REVIEW ARTICLE

A Discussion of the Properties of Nanoparticles

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ABSTRACT

Nanoparticles (NPs) have begun as versatile building blocks through applications spanning diverse fields. This review provides a general idea of nanoparticle properties, highlighting recent advancements and future prospects. Various techniques, such as sol-gel synthesis, chemical reduction, and green synthesis, offer control over shape, size, and composition, supporting custom-made production for precise applications. NPs possess high surface area-to-volume ratios and tunable optical, magnetic, and catalytic properties, alongside biocompatibility and functional ability, making them suitable for various applications. In medicine, NPs facilitate drug delivery, imaging, diagnostics, and therapeutics, ensuring targeted delivery and enhanced efficacy. In electronics, they drive advancements in displays, sensors, photovoltaics, and data storage. Additionally, NPs contribute to energy technologies like fuel cells, batteries, solar cells, and catalysis for renewable energy production. Despite their promise, NPs raise concerns about environmental and health impacts. Efforts are underway to address issues like toxicity, environmental persistence, and regulatory oversight for their safe use. In conclusion, NPs denote a rapidly progressing field with significant potential to address challenges and drive innovation across industries. Continued research and collaboration are crucial to explore their synthesis, properties, applications, and impacts, ensuring sustainable and responsible utilization of nanotechnology.

Keywords: Nanoparticles, Toxicity, Chemical reduction, Sol-gel synthesis, Green synthesis, Nano drug delivery systems.

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INTRODUCTION

Nanoparticles (NPs) are particles with dimensions in the nanometer (nm) scale, naturally fluctuating from 1 to 100 nm in at least one dimension.[1] Because of their tiny size, they display unusual physical, chemical, and biological characteristics. These things make NPs greatly multipurpose and cherished in various fields. NPs serve as building blocks for advanced materials with tailored properties. They are used in the expansion of high-performance coatings, composites, and ceramics NPs improve materials' electrical, mechanical, and thermal capabilities, leading to improved performance in diverse applications.

NPs are crucial components of drug delivery systems (DDS), which enable medicinal drugs to be released in a controlled and targeted manner. Many medical imaging procedures rely on them as contrast agents, including MRI, CT scans, etc. NPs facilitate early detection and diagnosis of diseases through biosensors and molecular imaging probes. The use of NPs in wastewater treatment allows for the elimination of organic contaminants, heavy metals, and pollutants. They can catalyze chemical reactions for the degradation of ecological pollutants, offering a sustainable approach to pollution remediation. NPs are utilized in sensors for monitoring air and water quality, enabling rapid detection of contaminants. Batteries, fuel cells, solar cells, and other renewable energy technologies rely heavily on NPs. They improve the productivity of photovoltaic devices by improving light absorption and charge transport properties. NPs facilitate reactions such as hydrogen evolution and oxygen reduction. NPs are integrated into electronic devices for miniaturization, improved performance, and novel functionalities. They enable the development of nanoscale transistors, memory devices, and conductive inks for flexible electronics. NPs show exclusive optical properties, including plasmonic effects and quantum confinement, making them suitable for applications such as sensors and LEDs. NPs are used in agriculture for crop protection, nutrient delivery, and soil remediation. Reduced environmental impact and increased agricultural yields are the results of their enhanced efficiency in applying fertilizers and herbicides.

NPs are engaged in food wrapping materials to outspread shelf life, prevent microbial growth, and ensure food safety. NPs play a pivotal role in advancing technology and addressing complex challenges in various fields, offering innovative solutions with significant economic, environmental, and societal benefits. Their unique properties

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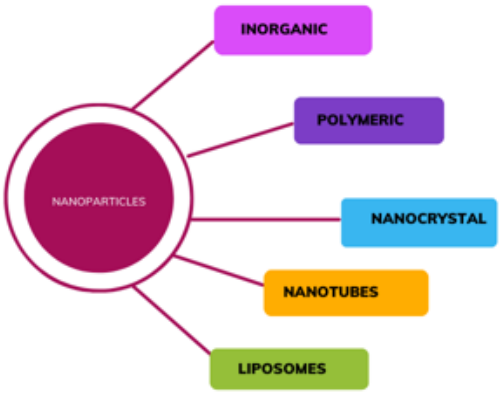

Figure 1: Types of nanoparticles

and versatile applications make them indispensable tools for scientific research, technological innovation, and sustainable development.

The concept of NPs has a rich historical background spanning centuries, with notable developments occurring across different disciplines. Although the term "nanoparticles" was not used, ancient artisans and craftsmen inadvertently created and utilized NPs in various forms, such as in pottery glazes and stained glass. The 19th century saw the advent of modern chemistry and physics, laying the groundwork for understanding matter at the atomic and molecular levels. However, deliberate manipulation of NPs was not yet a focus of scientific inquiry. The development of electron microscopy in the 1930s provided scientists with the ability to visualize structures at the nanoscale for the first time. This milestone allowed for the observation of NPs and their properties. In the 1950s and 1960s, researchers began synthesizing NPs for specific applications, particularly in the field of catalysis. For example, metal NPs were investigated for their catalytic activity in hydrogenation reactions. The late 20th century marked a significant turning point in the study and application of NPs. An upsurge in curiosity about NPs and what they could be used for resulted from developments in nanotechnology, materials science, and surface chemistry. In 1985, the discovery of fullerenes, a class of carbon NPs with unique properties, opened new avenues for nanomaterial research and nanotechnology development. The 1990s witnessed the emergence of nanoscience as a distinct interdisciplinary field, with research efforts focusing on the synthesis, characterization, and manipulation of NPs across various disciplines. Breakthroughs in nanomaterial synthesis techniques, such as sol-gel, chemical vapor deposition, and laser ablation, paved the way for the controlled production of NPs with tailored properties. Different types of nanoparticles were illustrated in Figure 1.

The 21st century has seen exponential growth in NPs research and use in an extensive range of disciplines. NPs have become indispensable tools in biomedical, ranging from DDS and medical imaging to tissue engineering and diagnostic assays. In electronics and optoelectronics, NPs are integrated into devices for enhanced performance, miniaturization, and novel functionalities. NPs play a vital role in addressing global challenges such as environmental pollution, energy sustainability, and food security through innovative solutions and sustainable technologies.

Overall, the historical trajectory of NPs reflects a gradual evolution from accidental discovery and observation to deliberate synthesis and manipulation, ultimately leading to their widespread exploration and application in the modern era of nanotechnology. The current review focuses on the properties of NPs.

Properties of Nanoparticles

Size-dependent properties (quantum size effect)

The size-dependent properties of NPs arise from quantum confinement effects and increased surface area-to-volume ratio compared to bulk materials. As NPs decrease in size, their properties can change significantly, leading to unique behaviors and applications· Quantum confinement effects result in changes in the absorption and emission spectra of NPs. This tunability makes them valuable for applications in displays, lighting, and biomedical imaging. In metal NPs, the electronic structure undergoes changes with size, affecting conductivity and optical properties. Small metal NPs exhibit discrete energy levels due to quantum confinement, leading to enhanced catalytic activity and plasmonic effects.

These properties are exploited in applications such as catalysis, sensors, and surface-enhanced Raman spectroscopy (SERS). Magnetic NPs exhibit superparamagnetism at the nanoscale, characterized by size-dependent magnetic performance.

The magnetic NPs size decreases, and thermal energy becomes comparable to magnetic anisotropy, resulting in enhanced Brownian motion and reduced coercivity. This behavior is utilized in applications such as MRI, magnetic hyperthermia for cancer treatment, and magnetic data storage.[42] This includes increased hardness, tensile strength, and elasticity, making them suitable for reinforcing composite materials and nanocomposites used in aerospace, automotive, and structural applications. NPs have a higher surface area per unit volume compared to bulk materials, leading to increased reactivity and surface energy. This influences their chemical properties, including adsorption, catalysis, and surface modification. The design and optimization of NPs for specific applications in disciplines including electronics, photonics, biomedicine, and environmental remediation relies on understanding and utilizing these size-dependent features.

Surface area and surface energy

Surface area and surface energy are crucial properties of NPs that significantly influence their behavior and interactions with surrounding environments. Surface area refers to the total area of all exposed surfaces of a nanoparticle. The high surface area of NPs results in increased reactivity, making them effective catalysts for chemical reactions. The greater surface area provides more sites for the adsorption of target

molecules, improving the sensitivity of nanoparticle-based sensors and detectors. NPs with high surface area can carry a larger payload of drugs or therapeutic agents, increasing their efficacy in drug delivery applications.

Surface energy is a measure of the tendency of the surface to minimize its area. Surface energy influences the interactions of NPs with their surroundings, including adsorption, aggregation, and dispersion. NPs with high surface energy tend to aggregate to minimize their surface area, leading to reduced stability in suspension. Surface modification or functionalization can lower surface energy and improve stability. Surface energy affects the wetting behavior of NPs on solid surfaces. NPs with high surface energy typically exhibit better wetting and adhesion properties. Surface energy plays a significant role in decisive the effectiveness of surface modification techniques, such as coating or functionalization, for tailoring the properties of NPs for specific applications.

Understanding and controlling surface area and surface energy are essential for optimizing the performance of NPs in different fields, including sensing, drug delivery, and nanocomposite materials. Strategies for surface modification and functionalization are often employed to tailor these properties and enhance the functionality and stability of NPs for desired applications.

Optical properties (plasmonic effects, quantum dots)

Nanoparticles' size, composition, shape, and structure all impact their optical characteristics. These properties can be tuned and optimized for various applications by controlling these parameters. Nanoparticles made of metals, like silver and gold, show plasmonic resonance, the collective oscillation of free electrons in reaction to electromagnetic radiation. The nature, size, and composition of the NPs determine the resonance wavelength. Plasmonic NPs can absorb and scatter light at specific wavelengths. These properties are utilized in applications such as bio-sensing, imaging, and photothermal therapy.

Semiconductor NPs, also known as quantum dots. It can emit light of different colors by varying its size, creating them valued for exhibitions such as lighting, displays, lighting, and biological imaging.

NPs can scatter and absorb light depending on their size, shape, and composition. Light scattering by NPs contributes to phenomena such as the Tyndall effect and Rayleigh scattering, which are exploited in applications such as colloidal stability measurements and nanoparticle characterization. NPs can also absorb light at specific wavelengths, leading to changes in their optical properties and potential applications in photothermal therapy and photodynamic therapy.

Interactions between plasmonic NPs can lead to collective optical phenomena such as plasmon coupling and plasmon hybridization. This behavior is utilized in applications such as nanoparticle assemblies, metamaterials, and surface-enhanced spectroscopy.

NPs with asymmetric shapes, such as nanorods, nanowires, and nanocubes, exhibit optical anisotropy; it depends on the polarization and orientation of incident light. This property is exploited in applications such as polarization-sensitive imaging, optical data storage, and photonic devices. Tailoring the size, shape, and composition of NPs allows for precise control over their optical behavior, opening up opportunities for innovative technologies and advancements (Table 1).

Mechanical, electrical, and magnetic properties

Understanding and manipulating these properties are crucial for designing NPs for specific applications. NPs can exhibit enhanced mechanical strength compared to their bulk and, are particularly evident in materials like nanocomposites, where NPs act as reinforcements, improving the overall mechanical properties of the material. Some NPs, especially those made of polymers or organic materials, can exhibit flexibility or deformability, allowing them to conform to different shapes or environments.

The fracture toughness of NPs can vary on size, shape, and composition. Understanding and controlling fracture toughness are essential for designing durable NPs for applications in structural materials, coatings, and biomedical devices. NPs made of metals or conductive polymers can exhibit electrical conductivity. The conductivity of metal NPs depends on size, crystal nature and shape.

Dielectric NPs[1] can exhibit unique electrical properties, including high dielectric constants and low loss factors. These properties make them valuable for applications such as capacitors, energy storage devices, and dielectric coatings. Quantum mechanical tunneling phenomena become significant at the nanoscale, influencing electrical conductivity and behavior in devices such as tunneling diodes and molecular electronics.

Magnetic NPs below a critical size exhibit superparamagnetic behavior. This property is exploited in MRI agents, magnetic separation, and DDS. Asymmetrically shaped NPs, such as nanorods or nanowires, can exhibit magnetic anisotropy, where their magnetic properties depend on the orientation of the magnetic moments relative to the nanoparticle axis. Magnetic anisotropy is crucial for applications such as magnetic data storage and magneto-optical devices.

Understanding the properties of NPs enables the development of advanced materials and devices for diverse applications, ranging from electronics and sensors to biomedicine and energy storage. Manipulating these properties at the nanoscale opens up new opportunities for innovation and technological advancements.[2]

Table 1: Property variation with particle size

Particles	*Bulk level*	*Nano level*
Copper	Opaque	Transparent
Platinum	Inert	Catalytic
Aluminum	Stable	Combustible
Gold	Solid	Liquid
Silicon	Insulator	Conductor

Stability and reactivity[3]

The NPs are critical factors that influence their behavior, performance, and applications. NPs can undergo chemical reactions, such as oxidation, reduction, and dissolution, which can affect their stability over time. Surface oxidation alters the properties of NPs and can lead to the formation of oxides or other chemical species. Surface modification, such as capping or coating with stabilizing agents, can enhance the chemical stability of NPs.[4]

In dispersion or suspension, NPs can aggregate or flocculate due to attractive van der Waals forces or electrostatic interactions. Colloidal stability refers to the ability of NPs to remain dispersed and prevent aggregation over time. Surface functionalization, electrostatic stabilization, and steric hindrance techniques are commonly employed to improve colloidal stability.

Surface defects, edges, and functional groups play crucial roles in determining the surface reactivity of NPs. Tuning surface properties through surface modification or doping can control the reactivity of NPs for specific catalytic applications. The reactivity of NPs in biological environments depends on factors such as size, shape, surface chemistry and charge.[5-9]

The environment can be negatively affected by NPs when they are discharged into the air, water, and soil and by living beings when they interact with these elements. Several variables, including surface characteristics, mobility, and transformation processes, determine the environmental reactivity of nanoparticles. If we want to know how dangerous NPs are and how to clean them up, we need to study their environmental fate and behavior.[10-14]

Balancing stability and reactivity is essential for maximizing the performance and minimizing the potential risks of NPs in various applications. Tailoring the surface chemistry, structure, and environment of NPs enables precise control over their stability and reactivity for desired functionalities and applications.[15,16]

CONCLUSION

In conclusion, the field of NPs has witnessed tremendous growth and innovation in recent years, driven by advancements and diverse applications across various industries. NPs represent a rapidly evolving field with significant potential to address challenges and drive innovation across diverse industries.

REFERENCES

1. Devadasu VR, Bhardwaj V, Kumar MR. Can controversial nanotechnology promise drug delivery? Chemical reviews. 2013; 113(3):1686-735.
2. Sapavatu SN, Chinthala R, Jadi RK. An overview on pharmacokinetics of polymeric nanoparticles intended for oral delivery. Journal of Young Pharmacists. 2020; 12(3): 187-9.
3. Avula PR, Chettupalli AK, Chauhan V, Jadi RK. Design, formulation, in-vitro and in-vivo pharmacokinetic evaluation of Nicardipine-nanostructured lipid carrier for transdermal drug delivery system. Materials today: Proceedings. 2023.
4. Al-Awsi GR, Alameri AA, Al-Dhalimy AM, Gabr GA, Kianfar E. Application of nano-antibiotics in the diagnosis and treatment of infectious diseases. Brazilian Journal of Biology. 2023; 84:e264946.
5. Chavan T, Muttil P, Kunda NK. Introduction to nanomedicine in drug delivery. Mucosal Delivery of Drugs and Biologics in Nanoparticles. 2020:3-26.
6. Sun F, Ju C, Chen J, Liu S, Liu N, Wang K, Liu C. Nanoparticles based on hydrophobic alginate derivative as nutraceutical delivery vehicle: vitamin D3 loading. Artificial Cells, Blood Substitutes, and Biotechnology. 2012; 40(1-2):113-9.
7. Kışla D, Gökmen GG, Evrendilek GA, Akan T, Vlčko T, Kulawik P, Jambrak AR, Ozogul F. Recent developments in antimicrobial surface coatings: Various deposition techniques with nanosized particles, their application and environmental concerns. Trends in Food Science and Technology. 2023; 135:144-72.
8. Yalçın RA, Blandre E, Joulain K, Drévillon J. Colored radiative cooling coatings with nanoparticles. ACS photonics. 2020;7(5):1312-22.
9. Chauhan R, Singh B, Singh MP, Malik A. Pharmacokinetic Study of Aloin Nanoparticulate: Enhanced Oral Formulation Bioavailability. International Journal of Pharmaceutical Quality Assurance. 2024;15(1): 94-100
10. Wang L, Li S, Yin J, Yang J, Li Q, Zheng W, Liu S, Jiang X. The density of surface coating can contribute to different antibacterial activities of gold nanoparticles. Nano Letters. 2020; 20(7):5036-42.
11. Zhou L, Wang H, Li Y. Stimuli-Responsive Nanomedicines for Overcoming Cancer Multidrug Resistance. Theranostics. 2018; 8(4):1059.
12. Cao Y, Chen Y, Yu T, Guo Y, Liu F, Yao Y, Li P, Wang D, Wang Z, Chen Y, Ran H. Drug release from phase-changeable nanodroplets triggered by low-intensity focused ultrasound. Theranostics. 2018; 8(5):1327.
13. Lombardo D, Kiselev MA. Methods of liposomes preparation: formation and control factors of versatile nanocarriers for biomedical and nanomedicine application. Pharmaceutics. 2022; 14(3):543.
14. Sim S, Wong NK. Nanotechnology and its use in imaging and drug delivery. Biomedical reports. 2021; 14(5):1-9.
15. Israel LL, Galstyan A, Holler E, Ljubimova JY. Magnetic iron oxide nanoparticles for imaging, targeting and treatment of primary and metastatic tumors of the brain. Journal of Controlled Release. 2020; 320:45-62.
16. Singh C, Yashwant, Gupta AK, Garg V. Formulation Development and Evaluation of Divalproex Sodium Extended-release Tablets. International Journal of Drug Delivery Technology. 2022;12(4):1769-1773.DOI: 10.25258/ijddt.12.4.46