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Carbon-Based, Organic, and Metallic Nanoparticles: Biomedical Applications and Environmental Insights

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Abstract:

Nanoparticles, including carbon-based, organic, and metallic types, have gained increasing attention due to their unique physicochemical properties at the nanoscale, which enable innovative biomedical applications. Carbon-based nanoparticles, such as carbon nanotubes, fullerenes, and graphene derivatives, are explored for drug delivery, imaging, and tissue engineering. Organic nanoparticles, composed of lipids and polymers, provide biocompatible carriers for targeted therapies. Metallic nanoparticles, including gold, silver, and magnetic iron oxides, offer precise diagnostic and therapeutic functions, particularly in oncology. This review aims to provide a comprehensive overview of the design principles, biomedical applications, and environmental considerations of these nanoparticles, highlighting their potential to advance next-generation nanomedicine while addressing challenges related to biocompatibility and safety.

1. Introduction

Nanotechnology has transformed science and medicine by enabling the manipulation of materials at the nanoscale, typically between 1 and 100 nanometers (Duncan, 2011; Azzaoui *et al.,* 2022). The term “nano” originates from the Greek word for “dwarf,” reflecting the extremely small size of these particles. Since its conceptual introduction by Richard P. Feynman in 1959 at CalTech, nanotechnology has expanded into multiple domains, including pharmacy, medicine, and biotechnology (Toumey, 2005; Arabani *et al.,* 2025). At this scale, materials display unique physicochemical properties, distinct from their bulk counterparts, making them ideal for targeted biomedical applications (Limongi *et al.,* 2019; Aaddouz *et al.,* 2024).

Nanoparticles (NPs) can be synthesized through top-down or bottom-up approaches. The top-down method breaks down larger structures into nanoscale units, whereas the bottom-up approach assembles atoms or molecules into nanostructures (Duncan, 2011; Aldwayyan *et al.,* 2013; Limongi *et al.,* 2019). These techniques allow precise control over size, morphology, and surface chemistry, which are critical for optimizing biomedical functions such as drug delivery and imaging (Ankamwar, 2012). Natural processes, including volcanic eruptions, microbial activity, and plant or animal material shedding, also produce nanoparticles, although engineered NPs provide controlled properties and enhanced functionalities (Arabani et al., 2025).

Nanotechnology leverages materials at the nanoscale (one billionth of a meter) to address medical and environmental challenges, offering enhanced drug delivery systems, advanced diagnostics, and more efficient water purification and pollution remediation techniques (Abouri *et al.,* 2025; Ochs *et al.,* 2020; Alshahateet *et al.,* 2024; Abouri *et al.,* 2025). In medicine, nanoparticles and nanocarriers are used for targeted drug delivery, improved medical imaging, and real-time disease monitoring (Tabaght *et al.,* 2020). For the environment, nanomaterials are employed to detect pollutants at low concentrations, filter contaminated water and air, and catalyze the breakdown of organic contaminants (Suleiman *et al.,* 2013; Kasinathan *et al.,* 2016; Lakrat *et al.,* 2017; Limongi *et al.,* 2019; Aaddouz *et al.,* 2023a; El Yousfi *et al.,* 2023; Durgam and Oroszi, 2025).

Based on composition, nanoparticles are broadly classified into carbon-based, organic, and metallic types. Carbon-based nanoparticles (CBNPs), such as carbon nanotubes, fullerenes, and graphene derivatives, offer high mechanical strength, electrical conductivity, and fluorescence for bioimaging and therapeutic delivery (Gupta *et al.,* 2018; Augustine *et al.,* 2017; Castro *et al.,* 2017). Organic nanoparticles, including liposomes and polymeric carriers, are valued for their biodegradability, biocompatibility, and versatility in encapsulating both hydrophilic and hydrophobic drugs (Crucho & Barros, 2017; Ferreira-Souza *et al.,* 2020). Metallic nanoparticles, such as gold, silver, and magnetic iron oxide NPs, demonstrate tunable surface properties, stability, and effective targeting capabilities, particularly in cancer therapy (Nikalje, 2015; Khandel P., Shahi, 2018; Ammar *et al.,* 2025).

The clinical translation of NPs requires understanding their interactions with biological systems, including blood cells, plasma proteins, and immune pathways. Parameters such as size, shape, surface charge, and functionalization influence cellular uptake, circulation time, and therapeutic efficiency (Ahn *et al.,* 2020; Chang *et al.,* 2020). Additionally, PEGylation and ligand functionalization enhance biocompatibility, prevent rapid clearance, and allow targeted delivery (Ahn *et al.,* 2020; Chang *et al.,* 2020).

This review aims to provide a comprehensive overview of the synthesis, functionalization, and biomedical applications of carbon-based, organic, and metallic nanoparticles. It also highlights emerging strategies in nanomedicine, their therapeutic potential, and the challenges associated with safe and effective clinical use. By integrating knowledge of NP design and biological interactions, this work seeks to guide the development of next-generation nanodrugs for enhanced treatment outcomes.

2. Methodology

2.1. Carbon-Based Nanoparticles (CBNPs)

Carbon-based nanoparticles (CBNPs) encompass a diverse group of nanomaterials, including carbon nanotubes (CNTs), fullerenes, graphene oxide (GO), nanodiamonds, quantum dots, and graphene derivatives. These nanoparticles have attracted considerable attention in biomedical research due to their unique optical, mechanical, thermal, and chemical properties (Gupta *et al.,* 2018).

CBNPs exhibit strong fluorescence, both single-photon and two-photon, which enables deep-tissue imaging. Their high surface area and ease of functionalization facilitate the attachment of therapeutic agents, enhancing drug delivery efficiency while maintaining biocompatibility (Wang *et al.,* 2020; Murjani *et al.,* 2022; Arabani *et al.,* 2025). Fullerenes, spherical molecules composed of 60 carbon atoms, are hydrophobic but can be functionalized for diagnostic and therapeutic applications, including imaging and drug delivery. They are also applied in combination therapies such as photodynamic therapy, hyperthermia, and acoustic wave therapy (Augustine *et al.,* 2017; Castro *et al.,* 2017).

CNTs are classified as single-walled (SWCNTs) or multi-walled (MWCNTs) based on the number of rolled graphene sheets. Their structural, electronic, and mechanical characteristics allow applications in drug delivery, tissue engineering, biosensing, and therapeutic systems (Limongi *et al.,* 2017). Beyond biomedical uses, CNTs and fullerenes are applied in industrial fields such as catalysis, gas adsorption, and nanocomposite fabrication due to their electrical conductivity and high electron affinity (Wang et al., 2020).

Over the past two decades, functionalized CBNPs have demonstrated improved biocompatibility and targeting capability by conjugating with proteins, peptides, nucleic acids, or drugs. These functionalized nanoparticles enable precise delivery to specific sites while minimizing toxicity (Wang *et al.,* 2020; Murjani *et al.,* 2022). Consequently, carbon-based nanomaterials offer promising platforms for drug delivery, bioimaging, tissue engineering, and molecular diagnostics, supporting their continued exploration in next-generation biomedical applications (Oyebamiji A. *et al,* 2025).

2.2.Organic Nanoparticles

Organic nanoparticles (NPs) are synthesized from materials such as lipids and polymers and have significant roles in biomedical applications, particularly in drug delivery and imaging. Their advantages, including biocompatibility, biodegradability, and tunable properties, have led to widespread use in modern nanomedicine (Arabani et al., 2025).

Polymeric nanoparticles can be produced using natural or synthetic polymers, providing versatility in drug encapsulation and controlled release. Various fabrication techniques, including fluid dialysis and emulsion methods, allow fine-tuning of particle size, solubility, and morphology depending on the intended application (Crucho & Barros, 2017; Ferreira-Souza *et al.,* 2020; Jiang & Poo, 2017; Li *et al.,* 2020; Patra *et al.,* 2018). Organic nanoparticles are often referred to as precision nanocarriers because of their enhanced drug-loading capacity, therapeutic efficiency, and biocompatibility. Their relatively large size and colloidal stability enable simultaneous

encapsulation of hydrophilic and hydrophobic drugs, providing flexibility for combination therapies (Ferreira-Souza *et al.,* 2020; Jiang & Poo, 2017; Li *et al.,* 2020; Patra *et al.,* 2018).

Based on the synthesis method, organic nanoparticles are generally categorized into two types: (i) self-assembled nanostructures, such as amphiphilic systems, and (ii) nanostructures generated via specialized techniques, including dendrimers and carbon nanotubes. Recent research has increasingly focused on hybrid approaches that combine self-assembly and supramolecular techniques to create multifunctional nanocarriers with advanced therapeutic capabilities.

Organic nanoparticles' precise design, tunable surface chemistry, and versatile morphology make them indispensable tools in contemporary nanomedicine, enabling targeted therapy, reduced side effects, and improved drug delivery efficiency. Their application spans from conventional drug delivery to sophisticated diagnostic imaging, underscoring their critical role in next-generation biomedical innovations.

2.3. Metallic Nanoparticles (MNPs)

Metallic nanoparticles (MNPs) are produced from metal precursors and exhibit unique physicochemical properties that differ significantly from their bulk counterparts. Metals such as gold, silver, and copper form nanoparticles with distinctive optical, magnetic, and electronic behaviors, enabling diverse biomedical applications (Arabani *et al.,* 2025). These properties include broad absorption in the visible spectrum and tunable surface plasmon resonance, which are advantageous for imaging, diagnostics, and therapeutic interventions.

Magnetic nanoparticles, engineered as nanoshells or nanocages, have been particularly useful in targeted drug delivery and diagnostic applications. Their magnetic responsiveness allows precise localization in tissues that are otherwise difficult to reach, making them valuable in oncology and other critical medical areas (Nikalje, 2015). Gold and silver nanoparticles have emerged as key candidates in cancer therapy due to their high biocompatibility, ease of functionalization, and ability to enhance imaging contrast (Nikalje, 2015).

MNPs can be functionalized with biomolecules such as DNA, RNA, peptides, or antibodies, facilitating targeted delivery and improving therapeutic efficacy (Yaqoob *et al.,* 2020). Their structure, size, and surface chemistry are critical determinants of biodistribution, cellular uptake, and toxicity (Nair *et al.,* 2007). Traditional synthesis methods include physical and chemical approaches; however, green synthesis techniques are increasingly preferred due to lower toxicity and environmental impact (Ahmed *et al.,* 2016; Kaliaraj, 2017).

MNPs are widely employed in diagnostic imaging, biosensing, and cancer therapy. Magnetic nanoparticles can specifically target CD44 receptors on cancer cells, enabling selective isolation and treatment of malignant tissues (Murray *et al.,* 2019). Furthermore, magnetically induced hyperthermia has demonstrated efficacy in ablating tumors in preclinical studies, highlighting the potential of MNPs for controlled therapeutic interventions (Alphandéry, 2020).

Gold nanoparticles (AuNPs) are extensively applied in targeted drug delivery, cancer cell detection, and nuclear transport. Their surface charge plays a critical role in hemocompatibility; positively charged NPs show higher hemolytic activity due to electrostatic interactions with red blood cells, whereas negatively charged NPs demonstrate variable hemolysis depending on membrane

accessibility (Lozano *et al.,* 2009; Lozano *et al.,* 2019). Overall, MNPs offer highly tunable platforms for biomedical applications, combining diagnostic and therapeutic functionalities with controlled targeting and minimal systemic side effects.

2.4.Nanomedicine and Nanodrugs

Nanoparticles (NPs) provide innovative strategies to overcome limitations in conventional systemic drug delivery. One of the major challenges is their restricted ability to cross physiological barriers, such as the blood–brain barrier. To address this, nanoparticles utilize mechanisms like absorptive transcytosis and receptor-mediated transcytosis. In absorptive transcytosis, NPs attach to the cell surface and are transported across endothelial cells, whereas in receptor-mediated transcytosis, nanoparticles are functionalized with specific ligands that bind to targeted receptors, promoting efficient cellular uptake through endocytosis (Ahn *et al.,* 2020; Li *et al.,* 2020).

Receptor-mediated transcytosis can be further classified into clathrin-mediated and caveolae-mediated endocytosis, depending on the type of receptor involved (Ahn *et al.,* 2020; Li *et al.,* 2020). The physicochemical properties of nanoparticles—such as size, surface charge, and functional modifications—significantly influence their biological fate. For instance, particles smaller than 200 nm are generally considered optimal for endothelial uptake. Surface charge also affects circulation: positively charged NPs interact more effectively with negatively charged cell membranes, whereas neutral or negatively charged NPs exhibit slower uptake and prolonged systemic circulation.

Surface engineering, such as PEGylation, provides steric stabilization around NPs, extending their circulation time while reducing opsonization and clearance by the mononuclear phagocyte system (Ahn *et al.,* 2020; Chang *et al.,* 2020). Other strategies, such as zwitterionic coatings and multifunctional ligand attachment, further enhance cellular penetration and receptor targeting. Peptide conjugation allows nanoparticles to bypass traditional endocytic pathways, delivering therapeutic payloads directly into the cytoplasm (Ahn *et al.,* 2020; Chang *et al.,* 2020).

The integration of nanoparticles into medicine has expanded the development of nanodrugs, enabling controlled, targeted, and highly effective therapeutic delivery. These advancements offer opportunities for addressing challenges in diseases that require precise drug localization, such as cancer and neurological disorders.

2.5.Emerging Applications

Red blood cells (RBCs) play a critical role in maintaining proper blood flow and hemostasis. When nanoparticles (NPs) interact with RBCs, they may cause aggregation, hemolysis, or reduced deformability, potentially disrupting normal physiological functions (Rezaei *et al.,* 2019). RBCs also contribute to axial migration and flow dynamics, but NP exposure can elevate thrombosis risk by promoting phosphatidylserine exposure on RBC membranes, creating a prothrombotic surface (Eskan-Lone, 2018).

Platelets are central to hemostasis, forming hemostatic plugs following vascular injury to prevent excessive blood loss. Beyond hemostasis, platelets influence vascular inflammation, innate immunity, tumor progression, and angiogenesis (Fröhlich, 2016; Heidari-Dalfard *et al,* 2025). Interactions of NPs with platelets may modulate these functions, producing both beneficial and adverse outcomes (Dew, 2020).

White blood cells (WBCs), including monocytes, lymphocytes, and granulocytes, are essential for immune defense and the maintenance of homeostasis. Recent studies indicate that immune cells dynamically contribute to hemostasis and thrombosis (Dew, 2020), highlighting the intricate link between coagulation and innate immunity (La Cruz *et al.,* 2017). Understanding NP interactions with blood components and immune pathways is crucial for developing artificial blood substitutes, improving oxygen transport, and evaluating potential toxicological effects.

All nanoparticles intended for clinical or biomedical use inevitably interact with biological tissues. Upon entering the bloodstream, NPs encounter RBCs, WBCs, platelets, and plasma proteins. Characterizing these interactions is essential to assess both safety and therapeutic potential.

2.6.Functionalization of Nanoparticles

The concept of metallic nanoparticles (MNPs) dates back to Michael Faraday in 1857, who demonstrated their existence in solution. Subsequent studies characterized their color, morphology, and physicochemical properties (Yaqoob *et al.,* 2020; Kumar *et al.,* 2018). Metallic nanoparticles, including metal NPs (MNPs) and metal oxide NPs (MONPs), are defined by features such as size, morphology, molar volume, and surface chemistry, all of which govern their biomedical applications (Murray *et al.,* 2019).

Functionalization with biomolecules—such as DNA, RNA, peptides, and antibodies—enables noble metal nanoparticles (e.g., gold, silver, platinum) to serve as ideal platforms for cancer diagnostics and therapeutic interventions (Yaqoob *et al.,* 2020). The chosen preparation method significantly affects the resulting nanoparticle properties (Nair *et al.,* 2007). Traditional approaches include physical and chemical synthesis, but these methods may produce toxic byproducts. Green synthesis offers a safer and more sustainable alternative, minimizing potential hazards (Ahmed *et al.,* 2016; Kaliaraj, 2017).

Among the two general fabrication strategies, top-down and bottom-up, the bottom-up approach is most widely adopted due to its precise control over particle size and structure (Wang *et al.,* 2017; Yeap *et al.,* 2014). Metallic NPs, such as copper, gold, silver, and palladium, exhibit stability under hypoxic tumor conditions and have been utilized in diagnostic imaging, biosensing, and therapeutic applications (Murray *et al.,* 2019). Metal oxide nanoparticles, known for chemical stability and catalytic activity, are suitable for drug delivery and biomedical imaging. Magnetic nanoparticles (MNPs) demonstrate high biocompatibility and have been applied in isolating lymphoma cells, targeting CD44 receptors, and selectively removing cancer cells (Murray *et al.,* 2019).

In addition to synthetic routes, magnetic bacteria produce magnetosomes—iron oxide nanoparticles tested in tumor models. Preclinical studies demonstrated that hyperthermia induced by magnetic fields can effectively ablate tumors. These MNPs enable controlled cancer therapy via localized heating, targeted drug release, and enhanced radiotherapy (Alphandéry, 2020).

Gold nanoparticles (AuNPs) have been widely employed for cancer cell detection and targeted drug delivery, even facilitating nuclear transport. Positively charged nanoparticles exhibit higher hemolytic activity than negatively charged ones due to electrostatic interactions with negatively charged RBC membranes (Lozano *et al.,* 2009). Nevertheless, hemolysis may still occur with

negatively charged NPs depending on RBC membrane accessibility. Overall, hemocompatibility assessments indicate that NP surface charge, size, and morphology are key factors influencing safety and biomedical efficacy (Lozano *et al.,* 2019).

Nanotechnology has brought transformative changes to biomedical applications, particularly through the development of carbon-based, organic, and metallic nanoparticles. Carbon-based nanoparticles (CBNPs), such as carbon nanotubes (CNTs), fullerenes, graphene derivatives, and quantum dots, exhibit remarkable physicochemical properties including optical fluorescence, mechanical strength, and chemical stability. These properties make CBNPs highly suitable for deep-tissue imaging, targeted drug delivery, and combinatorial therapeutic strategies (Gupta *et al.,* 2018; Augustine *et al.,* 2017; Castro *et al.,* 2017; Limongi *et al.,* 2017). Functionalization of CBNPs with biomolecules, drugs, or ligands further enhances biocompatibility, reduces toxicity, and improves selective targeting, positioning them as versatile platforms for future biomedical applications (Wang *et al.,* 2020; Murjani *et al.,* 2022).

Organic nanoparticles offer complementary advantages in drug delivery and imaging due to their biodegradability, biocompatibility, and ability to encapsulate both hydrophilic and hydrophobic agents (Crucho & Barros, 2017; Ferreira-Souza *et al.,* 2020). Polymeric and lipid-based NPs, including liposomes and extracellular vesicles, can be synthesized via controlled techniques such as fluid dialysis and emulsion methods, enabling precise tuning of particle size, morphology, and solubility. These attributes allow organic nanoparticles to act as precision nanocarriers, enhancing therapeutic efficiency while minimizing adverse effects (Jiang & Poo, 2017; Li *et al.,* 2020; Kirubakaran *et al.,* 2025).

Metallic nanoparticles (MNPs), including gold, silver, copper, and palladium nanoparticles, offer unique optical, magnetic, and catalytic properties distinct from their bulk counterparts (2005; Nikalje, 2015; Yaqoob *et al.,* 2020). Their capacity for surface functionalization withbiomolecules enables targeted therapy and diagnostic applications, particularly in oncology (Lozano *et al.,* 2009; Murray *et al.,* 2019; Alphandéry, 2020). Magnetic nanoparticles, including naturally synthesized magnetosomes, demonstrate effective tumor targeting and controlled drug release through localized hyperthermia, highlighting their potential for precision medicine (Alphandéry, 2020). Importantly, nanoparticle properties such as size, surface charge, and functionalization critically influence cellular uptake, biodistribution, and hemocompatibility, requiring careful design to maximize efficacy and minimize toxicity (Ahn *et al.,* 2020; Chang *et al.,* 2020; Lozano *et al.,* 2019). Across all nanoparticle types, interactions with biological systems are central to their biomedical applications. Blood components, including red blood cells, white blood cells, platelets, and plasma proteins, interact dynamically with nanoparticles, affecting hemostasis, immune responses, and therapeutic outcomes (Rezaei *et al.,* 2019; Eskan-Lone, 2018; Dew, 2020; La Cruz *et al.,* 2017). Surface modifications such as PEGylation and zwitterionic coatings can improve circulation time, reduce opsonization, and enhance cellular uptake, enabling more effective delivery of therapeutic payloads (Ahn *et al.,* 2020; Chang *et al.,* 2020). Moreover, understanding these interactions is critical for designing nanomaterials that balance therapeutic benefits with biocompatibility and minimal adverse effects (**Table 1**, **Table 2**)

Table 1. Comparison of Carbon-Based, Organic, and Metallic Nanoparticles: Properties and Applications

Nanoparticle Type	Features	Biomedical Applications	Environmental / Other Applications	References
Carbon-Based NPs (CBNPs)	Includes carbon nanotubes, fullerenes, graphene, nanodiamonds; excellent optical, mechanical, and thermal properties; high functionalization potential	Drug delivery, cellular imaging, tissue repair, combination therapies (photodynamic, hyperthermia)	Industrial applications: catalysis, gas adsorption, nanocomposites; environmental accumulation possible, potential carbon particle effects	Gupta et al., 2018; Augustine et al., 2017; Maiti et al., 2018; Yamashita et al., 2012
Organic NPs	Made from lipids and polymers; biocompatible and biodegradable; can co-encapsulate hydrophilic and hydrophobic drugs	Targeted drug delivery, imaging, vaccines, chronic disease therapy	Lower environmental impact; metabolized and biodegradable; limited environmental effects	Crucho & Barros, 2017; Ferreira-Souza et al., 2020; Li et al., 2020
Metallic NPs	Includes gold, silver, metal oxides, and magnetic nanoparticles; outstanding optical and magnetic properties; can be functionalized with biomolecules	Cancer detection, targeted drug delivery, cancer therapy, medical imaging	Potential cellular and tissue toxicity; disposal and environmental accumulation require control	Nikalje, 2015; Murray et al., 2019; Yaqoob et al., 2020; Alphandéry, 2020

In summary, the synthesis, functionalization, and application of nanoparticles in biomedicine are tightly interlinked. Carbon-based, organic, and metallic nanoparticles each offer unique advantages that can be exploited for targeted drug delivery, imaging, and combinatorial therapies (Wang *et al.,* 2020; Jayaprakash *et al.,* 2024; Salehirozveh *et al.,* 2024). However, their clinical translation requires careful consideration of nanoparticle design, physicochemical properties, and interactions with biological systems. Future research should focus on optimizing multifunctional nanocarriers, minimizing toxicity, and expanding applications in disease diagnosis and treatment.

Table 2. Nanoparticle Synthesis and Functionalization Techniques

Type of NP	Synthesis Method	Functionalization / Surface Modification	Key Advantages	References	Type of NP	Synthesis Method
Gold NPs (AuNPs)	Chemical reduction, green synthesis, seed-	Conjugation with DNA, RNA, peptides,	Targeted delivery, biocompatibilit	Nair & Laurencin, 2007; Yaqoob et al., 2020;	Gold NPs (AuNPs)	Chemical reduction, green synthesis, seed-

	mediated growth	antibodies; PEGylation	y, tunable size & shape	Murray et al., 2019		mediated growth
Silver NPs (AgNPs)	Chemical reduction, plant-mediated green synthesis, photochemical	Surface coating with polymers, proteins, small molecules	Antimicrobial activity, improved stability, controlled release	Ahmed et al., 2016; Kaliaraj, 2017	Silver NPs (AgNPs)	Chemical reduction, plant-mediated green synthesis, photochemical
Copper NPs (CuNPs)	Chemical reduction, thermal decomposition	Ligand functionalization, polymer coating	High conductivity, catalytic activity, enhanced biocompatibility	Yaqoob et al., 2020; Murray et al., 2019	Copper NPs (CuNPs)	Chemical reduction, thermal decomposition
Metal Oxide NPs (Fe3O4, TiO2, ZnO)	Co-precipitation, sol-gel, hydrothermal	Silanization, polymer coating, biomolecule attachment	Magnetic targeting, catalytic activity, chemical stability	Murray et al., 2019; Alphandéry, 2020	Metal Oxide NPs (Fe3O4, TiO2, ZnO)	Co-precipitation, sol-gel, hydrothermal

Conclusion

In summary, carbon-based, organic, and metallic nanoparticles offer remarkable opportunities in biomedical applications. Their unique physicochemical characteristics, including tunable size, surface properties, and multifunctional capabilities, enable efficient drug delivery, imaging, and targeted therapies. Organic nanoparticles provide high biocompatibility and controlled release, metallic nanoparticles support precise diagnostics and cancer treatment, and carbon-based nanoparticles combine optical, mechanical, and chemical features for versatile biomedical uses. Careful design and evaluation of nanoparticle interactions with biological systems are essential to maximize therapeutic benefits while minimizing potential risks. These nanomaterials hold significant promise for advancing nanomedicine and developing innovative diagnostic and therapeutic strategies for a wide range of diseases.

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