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Review Article

# Nanomaterial marvels: Pioneering applications and cutting-edge advancements in drug delivery

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**ABSTRACT:** Nanotechnology has revolutionized the field of medicine, particularly in the development of novel drug delivery systems. Nanomaterial-based drug delivery systems offer several advantages over traditional methods, including enhanced therapeutic efficacy, improved bioavailability, targeted delivery, and reduced side effects. This review provides an overview of the applications and recent advancements in nanomaterial-based drug delivery systems. The first section of this review focuses on the different types of nanomaterials used in drug delivery, including liposomes, polymeric nanoparticles, dendrimers, carbon-based nanomaterials, and metallic nanoparticles. Each nanomaterial has unique physicochemical properties that can be tailored to optimize drug encapsulation, release, and targeting. The second section highlights the importance of nanoscale characterization techniques in evaluating the properties and performance of nanomaterial-based drug delivery systems. Characterization techniques such as dynamic light scattering, transmission electron microscopy, atomic force microscopy, and spectroscopic methods enable researchers to analyze particle size, morphology, surface charge, drug loading, and release kinetics. The third section discusses the application of nanomaterial-based drug delivery systems in various therapeutic areas, including cancer treatment, cardiovascular diseases, infectious diseases, and neurological disorders. These systems can be engineered to selectively accumulate at the target site, enhancing drug efficacy and minimizing off-target effects. The fourth section explores recent advancements in nanomaterial-based drug delivery systems, including stimulus-responsive and multifunctional nanocarriers. Stimuli-responsive systems can release drugs in response to specific triggers, such as changes in pH, temperature, or enzymatic activity, leading to site-specific drug release. Multifunctional nanocarriers combine drug delivery with diagnostic imaging, allowing real-time monitoring of drug distribution and therapeutic response. The final section addresses the challenges and future perspectives in the field of nanomaterial-based drug delivery systems. Challenges include regulatory considerations, toxicity concerns, scalability, and clinical translation. Future directions involve the development of personalized nanomedicine, combination therapy approaches, and integration with other emerging technologies, such as

artificial intelligence and gene editing. In conclusion, nanomaterial-based drug delivery systems have shown great potential for improving the efficacy and safety of therapeutic interventions. The advancements in nanotechnology offer exciting opportunities for the development of next-generation drug delivery platforms, opening new avenues for personalized medicine and targeted therapies. However, further research and collaborations are required to address the challenges associated with clinical translation and ensure the safe and effective implementation of these systems in clinical practice.

***KEYWORDS:*** nanomaterials; drug delivery systems; nanotechnology; targeted delivery; artificial intelligence

# 1. Introduction

The rapid advancements in nanotechnology have sparked a revolution in various industries, with medicine being no exception (**Figure 1**). The integration of nanotechnology in drug delivery systems has shown immense promise, offering a novel approach to enhance therapeutic outcomes while mitigating side effects.

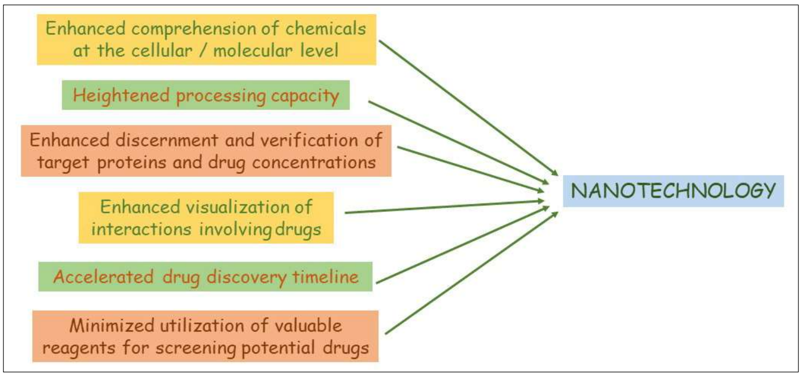



**Figure 1.** Advancement in nanomaterial-based drug delivery systems.

Nanomaterial-based drug delivery systems leverage unique physicochemical properties and customizable surface modifications of nanomaterials to precisely deliver therapeutic agents to targeted sites. Nanomaterials encompass a diverse array of structures, such as liposomes, polymeric nanoparticles, dendrimers, carbon nanotubes, and metallic nanoparticles, each exhibiting distinct advantages and limitations[1]. Liposomes, for instance, mimic cell membranes and can encapsulate both hydrophilic and hydrophobic drugs, while polymeric nanoparticles provide a tunable release profile for sustained drug delivery[2]. This versatility allows researchers to tailor drug carriers for specific applications. One of the primary benefits of nanomaterial-based drug delivery systems is their ability to enhance drug targeting and bioavailability significantly. These systems can be engineered to selectively accumulate in diseased tissues or cells, reducing off-target effects and improving therapeutic efficacy. Additionally, nanomaterials shield drugs from premature degradation and clearance by the body, extending their circulation time and improving bioavailability[3]. Moreover, nanomaterial-based drug delivery systems offer a unique advantage in overcoming biological barriers, such as the blood-brain barrier, which restricts the delivery of therapeutics to the brain. By leveraging specific surface modifications and receptor-mediated interactions, nanocarriers can breach these barriers and enable drug delivery to previously inaccessible sites, holding great potential for the treatment of neurological disorders and brain tumors[4]. Another critical aspect of nanomaterial-based drug delivery is the ability to achieve controlled drug release. These systems can be designed to release therapeutic agents in a sustained manner, minimizing the frequency of dosing and ensuring a more consistent drug concentration at the target site. This controlled release can enhance patient compliance and reduce side effects associated with high-peak drug concentrations[5]. While nanomaterial-based drug delivery systems hold tremendous promise, ensuring their safety and biocompatibility is paramount. Researchers conduct comprehensive safety evaluations to assess the potential toxicity and biocompatibility of these nanocarriers, addressing any concerns before clinical translation[6]. In conclusion, nanomaterial-based drug delivery systems represent a cutting-edge approach to revolutionizing modern medicine. By leveraging the unique properties of various nanomaterials, these systems enable enhanced drug targeting, improved bioavailability, and controlled drug release. Overcoming biological barriers further expands the potential applications of nanocarriers in treating challenging diseases. However, rigorous safety evaluations are essential to harnessing the full potential of these systems for safe and effective clinical use.

## 2. Current status of nanotechnology

Nanotechnology, the manipulation of materials and devices at the nanoscale level, has emerged as a powerful and versatile field with applications spanning across electronics, medicine, energy, and environmental sciences. In the medical realm, nanotechnology has made remarkable strides in drug delivery systems. Nanoparticles designed for targeted drug delivery have shown immense promise in cancer treatment. By delivering medications directly to tumor cells, these nanoparticles enhance treatment effectiveness while reducing adverse effects on healthy tissues[7]. Nano-sensors, another breakthrough in nanotechnology, have proven invaluable in various sectors. These advanced sensors can detect even the slightest concentrations of specific molecules, opening up possibilities for environmental monitoring, food safety, and medical diagnostics. Notably, nano-sensors have been investigated for their potential in the early detection of diseases like Alzheimer's and diabetes, offering hope for improved healthcare[8]. The electronics industry has experienced a revolution due to nanotechnology's contributions. Nanoscale transistors and components have facilitated the continuous miniaturization of electronic devices, leading to more powerful and energy-efficient computers and smartphones. The exploration of novel materials like carbon nanotubes and graphene has opened new avenues for future electronic applications[9]. Nanotechnology's influence extends to renewable energy technologies. Researchers have developed nanomaterials that boost the efficiency of solar cells, energy storage devices, and catalysis for hydrogen production. These advancements promise to enhance sustainable energy solutions, which are critical for addressing global energy challenges[10]. Amidst the excitement and progress, nanotechnology faces essential challenges. Environmental impact, health and safety concerns, and ethical considerations require careful attention. It is crucial for researchers, policymakers, and industries to collaborate in addressing these challenges to ensure the responsible and sustainable development of nanotechnology.

## 3. Overview of various industrial implications of nanotechnology

### 3.1. Food industry

Nanotechnology has emerged as a revolutionary field with significant implications for various industries, including the food sector. Its application in the food industry has the potential to enhance food quality, safety, and sustainability while creating new opportunities for innovation (**Figure 2**). Nanotechnology permits the development of advanced packaging materials with improved barrier properties, thus enhancing the preservation of food products and reducing food spoilage. Nanocomposite films and coatings can protect against oxygen, moisture, and microbial contamination, extending the shelf life of perishable goods[11]. Nanoencapsulation enables the delivery of bioactive compounds such as vitamins, antioxidants, and omega-3 fatty acids to specific target sites within the body, leading to better nutrient absorption and bioavailability. This can help address nutrient deficiencies and improve overall consumer health[12].

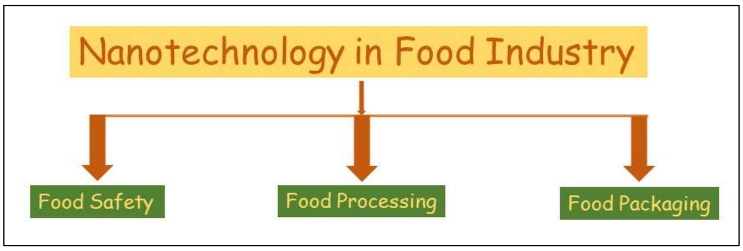



**Figure 2.** Nanotechnology in food industry.

Nanoscale sensors can be integrated into packaging materials to detect and monitor food spoilage, contamination, and pathogens. These smart sensors can provide real-time information about food quality, ensuring consumer safety and reducing foodborne illnesses[13]. Nano-emulsions and nanoliposomes enable the controlled release of flavor compounds, enhancing the taste and aroma of food products. Additionally, nanostructured ingredients can improve the texture and mouthfeel of processed foods[14]. Nanoparticles such as silver nanoparticles have antimicrobial properties and can be incorporated into food packaging or coatings (**Figure 3**) to inhibit the growth of bacteria and fungi, leading to improved food safety and reduced reliance on chemical preservatives[15].


**Figure 3.** Application of nanotechnology in food packaging[16].

Nanotechnology can optimize food processing methods by improving emulsification, stabilizing formulations, and facilitating the controlled release of additives. This results in better product uniformity and consistency[17]. Nanotechnology can be applied in agriculture to improve crop protection, nutrient uptake, and soil fertility. Nano-pesticides, for example, can reduce the number of chemical pesticides used, leading to reduced environmental impact and potential health benefits[18].

While nanotechnology holds great promise for the food industry, there are also concerns about potential risks related to the safety of nanomaterials. As the industry explores nanotechnology applications, it is crucial to address these concerns and conduct thorough risk assessments to ensure consumer safety and regulatory compliance.

### 3.2. Cosmetic industry

Nanotechnology has made significant advancements in the cosmetic industry, providing numerous applications that enhance product effectiveness, stability, and overall performance (**Figure 4**).

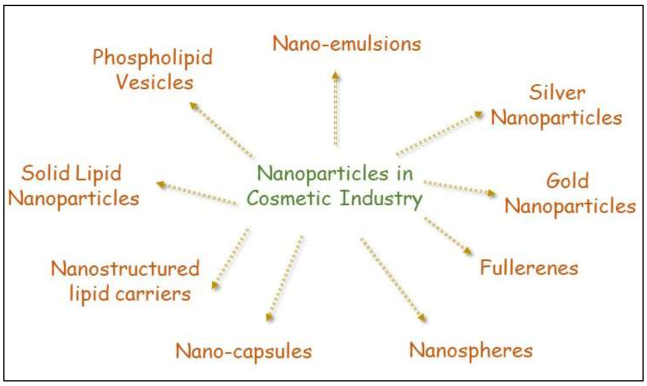
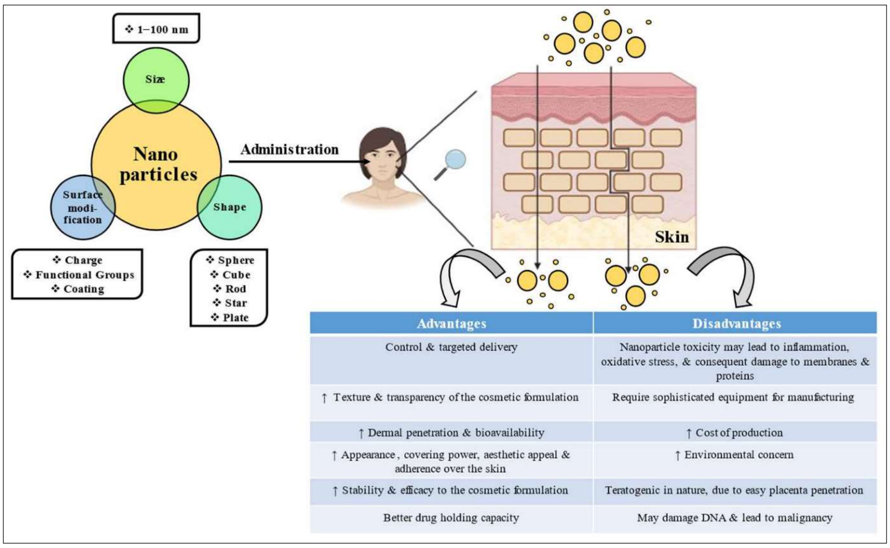



**Figure 4.** Nanoparticles in cosmetic industry.

Nano-emulsions and nanoliposomes: Nano-sized emulsions and liposomes enable better delivery of active ingredients like vitamins, antioxidants, and skin-nourishing compounds. They enhance the penetration of these ingredients into the deeper layers of the skin, improving their effectiveness and providing long-lasting benefits[19]. Sun-screen Formulations: Nanoparticles such as zinc oxide and titanium dioxide are used in sunscreens to create transparent, broad-spectrum UV protection. The nanoparticles scatter and absorb UV rays more effectively, reducing the appearance of white residues and providing enhanced sun protection[20]. Skin Care Products: Nanotechnology facilitates the development of nanostructured materials that can mimic the natural skin structure and functions. These materials can hydrate the skin, improve moisture retention, and protect against environmental stressors, contributing to healthier and younger-looking skin[21]. Nano-delivery systems enable the controlled release of anti-aging compounds, such as retinoids and peptides, to target specific skin layers. This helps reduce wrinkles, fine lines, and age-related skin damage[22]. Nanocarriers like nanogels and nanoparticles can encapsulate and deliver cosmetic ingredients precisely to the desired skin areas, allowing targeted treatment for various skin conditions[23].




| Advantages | Disadvantages |
|---|---|
| Control & targeted delivery | Nanoparticle toxicity may lead to inflammation, oxidative stress, & consequent damage to membranes & proteins |
| ↑ Texture & transparency of the cosmetic formulation | Require sophisticated equipment for manufacturing |
| ↑ Dermal penetration & bioavailability | ↑ Cost of production |
| ↑ Appearance, covering power, aesthetic appeal & adherence over the skin | ↑ Environmental concern |
| ↑ Stability & efficacy to the cosmetic formulation | Teratogenic in nature, due to easy placenta penetration |
| Better drug holding capacity | May damage DNA & lead to malignancy |

**Figure 5.** Advantages and disadvantages of nanocosmetics[24].

Nano-sized ingredients in hair care products can penetrate hair strands more effectively, offering improved conditioning, repair, and protection against damage caused by heat and styling[25]. Nanotechnology enables the encapsulation of fragrances in nano-sized carriers, leading to sustained release and longer-lasting scents in perfumes and cosmetic products[26]. Nanoparticles can modify the texture and consistency of cosmetic formulations, providing smoother textures, better communication, and enhanced sensory experiences during product application[27]. It is essential to note that while nanotechnology offers significant benefits in cosmetic applications, safety considerations are crucial. The potential risk of nanoparticle penetration into the skin or other adverse effects must be carefully evaluated through thorough research and regulatory assessments (**Figure 5**).

### 3.3. Nanomedicine

Nanotechnology has revolutionized the field of nanomedicine, offering exciting applications that hold immense promise for the diagnosis, treatment, and prevention of various diseases (**Figure 6**).

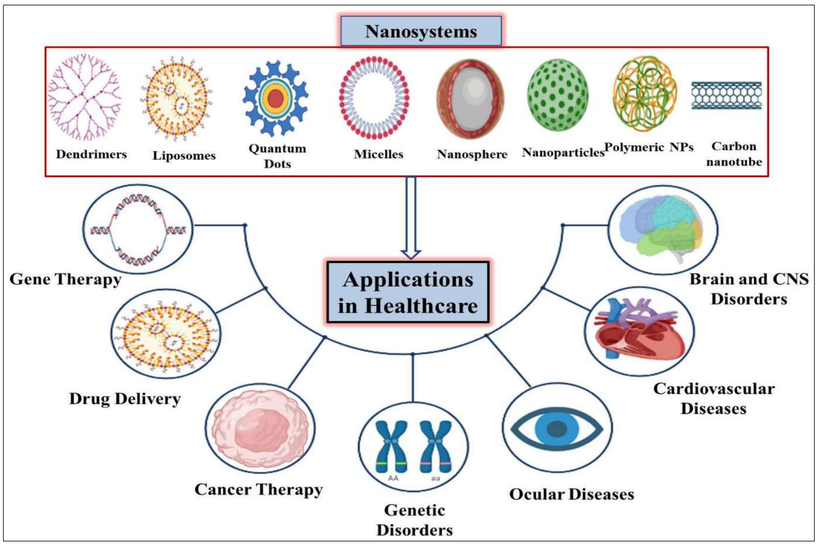



**Figure 6.** Nanotechnology in health care[28].

Nanoparticles and nanocarriers can be engineered to deliver drugs and therapeutic agents more effectively to specific target sites in the body. This targeted drug delivery minimizes side effects, increases drug bioavailability, and allows for sustained release, improving treatment outcomes[29]. Nanoparticles can be functionalized with imaging agents, such as quantum dots or iron oxide nanoparticles, to improve contrast in medical imaging techniques like MRI, CT, and optical imaging. These nanoprobes enable earlier and more accurate disease detection[30]. Nanotechnology has enabled the development of innovative cancer treatments, including photodynamic therapy (PDT), hyperthermia, and gene therapy. Nanoparticles can be used to deliver photosensitizers, heat-inducing agents, or therapeutic genes directly to cancer cells, leading to targeted and personalized treatment strategies[31]. Nanoparticles can be utilized to enhance vaccine efficacy by improving antigen stability and promoting targeted delivery to immune cells. This approach has the potential to revolutionize vaccination strategies for infectious diseases and cancer[32]. Nanotechnology plays a vital role in tissue engineering and regenerative medicine by providing nanomaterials and scaffolds that support cell growth, differentiation, and tissue repair. Nanoparticles can also be used to deliver growth factors and other bioactive molecules to promote tissue regeneration[33]. Nanotechnology enables the development of nanoscale diagnostics and therapeutics tailored to individual patient characteristics, allowing for personalized treatment plans based on genetic and molecular profiles[34]. Nanoparticles with antimicrobial properties, such as silver nanoparticles, have been explored for their potential to combat drug-resistant bacteria and viruses, opening up new avenues for infectious disease control[35]. Nanoscale materials can be utilized in blood purification devices to remove toxins, pathogens, and metabolic waste products from the bloodstream, offering potential treatments for conditions like sepsis and kidney failure[36]. The application of nanotechnology in nanomedicine is continuously evolving, and ongoing research is expected to yield even more innovative solutions to tackle various medical challenges. However, it is crucial to conduct thorough safety assessments and address potential toxicity concerns associated with nanomaterials to ensure their safe and effective use in clinical settings.

## 4. Different modes of drug delivery system

Drug delivery systems have evolved significantly to enhance drug efficacy and patient compliance (**Figure 7**). Several modes of drug delivery have been developed, each catering to specific therapeutic needs and targeting mechanisms. Some prominent modes include:

1) Drug delivery through oral pathways: Oral delivery remains the most common and convenient mode for drug administration, though challenges like poor solubility and enzymatic degradation have led to the development of advanced drug delivery systems[37].
2) Drug delivery through inhalation: Inhaled aerosols deliver drugs directly to the respiratory system, making them effective for treating respiratory conditions like asthma or chronic obstructive pulmonary disease (COPD)[38].
3) Drug delivery through targeted ways: Utilizing ligands or antibodies, drugs can be precisely targeted to specific cells or tissues, reducing off-target effects and enhancing therapeutic outcomes[39].

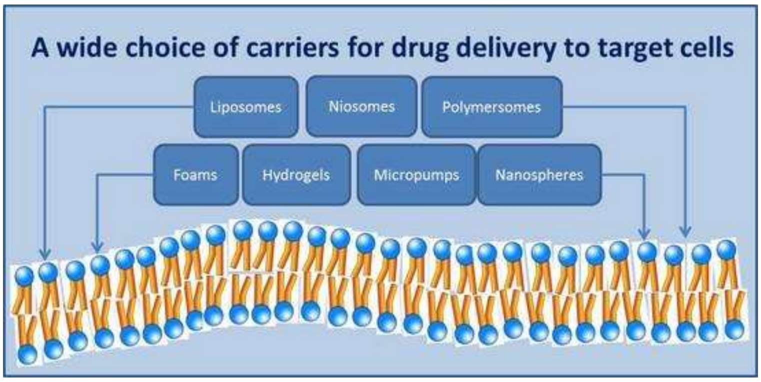



**Figure 7.** Carriers for drug delivery[40].

### Nanoparticle-based drug delivery

Utilizing nanoparticles as carriers for drugs allows for improved bioavailability, sustained release, and targeted delivery. Examples include liposomes, polymeric nanoparticles, and solid lipid nanoparticles (SLNs)[41].

1) Microneedle drug delivery: Microneedles facilitate painless and efficient drug delivery through the skin's outer layer, offering a promising alternative to traditional injections[42].
2) Implantable drug delivery devices: Implantable devices like drug-eluting stents and implantable pumps offer localized and prolonged drug release, ideal for specific conditions such as cardiovascular diseases or chronic pain management[43].
3) Transdermal drug delivery: Transdermal patches provide controlled and continuous drug release through the skin, offering convenience and improved patient compliance[44].
4) Intranasal drug delivery: This mode delivers drugs through the nasal route, enabling rapid systemic absorption and direct access to the central nervous system[45].

5) Targeted drug delivery: Utilizing ligands or antibodies, drugs can be precisely targeted to specific cells or tissues (**Figure 8**), reducing off-target effects and enhancing therapeutic outcomes[46].

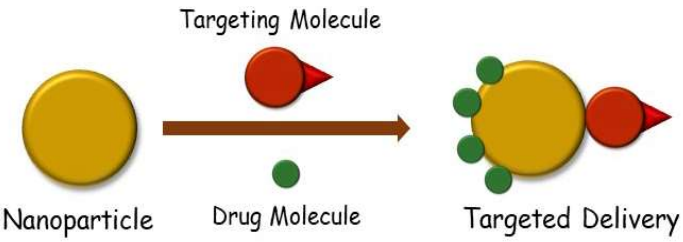



**Figure 8.** Nanoparticle-based targeted drug delivery.

6) Inhaled drug delivery: Inhaled aerosols deliver drugs directly to the respiratory system, making them effective for treating respiratory conditions like asthma or chronic obstructive pulmonary disease (COPD)[38].
7) Oral drug delivery: Oral delivery remains the most common and convenient mode for drug administration, though challenges like poor solubility and enzymatic degradation have led to the development of advanced drug delivery systems[37].

These diverse drug delivery modes continue to be refined and expanded upon, contributing to the advancement of pharmaceutical science and improved patient care.

## 5. Physiochemical properties of nanoparticles in medicine

Nanoparticles used in medicine possess unique physicochemical properties (**Figure 9)** that make them highly versatile and valuable in various medical applications. These properties play a crucial role in their performance as drug carriers, imaging agents, diagnostic tools, and therapeutics. Some of the key physicochemical properties of nanoparticles in medicine are as follows:

1) Size and surface area: Nanoparticles are typically in the size range of 1 to 100 nanometers. Their small size provides a high surface-to-volume ratio, allowing for efficient drug loading and surface functionalization with ligands or targeting moieties[46].

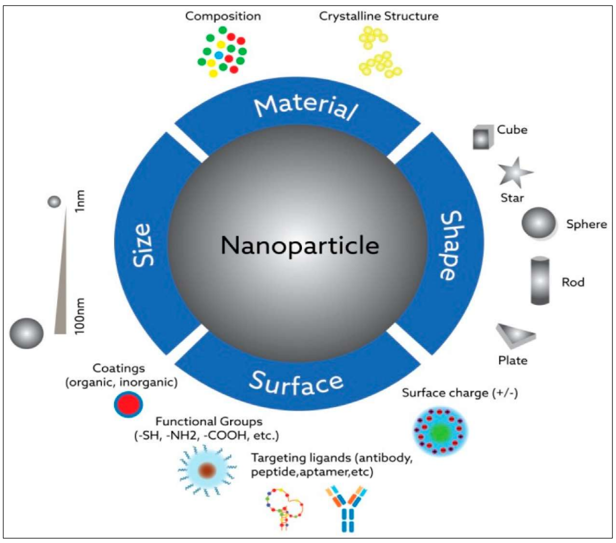



**Figure 9.** Physicochemical properties of nanoparticles[47].

2) Surface charge and functional groups: The surface of nanoparticles can be modified to carry different charges and functional groups, enabling specific interactions with biological molecules, cells, or tissues. This surface engineering facilitates targeted drug delivery and improved cellular uptake[48].
3) Drug encapsulation and release: Nanoparticles can encapsulate a wide variety of drugs, including hydrophobic and hydrophilic compounds. This encapsulation protects the drug from degradation and allows for controlled release over time, improving therapeutic efficacy and reducing side effects[49].
4) Biocompatibility and biodistribution: The biocompatibility of nanoparticles is essential to minimizing adverse reactions in the body. Surface modifications and choice of materials influence the interaction of nanoparticles with biological systems, affecting their biodistribution and pharmacokinetics[50].
5) Targeting capabilities: Nanoparticles can be engineered to target specific tissues or cells through ligand-receptor interactions, antibody targeting, or stimuli-responsive mechanisms. Targeted nanoparticles can enhance drug delivery to diseased sites while reducing off-target effects[39].
6) Imaging and contrast: Nanoparticles can carry imaging agents, such as fluorescent dyes, quantum dots, or metal nanoparticles, which offer improved contrast and sensitivity in medical imaging modalities like MRI, CT, and optical imaging[30].
7) Stability and long circulation time: Surface modifications and proper formulation can enhance the stability of nanoparticles in biological environments, allowing for prolonged circulation in the bloodstream, thus increasing the chances of reaching the target site[48].
8) Clearance and biodegradability: Biodegradable nanoparticles are preferred for many applications, as they can undergo natural degradation and clearance from the body over time, reducing the potential for long-term accumulation or toxicity[49].

The combination of these physicochemical properties makes nanoparticles valuable tools in personalized medicine, where individualized treatments can be developed based on patient characteristics and medical needs[34].

## 6. Nanoparticle cytotoxicity

The cytotoxicity of nanoparticles is a critical consideration when exploring their applications in medicine and other fields. While nanoparticles offer numerous advantages, their small size and unique properties can also raise concerns about their potential adverse effects on cells and tissues. Cytotoxicity refers to the ability of nanoparticles to cause damage or cell death in biological systems. Some factors influence the cytotoxicity of nanoparticles:

1) Size: Nanoparticle size plays a crucial role in their cytotoxicity. Smaller nanoparticles may have higher surface area-to-volume ratios, allowing for increased interactions with cells and potentially leading to greater cytotoxic effects[37].
2) Surface charge: The surface charge of nanoparticles can affect their interaction with cell membranes and intracellular structures. Positively charged nanoparticles may exhibit higher cytotoxicity due to enhanced cellular uptake and possible disruption of cell membranes[51].
3) Composition: The material used to fabricate nanoparticles can significantly influence their cytotoxicity. Some materials, such as certain metal oxides or quantum dots, may release toxic ions or generate reactive oxygen species (ROS), leading to cytotoxic effects[52].

4) Surface coatings: Surface modifications and coatings can alter the biocompatibility of nanoparticles. Properly engineered coatings can enhance biocompatibility and reduce cytotoxicity by minimizing unwanted interactions with cellular components[52].
5) Stability and aggregation: Nanoparticles that aggregate or undergo degradation in biological environments can lead to increased cytotoxicity. Stable nanoparticles are less likely to release toxic components and are generally more biocompatible[53].

It is essential to thoroughly assess the cytotoxicity of nanoparticles before their clinical or industrial applications. Comprehensive in vitro and in vivo studies are conducted to understand the potential risks associated with exposure to nanoparticles. These studies involve cell viability assays, ROS generation measurements, and examinations of cellular morphology and function. Additionally, researchers and regulatory bodies continuously work to develop standardized protocols and guidelines for the safe use of nanoparticles. The goal is to ensure that any potential cytotoxic effects are carefully considered and that the benefits of using nanoparticles outweigh the risks in various applications.

## 7. Nanoparticle Drug Delivery Systems (DSSs) in disease treatment

Nanoparticle Drug Delivery Systems (DDSs) have emerged as a promising approach for disease treatment, offering several advantages over traditional drug delivery methods (**Figure 10**). These systems utilize nanoscale carriers to transport therapeutic agents, such as drugs or genetic material, to specific target sites in the body, resulting in enhanced drug efficacy, reduced side effects, and improved patient outcomes.

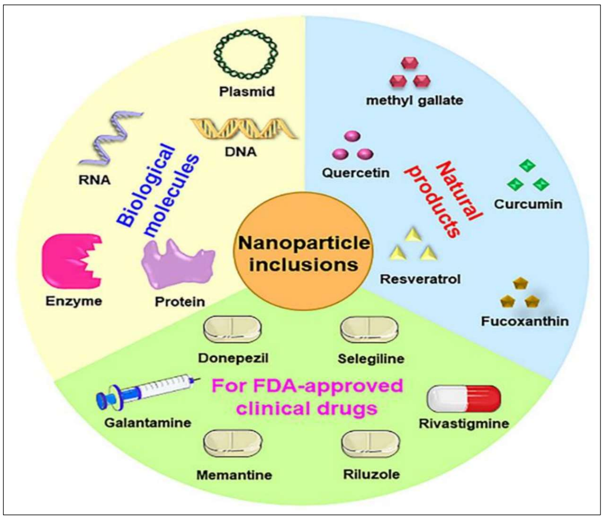



**Figure 10.** Nanoparticle Drug Delivery Systems (DSSs) in disease treatment[5].

1) Targeted drug delivery: Nanoparticle DDSs can be designed to target specific cells, tissues, or organs by functionalizing their surfaces with ligands or antibodies that recognize and bind to specific receptors on the target cells[49]. This targeted delivery minimizes drug exposure to healthy tissues, increasing the concentration of the drug at the disease site and enhancing treatment effectiveness.
2) Improved drug solubility: Many drugs, especially those used in cancer treatment, have poor solubility, which limits their effectiveness. Nanoparticles can encapsulate hydrophobic drugs, improving their solubility and bioavailability, thus allowing for more efficient drug delivery and uptake[46].

3) Controlled drug release: Nanoparticle DDSs offer controlled drug release kinetics, enabling sustained drug delivery over an extended period. This controlled release can reduce the frequency of drug administration and maintain therapeutic drug levels in the body, leading to improved patient compliance and reduced side effects[49].
4) Overcoming drug resistance: Nanoparticle DDSs can help overcome drug resistance in certain diseases, including cancer. By delivering drugs directly to resistant cells or by using combination therapies with multiple drugs encapsulated in nanoparticles, the development of drug-resistant cell populations can be mitigated[46].
5) Intracellular drug delivery: Nanoparticles can facilitate drug delivery into cells by crossing cellular barriers, such as the cell membrane or the blood-brain barrier. This property is particularly relevant in treating intracellular infections and neurodegenerative diseases[49].
6) Personalized medicine: Nanoparticle DDSs can be tailored for specific patients or disease subtypes, allowing for personalized medicine approaches. This customization can be achieved by choosing the appropriate drug and nanoparticle composition and targeting ligands based on individual patient characteristics[34].
7) Combination therapy: Nanoparticles can be engineered to carry multiple therapeutic agents simultaneously, enabling combination therapies that target different aspects of disease progression. This approach can lead to synergistic effects and improved treatment outcomes[34].

The applications of nanoparticle DDSs are extensive, spanning various diseases, including cancer, infectious diseases, inflammatory disorders, and neurological conditions. As research in nanotechnology and drug delivery advances, nanoparticle DDSs are expected to continue playing a crucial role in disease treatment and revolutionizing the field of medicine.

## 8. Challenges and limitations of nano-targeted delivery systems

Nano-targeted delivery systems have shown great promise in enhancing drug delivery and improving therapeutic outcomes. However, they also face several challenges and limitations that need to be addressed for their successful translation into clinical practice. The interaction of nanoparticles with biological systems must be thoroughly assessed to ensure their biocompatibility and minimize potential toxic effects. Some nanoparticles may induce immune responses or accumulate in certain organs, raising safety concerns[52]. The fabrication and scale-up of nanoparticle-based delivery systems can be complex and costly. Achieving reproducibility and standardization in manufacturing processes is crucial to ensure product consistency[54]. Efficient loading of therapeutic agents into nanoparticles is essential to maximize drug delivery and therapeutic efficacy. Some drugs may have low encapsulation efficiency, limiting the amount of drug that can be delivered to the target site[46]. Nanoparticles may exhibit instability over time, leading to changes in drug release kinetics or reduced therapeutic activity. Proper storage conditions and improved nanoparticle stability are critical for maintaining the shelf life of nano-targeted delivery systems[55]. Understanding the fate of nanoparticles after administration is crucial to predict their biodistribution, circulation time, and clearance from the body. Unintended accumulation in certain organs or tissues may impact safety and efficacy[49]. Nanoparticles face challenges in crossing physiological barriers, such as the blood-brain barrier or mucus layers. The design of nanoparticles with surface modifications or functionalization can improve their ability to overcome these barriers[56]. The production and use of nanoparticle-based systems may incur additional costs compared to conventional drug delivery methods. Ensuring affordability and accessibility of these technologies is essential for wider clinical adoption[54]. Regulatory bodies require rigorous safety and efficacy data before approving nanoparticle-based drugs or delivery systems for clinical use. Complying with regulatory requirements adds to the challenges of translating nano-targeted delivery systems to the market[57].

Despite these challenges, ongoing research and advancements in nanotechnology are addressing many of these limitations. Researchers are developing new nanoparticle formulations, surface modifications, and targeting strategies to improve the safety and efficacy of nano-targeted delivery systems. Furthermore, interdisciplinary collaborations between scientists, clinicians, and regulatory authorities are critical to overcome these challenges and unlock the full potential of nano-targeted drug delivery in medicine.

## 9. Discussion and future perspective

Nanomaterial-based drug delivery systems have revolutionized the field of medicine, offering significant advancements in targeted and controlled drug delivery (**Figure 11**). These systems utilize nanoscale carriers to transport therapeutic agents to specific sites in the body, improving drug efficacy, reducing side effects, and enhancing patient outcomes. Here, we discuss the current state and future perspectives of nanomaterial-based drug delivery systems. Nanomaterial-based drug delivery systems enable targeted drug delivery by functionalizing the surface of nanoparticles with ligands or antibodies that recognize specific receptors on target cells[46]. This targeted approach increases drug concentration at the site of action while minimizing exposure to healthy tissues. Nanoparticles can encapsulate hydrophobic drugs, improving their solubility and bioavailability[46]. This capability enhances drug delivery and enables the use of poorly water-soluble drugs in clinical applications. Nanomaterial-based drug carriers allow for sustained and controlled drug release over time[49]. This controlled release profile can lead to reduced dosing frequency and more stable therapeutic drug levels in the body. Nanoparticles can carry multiple therapeutic agents simultaneously, facilitating combination therapies for complex diseases such as cancer[34]. This approach can enhance treatment efficacy and overcome drug resistance.

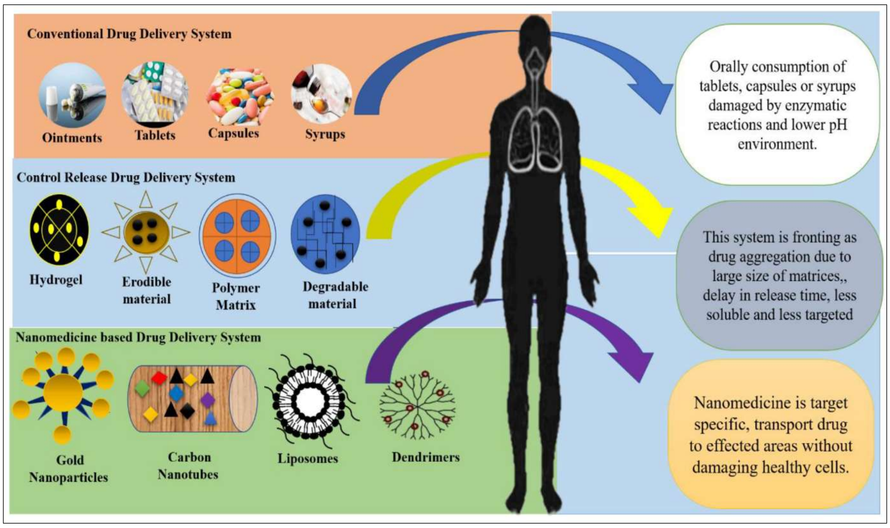



**Figure 11.** Illustration on conventional versus nanomaterial-based drug delivery[58].

Nanomaterial-based drug delivery systems hold promise for personalized medicine approaches, allowing tailored treatments based on individual patient characteristics, such as genetic profiles or disease stages[34]. Nanoparticles are being developed for efficient delivery of genetic material, such as siRNA or CRISPR-Cas9, for gene therapy applications[32]. This opens up new possibilities for treating genetic disorders and addressing disease at the molecular level. Nanomaterials can improve the delivery of immunomodulatory agents, such as immune checkpoint inhibitors or immune adjuvants, to stimulate the immune response against cancer and infectious diseases[30]. This can enhance the effectiveness of immunotherapies. Future nanomaterial-based drug delivery systems are likely to be designed with stimuli-responsive properties, releasing drugs in response to specific cues, such as pH, temperature, or enzyme activity[49]. This provides spatiotemporal control over drug release, optimizing therapeutic outcomes. Nanoparticles can serve as contrast agents in various imaging modalities, offering earlier disease detection and real-time monitoring of drug delivery[30]. This integration of imaging and drug delivery allows for theragnostic applications. Advancements in biodegradable nanomaterials are being pursued to improve nanoparticle clearance from the body and minimize potential long-term accumulation[49]. As nanotechnology continues to advance, nanomaterial-based drug delivery systems are expected to play an increasingly important role in disease treatment and personalized medicine. However, it is crucial to address challenges related to biocompatibility, manufacturing, regulatory approval, and long-term safety to ensure the successful translation of these innovative technologies into clinical practice.

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## Conflict of interest

The authors declare no conflict of interest.

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