


# Chapter 2

# Nanomaterials in Medical Applications: An Introduction

**Yusuf Olatunji Waidi**

 <https://orcid.org/0000-0002-5728-1769>

*Indian Institute of Science, India*

## **ABSTRACT**

*Nanotechnology has revolutionized medicine, offering innovative solutions to longstanding healthcare challenges. This chapter provides a comprehensive overview of nanoparticles, their unique properties, and their diverse medical applications. It explores the historical context of nanoparticle use in therapeutic approaches and delves into various nanoparticle types, including their properties and applications. The chapter also examines the interaction between nanoparticles, cells, and tissues, discussing cellular uptake mechanisms, responses, and tissue distribution. Additionally, it addresses the challenges and future prospects of nanoparticle-based therapies, including safety, toxicity concerns, clinical translation barriers, and potential future directions. Overall, the chapter highlights the promising potential of nanoparticles to transform medicine by offering innovative solutions for diagnosis, treatment, and drug delivery.*

## **1. INTRODUCTION**

Nanoparticles (NPs), typically ranging from 1 to 100 nanometers in size, exhibit exceptional catalytic and adsorptive properties useful for various applications (Erisen & Uludag, 2024; Waidi & Jain, 2024a; Waidi et al., 2024). These “zero-dimensional” NPs, as they are often referred to, possess unique characteristics due to their nanoscale dimensions. In contrast to one-dimensional nanomaterials (NMs) like nanowires and nanotubes or two-dimensional NMs like self-assembled monolayer films, NPs have all three dimensions within the nanoscale range. This distinct feature, coupled with their large surface area, imparts unique chemical and physical properties, including size-dependent optical properties that result in distinct colors due to visible light absorption (Jain, Waidi, Vannaladsaysy, Pathote, & Datta, 2025). The unique properties of NPs have led to their incorporation into composite materials, such as the modern rubber tire, which utilizes silica NPs as a reinforcing filler. The early 21st century witnessed a significant surge in nanoparticle usage in various applications, driven by nanocomposite (NCP) technol-

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ogy advancements (Waidi, 2024a, 2024b). NCPs have found applications in various fields, including the creation of novel materials with tailored dielectric and magnetic properties. Moreover, organic materials incorporating NPs have enabled the development of ultra-thin solar panels that offer a relatively low cost and offer exceptional quantum efficiency and flexibility. Beyond their industrial applications, NPs have also shown promise in synthetic biology. Well-refined NPs of proteins and nucleic acids can self-assemble into highly ordered structures, exhibiting unusual properties that could potentially revolutionize fields like medicine and materials science (Kaltbeitzel & Wich, 2023).

Furthermore, other NPs, such as “quantum dots” or “artificial atoms,” are quasi-zero-dimensional (0D) nanostructures with unique properties. Their size-dependent behavior, distinct from bulk materials, arises from quantum mechanical effects (Szczyglewska, Feliczak-Guzik, & Nowak, 2023). They exhibit diverse characteristics based on their composition, structure, and size, leading to a wide range of applications (Mourdikoudis, Pallares, & Thanh, 2018). While traditional methods like physical and chemical synthesis have been employed, recent advancements in green nanotechnology have leveraged biological approaches, particularly plant-mediated synthesis, to produce NPs with controlled properties (Zou et al., 2022). These plant-based NPs offer advantages such as eco-friendliness, biocompatibility, and reduced toxicity compared to conventional methods (O’Dell, Schein, & Erickson, 2016). The applications of NPs span various fields, including medicine, electronics, materials science, and environmental remediation (Waidi, 2024a). Their potential in drug delivery, biosensing, catalysis, and water treatment has garnered significant attention. As research progresses, developing novel NP-based technologies continues to shape advancements in diverse industries.

The evolution of nanoparticles (NPs) in medicine, though termed “nanotechnology” in the 1970s, boasts ancient roots, with Egyptians using colloidal gold for glass coloration and likely tissue penetration, and Ayurvedic practitioners employing NP-containing herbal remedies (Amen et al., 2021; Kagdada, Bhojani, & Singh, 2023). However, modern NP technology truly began to flourish with key scientific advancements: the invention of the scanning electron microscope in the 1930s enabled unprecedented visualization of nanoscale materials (Sudha, Sangeetha, Vijayalakshmi, & Barhoum, 2018), directly impacting our ability to characterize and engineer NPs. The discovery of liposomes by Alec Bangham in the 1960s marked a pivotal moment, as it opened the door to encapsulating drugs and laid the foundation for modern targeted drug delivery systems (Amen et al., 2021). Further revolutionizing diagnostic capabilities, the emergence of quantum dots in the early 1980s transformed fluorescent imaging techniques, paving the way for advanced bioimaging (Amen et al., 2021). These foundational discoveries, coupled with subsequent research in the 21st century, have culminated in the FDA approval of numerous nanomedicine therapies, particularly in cancer treatment, demonstrating the significant impact of NPs in targeted drug delivery and diagnostics (Kagdada et al., 2023). Despite these successes, ongoing research and regulatory oversight remain critical to address persistent challenges in ensuring the safety and efficacy of NP applications in medicine.

Understanding nanoparticle-based therapies is crucial as they offer transformative medical potential through enhanced drug delivery, improved diagnostics, and novel therapeutic approaches. Engineered to target specific diseased cells, NPs significantly improve drug efficacy and minimize side effects (Yetisgin, Cetinel, Zuvin, Kosar, & Kutlu, 2020). Their ability to sustain drug release and penetrate biological barriers, such as the blood-brain barrier, facilitates access to previously unreachable areas (Zubair et al., 2024). Moreover, NPs enable early disease diagnosis through sensitive biomarker detection and enhance imaging modalities, providing valuable insights into disease progression (Umopathy, Natarajan, & Swamikannu, 2024). By delivering therapeutic genes and combining diagnostic and therapeutic functions,

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