations of uniformly sized mesopores (ranging from 2 nm to 50 nm) embedded within an amorphous silica matrix (7).

Nanotechnology is the intentional manufacturing and modification of particles sized between 1 nm to 100 nm, facilitating their redesign or integration to nano-systems having more efficient operation. The emergence of nanomaterials and its possible uses have placed Ireland in the vanguard of scientific research over this past century. Nanoparticles represent pinnacle of application alteration and are essential, and their dimensions are marginally more significant than those of atoms, resulting from the molecular manipulation of substances. Due to their superior attributes, including auto-reactive stability and self-reassembly, they exhibit remarkable adaptability. They may be tailored to attain particular traits or desired qualities, such as increased surface area, in contrast to traditional materials (8).

During the past two decades, nanotechnology has gained popularity and is rapidly moving from academia to industry. Nanotechnology, demonstrating its economic feasibility. Nanoparticles' special physicochemical features at the intersection of chemistry, health sciences, science, and technology explain this (9).

Nanotechnology is a fast-growing scientific discipline with significant advances in several sectors, and latest nanotechnology advances include energy, electronics, and others, while technology researchers are using nanoscale gadgets and other pieces to produce faster, smaller, and greener systems. Advanced materials and techniques for turning sunlight into electricity and storing it are developed using nanotechnology. The NPs provide new medical testing, treatment, and biotechnology methods. Nanotechnology is a vibrant and rapidly evolving field with many potential achievements and applications (10).

A promising use is medication delivery, whereby nanoparticles serve as trans to pharmaceuticals to target human cells. Nanoparticles may be designed with unique surface characteristics that enable selective targeting of sick cells while sparing healthy ones, enhancing effectiveness and minimizing therapeutic adverse effects. Furthermore, nanoparticles may be engineered to release their payload in a regulated fashion. Nanoparticles have been used for applications. In regenerative therapies, nanomaterials serve as templates for human biological processes or as aids for developmental variables and target derivatives that are synthesized to promote tissue regeneration. The nascent subject of synthesized nanomaterials has significant potential for enhancing the diagnosis and treatment of many medical problems (11).

Research on nanoparticle drug delivery still leaves critical questions unanswered because long-term toxicity data remain scarce, and most investigations have focused on short treatment periods. If future studies integrate systematic clinical trials with standardized manufacturing and real-time imaging, then outcomes will better clarify biodistribution, immune interactions, chronic organ effects, and patient variability.

The aim of this study is to evaluate how nanoparticle-based carriers enhance drug solubility, improve bioavailability, and regulate release while minimizing systemic toxicity. The review compares polymeric, liposomal, metallic, and mesoporous systems to identify the design factors that influence biodistribution, therapeutic performance, and safety across experimental models and clinical settings.

2. NANOTECHNOLOGY INDUSTRIAL UTILIZATION

2.1 FOOD INDUSTRIES

As knowledge and demand for healthy culinary goods rise, research has focused on developing strategies to enhance preservation duration and nutrition digestibility. In the past few years, nanomaterials have been widely used

for maintaining food and the distribution of dietary supplements. Nanomaterials have been put into containers as protection or antibacterial properties and have demonstrated considerable promise. Silver nanoparticles (AgNP) are among the most often used additions for this purpose, partly owing to silver's inherent antibacterial qualities. Silver nanoparticles (AgNP) may be used in food products as a consumable disposable layer for goods such as fruits and poultry. Numerous investigations have evaluated the preservation effectiveness of silver nanoparticle-infused material on the asparagus plant, chicken meat, and strawberries, all of which extended shelf life by inhibiting the activities of pathogens, exhibit effectiveness against many foodborne diseases., including S. aureus, Salmonella typhi, and Klebsiella pneumonia. As recorded, they preserve food products, comprising citrus juice, berries, and eggs with liquid albumen. TiO2 and ZnO2 were also employed as nutritional supplements due to their brightening and UV-protective attributes (12).

Nano-encapsulation is an established technique to safeguard and enhance the diffusion of advantageous nutrients and tastes in dietary supplements. It is mostly carbohydrate-modified starch, dextrin, and other sources. Phosphatidylcholine-based liposomes deliver vitamin C, demonstrating superior efficacy in preserving the nutrient's bioavailability, likely due to the controlled release of the content, in contrast to orally administered free supplements (13, 14).

Nanotechnology in the business has enabled the cost-effective and practical extension of the shelf life of fresh food goods. Although nanoparticles that enhance nutraceutical delivery are generally healthy and utilized in packaging, they may sometimes leak into the primary product, potentially leading to unhealthy. Although it is anticipated that daily consumption of up to 80 µg of AgNPs may occur, there are few contradictory data about the harmful effects of swallowed AgNPs. Some investigations indicate that AgNPs are safe for intake without hazardous consequences. Although this may raise concerns, evaluating if dietary sources can attain the concentration of AgNPs tested in this research is essential (15).

2.2 COSMETICS INDUSTRIES

Cosmetic companies use nanotechnology to incorporate NPs for various purposes, and due to their size, zinc oxide and titanium dioxide nanoparticles make excellent sunscreens. Their reduced particle size makes them effective UV radiation filters without health risks or white streaking. However, liposomes created from synthetic or organic lipids have various personal care benefits. These ethosomes and transferases help liposomal components enter and diffuse for transdermal therapeutic cosmetic ingredient administration. The AgNPs is significant components in some cosmetic formulations due to their efficacy as antibacterial agents, particularly in bathing products. Additionally, owing to their activity against various yeast strains, AgNPs are incorporated into diverse dental products, including mouthwash and toothpaste (16).

2.3 NANOMEDICINE

Dr. Richard P. Feynman first conceptualized nanotechnology for medical purposes during the late 1950s, proposing the creation of molecular instruments with atomic precision for medicinal applications. Dr. Richard P., elucidated the use of chemical devices can perform surgical procedures or inhabit humans to provide functional support for impaired organs. Nanotechnology has significantly impacted the medical industry, transforming illness treatment, especially using sophisticated drug delivery systems using both natural and synthetic substances. Scientists at the Wyss Institute for Nanotechnology at Harvard University created a "nano-robot" capable of precisely targeting cancer cells to administer chemotherapy medicines. Nano-robots capable of addressing cardiovascular illnesses. Therefore, significant attempts are being made to improve the effectiveness of several conventional medications (17).

Some nanomaterials are thought to exhibit superior chemical functions, return to material properties and small volume; they may choose to affect specific cells depending on the kind of particle. The resulting particles may easily penetrate the desired cells and cluster into inside cells to modify the functions of cells, perhaps assisting in the treatment of chronic diseases. As a result, the FDA has authorized some nanomaterials to be sold in the United States for clinical use (18).

Consequently, many nanoparticle delivery techniques have been developed, including liposomes, synthetic a new compounds, and others. Encapsulating hydrophobic and hydrophilic pharmaceuticals inside liposomes is feasible, facilitating the circumvention of toxicity linked to anticancer agents. Notably, nanoparticles, specifically liposomal delivery methods, are well established for disease therapy, exemplified by DoxilTM (liposomal doxorubicin), which has received FDA approval for treating Kaposi sarcoma and ovarian cancer. Effective liposomal encapsulation boosts medication effectiveness. Liposome modification allows passive or aggressive tumor inhibition (Figure 1). This permits cancer cells to get drug payloads without harming non-cancerous cells. DPPC-based liposomes boost doxorubicin's cytotoxicity and reduce its toxic side effects, improving its antitumoral efficacy (19).

Nanoparticles are gradually used in healthcare and imaging techniques for the diagnosis of internal structures and tissues, owing to their relationship to human cells, which are ascribed to their tunable chemical and physical characteristics, such as dimensions, form, visible, attracting, and electronic attributes (19).

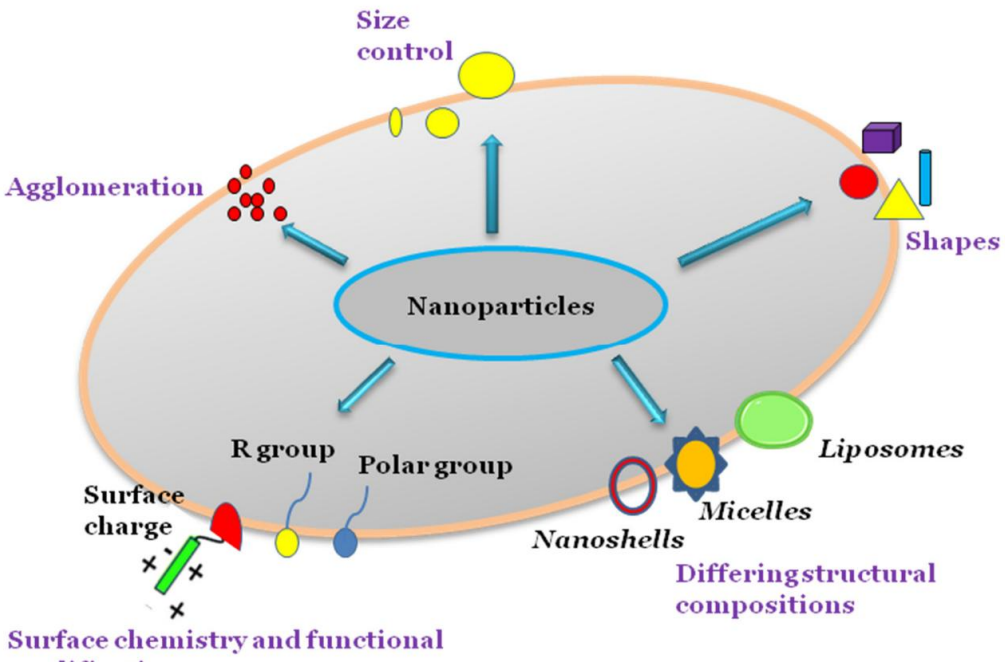

FIGURE 1. - Physicochemical properties of nanoparticles (19)

As previously mentioned, nanoparticles possess adjustable dimensions, and their shapes may also be regulated throughout production. The morphology of nanoparticles may be modified until the final synthesis step, which often entails the nucleation of nanomaterials from a single seed. The formation process involves the aggregation of nanoparticles that deliver nuclei, which are known as plants and serve as a foundation for the development of nanoparticle structures. The morphology of a nanomaterials, similar to its dimensions. Particles that are spherical are often more efficiently endocytosed than rod or tube-shaped nanomaterials. The diminished process of nano-rods or alternative morphologies is probably attributable to the cellular incapacity. This rationale may clarify why most nanoparticles possessing pharmacological activities are mostly sphere in form. Conversely, recent research indicates that nanomaterials of various forms possess potential uses in medication delivery (20, 21).

The pronounced X-ray scattering of ceramic nanoparticles renders them advantageous for improving contrast in computed tomography (CT) images, facilitating the detection and monitoring of various diseases and disorders, including tumors. Conventional disinfection just generates a microbiological result, which may prove ineffectual after the disinfection process. Conversely, AgNP films on healthcare equipment and materials remain active against several kinds of bacteria, provided that the tiny particles are retained on the material's face. Nanotechnology seems very influential in medicine, as it is used as a medicinal agent due to its bactericidal qualities and for imaging and diagnostic applications. The unique features of nanoparticles facilitate these discoveries, and the surge in nanotechnology research within the medical domain exhibits no indications of abating (22). Designing these nanoplatforms necessitates the consideration of numerous critical characteristics to guarantee their efficacy and safety for the desired use. Several primary problems encompass, such as evaluating the release dynamics of the product from the small platform is essential for medical uses. The rate of release must be meticulously regulated to ensure the load gets delivered efficiently and accurately (20). In addition to assessment of aiming and concentration: Evaluating the aim and accumulation of the small platform in the designated tissue or function for use in medicine is essential. The micro platform must selectively target and accumulate at the designated spot to enhance its therapeutic efficacy (4).

3. APPLICATIONS OF NANOPARTICULATE DELIVERY SYSTEMS

Targeting tumours with nanoparticulate systems for delivery. The justification for employing tiny particles in tumor focusing is predicated on two factors:

- Nanoparticles can administer a high level of medication near tumor sites through the increased capacity for permeability and retention or targeted delivery via surface ligands (23).
- Nanoparticles minimize drug exposure to healthy tissues by restricting the distribution of drugs to the target organ (23).

Andrieux, et al. It was found that mice receiving doxorubicin encased in poly(isohexylcyanoacrylate) nanomaterials had increased levels of chemotherapeutic in the spleen, liver, and lung relative to those that received free chemotherapeutic. Studies demonstrate that the polymeric properties of small particles, such as type, hydrophobicity,

and biodegradation profile, in conjunction with the drug's molecular size, its positioning within the tiny particles, and its absorption method—whether adsorption or integration—substantially influence the drug transportation structure in vivo. The precise underlying mechanism remains incompletely elucidated; nevertheless, the biodistribution of nanoparticles occurs swiftly, between 30 minutes to 3 hours, and presumably includes the mononuclear phagocyte system and the processes of endocytosis and phagocytosis (24).

In recent years, Bhuyan, et al. demonstrated the distribution in the body and pharmacology. Distribution investigations indicated a decline in medication concentrations with time in the heart, lung, kidney, and plasma, whereas concentrations increased in the liver, spleen, and tumors (25). The predominant injected dosage localized in the liver (56%), with just 1.6% detected in the tumor at 48 hours post-injection, affirming the propensity of nanoparticles to be sequestered by the liver. The primary issue in using nanomaterials for cancer focusing is to prevent their absorption by the MPS in some parts of the human body (23).

The MPS's propensity for a process called end and absorption of nanoparticles offers an effective method for efficiently delivering medicinal medicines to these individuals. This biodistribution may improve the chemotherapeutic treatment of tumors situated in MPS-rich cells and organs, including hepatocarcinoma, hepatic metastases from the gastrointestinal tract or gynecological cancers, bronchopulmonary tumors, primary tumors and metastases, small cell tumors, myeloma, and leukemia. Studies indicate that doxorubicin-encapsulated conventional nanomaterials are efficacious in a systemic cancer model using mice. A more significant decrease in the extent of metastases was seen compared to using the free medication. The mechanism underpinning the enhanced therapeutic effectiveness of the formulation involves the transfer of doxorubicin from healthy tissue, which serves as a drug reservoir, to malignant cells (5, 14). The histological investigation demonstrated a significant accumulation of nanomaterials within the intracellular recesses of Kupffer cells, but nanomaterials were not seen in cancer cells.

As a consequence, Kupffer cells, after significant nanoparticle uptake by phagocytosis, promoted the release of doxorubicin, creating a concentration gradient that favored the continuous flow of the active and unbound drug towards neighboring metastatic cells (4).

4. CYTOTOXICITY OF NANOPARTICLES

The emergence of nanotechnology and its expanding use in all daily life raises concerns about potential risks from heightened human exposure. Extensive investigation into nanoparticle exposure's hazardous effects led to nanotoxicology's emergence. Recent advancements in this sector have shown the characteristics of nanoparticles that impart favorable pharmacologic qualities (26).

Numerous research studies have examined nanoparticles' toxicity using diverse cell lines and experimental settings. The detrimental effects of nanotubes made of carbon have been displayed to affect soil variety of bacteria, hinder the growth of Daphnia magna, Chlorella vulgaris, and Oryzias latipes, and provoke oxidative stress, membrane damage, and inflammation in the A549 human lung tumour cell line. Numerous studies demonstrate that the mechanism of nanoparticle size-dependent cytotoxicity stems from their ability to infiltrate physiological organs and then reach cells, disrupting critical cellular activities, including the disruption of subcellular membrane integrity. Elevated amounts of ROS produce oxidative stress, disrupting normal cellular physiological processes and leading to DNA damage, cell signalling dysregulation, and cell death (27).

Nanomaterials often modify their surfaces to enhance performance. The surface chemical composition of nanoparticles may increase nanocell death. Nanomaterials with reactive surface moieties may interact with intracellular or exterior molecules depending on their biological system location, changing tissue functions (25). Charged AuNPs are more cytotoxic than neutral ones because oxidative stress lowers mitochondrial activity and increases DNA damage-related gene expression. Ionic cyanoacrylic nanoparticles destroy macrophages better than cationic ones. PEGylated particle retention and stability may reduce cytotoxicity by lowering cellular absorption (27).

Nanoparticle size, shape, and aspect ratio determine in vivo toxicity. Due to slower clearance and increased bioavailability, larger aspect ratio nanomaterials increase cell death. Nanoparticles with a higher dimension ratio harm cells like mesothelioma (27).

5. DISCUSSION

Nanoparticles have expanded therapeutic and industrial applications because they improve drug solubility, extend circulation, and allow targeted release while reducing systemic toxicity. In medicine, liposomal doxorubicin has increased tumor drug concentration and lowered adverse effects, while mesoporous silica carriers have maintained the stability of hydrophobic compounds and delivered controlled payloads. Food packaging that integrates silver or zinc oxide nanoparticles has delayed microbial spoilage of strawberries, asparagus, and chicken by suppressing bacterial growth. In cosmetics, titanium dioxide and zinc oxide nanoparticles have improved ultraviolet protection without altering product texture, and liposomal carriers have enhanced dermal absorption of active agents. Diagnostic imaging has advanced because iron oxide nanoparticles have increased tissue contrast in computed tomography scans. These examples show that adjusting particle size, shape, and surface chemistry determines therapeutic performance. If future

studies integrate standardized manufacturing with clinical testing, then nanoparticle technologies will continue to broaden their safe and effective applications.

6. FUTURE PERSPECTIVES

Future research should prioritize large-scale clinical trials that integrate standardized nanoparticle synthesis with long-term safety monitoring because inconsistent production has limited reproducibility. If advanced imaging and molecular profiling are combined with optimized surface modifications, then drug carriers will achieve more precise targeting, reduce chronic toxicity, and support personalized therapeutic strategies across diverse patient groups.

7. CONCLUSION

Liposomal carriers such as Doxil and mesoporous silica systems have achieved the most consistent success because they improve drug solubility, prolong circulation, and allow controlled release with lower systemic toxicity. The main challenges remain unpredictable biodistribution in humans, limited long-term toxicity data, immune recognition, and variable manufacturing quality that reduces reproducibility and delays regulatory approval. Additional barriers include the difficulty of controlling release kinetics under physiological conditions and the limited understanding of how surface charge and morphology affect chronic organ accumulation. Future perspectives focus on integrating standardized large-scale production with advanced molecular imaging to monitor biodistribution in real time, improving surface functionalization to reduce immune clearance, and expanding controlled clinical trials in diverse patient populations. If these strategies are applied together with long-term safety assessments, then nanoparticle carriers will deliver more precise targeting, minimize chronic adverse effects, and support broader therapeutic use in oncology, infectious disease management, and regenerative medicine.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest

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