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ROLE OF NANOMATERIALS IN HEALTHCARE

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ABSTRACT
Nanotechnology is revolutionising medicine by enabling highly precise diagnostics, targeted therapies, and personalised healthcare solutions. This review explores the multifaceted applications of nanotechnology across medical fields such as oncology and infectious disease control. Engineered nanoparticles (NPs), such as liposomes, polymeric carriers, and carbon-based nanomaterials, enhance drug solubility, protect therapeutic agents from degradation, and enable site-specific delivery, thereby reducing toxicity to healthy tissues. In diagnostics, nanosensors and contrast agents enable ultra-sensitive biomarker detection, supporting early diagnosis and real-time monitoring. Nanotechnology also contributes to regenerative medicine, antimicrobial therapies, wearable devices, and theranostics, which integrate treatment and diagnosis into unified systems. Advanced innovations such as nanobots and smart nano systems further extend these capabilities, enabling responsive drug delivery and minimally invasive interventions. Despite its immense potential, nanomedicine faces challenges, including biocompatibility, environmental safety, manufacturing scalability, and regulatory oversight.

KEYWORDS: nanomedicine; healthcare; nanozyme; nanobots; drug delivery system.

INTRODUCTION
Nanotechnology encompasses a broad interdisciplinary field of science and engineering focused on understanding and manipulating matter at the atomic and molecular scale.[1] Over the past few decades, the potential of nanotechnology to revolutionize healthcare has garnered increasing attention, resulting in significant investment and research globally.[4] It has ramped up funding initiatives, recognising nanotechnology as a catalyst for innovation, economic development, and societal well-being. The profound impact of nanotechnology extends across industries, promising to reshape how we approach treatment, diagnostics, and disease prevention.[5] These innovations aim to reshape conventional medicine, advancing human health and longevity.[7] The influence of nanotechnology on the life sciences is profound. It enables breakthroughs across various branches of healthcare, from early disease detection to the creation of vaccines and minimally invasive surgical tools.[8] For instance, the blood–brain barrier, which acts as a selective gateway to the brain, has traditionally posed a challenge to drug delivery. However, specially engineered nanoparticles are now capable of crossing this barrier, offering new treatment strategies for neurological conditions.[11] Conventional treatments for conditions such as vascular thrombosis often suffer from limitations, including short circulation times and adverse effects. Nanotechnology-based delivery systems such as polymeric nanoparticles and liposomes can encapsulate drugs to increase stability and therapeutic efficacy. These carriers are biocompatible and biodegradable, making them ideal candidates for advanced drug delivery applications.[12]

RECENT PROGRESS
With recent progress in nanotechnology, clinicians and researchers are now able to target biological processes within the human body at an unprecedented molecular level, utilizing materials such as biocompatible nanoparticles and nanoscale robotic devices.[14] This broadened the scope and commercial potential of nanomedicine, offering tools like nanosensors and nanomachines capable of assessing biochemical activities within organs and accessing diseased tissues with remarkable precision.[15] One of the core strengths of nanomedical systems lies in their ability to shield therapeutic agents from degradation, thus prolonging their bioactivity and enhancing water solubility. This

protection ensures that drugs reach their target intact and remain effective within the body's harsh internal environment.[16] In diagnostics, nanoparticles serve as powerful tools for detecting biomarkers, including those associated with tumours and genetic conditions, enabling earlier and more accurate diagnosis. Applications of nanomedicine extend across a wide spectrum from traditional chemotherapy and biologic agents to next-generation immunotherapies.[17] This has proven particularly impactful in oncology, where nanocarriers enhance drug delivery efficiency while mitigating adverse side effects.[18] This precision not only boosts treatment outcomes but also reduces damage to surrounding healthy tissues.[2] Remarkable progress has been made in refining intracellular drug transport and controlled gene release using nanoparticles. Such advancements allow clinicians to fine-tune dosages and enhance treatment effectiveness.[12] Moreover, nanotechnology is playing a pivotal role in regenerative medicine, with innovations such as magnetic nanoparticles aiding neural regeneration and enzyme-responsive nanosystems designed for brain tumour therapy.[13] Nanorobotics, a cutting-edge application within nanomedicine, is especially promising. Additionally, the increasing reliance on nanorobotics is fueling expansion in the medical technology market, signaling a shift toward more efficient, responsive, and personalized healthcare solutions.[15] Nanozymes, an emerging class of nanomaterials, combine the catalytic activity of enzymes with the distinct physicochemical features of nanoscale molecules.[16] This study seeks to give a complete overview of nanomedicine's involvement across the illness management continuum, from early detection to tailored treatment. It focuses on current advancements in nanoscale diagnostic tools, drug delivery systems, and therapeutic nanoplatforms, as well as their clinical promise, limitations, and prospects. By connecting nanotechnology's diagnostic and therapeutic uses, the paper underlines nanomedicine's integrative potential in improving patient outcomes and promoting personalised medicine.

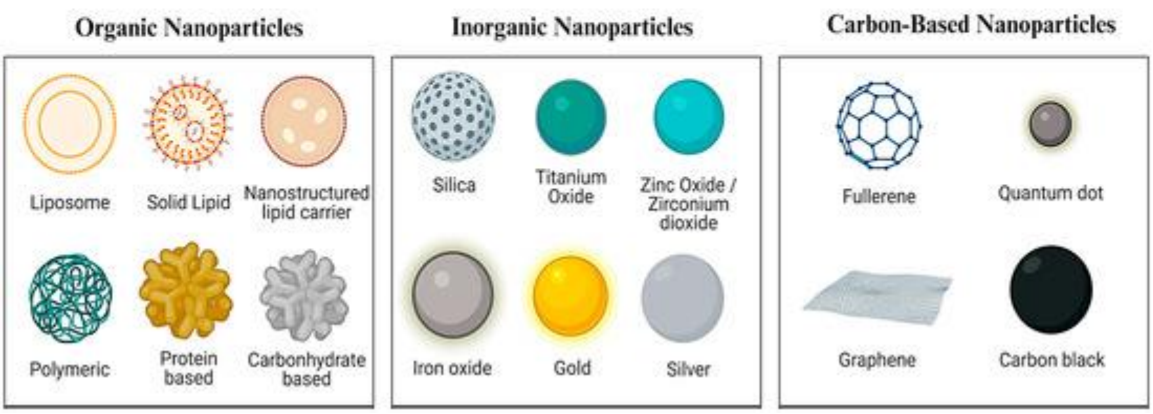


Figure 2: Different types of nanoparticles used in the medical field.

METHODOLOGY

The methodology of this review involved a comprehensive and systematic search of the scientific literature to gather current information on the diagnostic and therapeutic applications of nanotechnology in medicine and healthcare. A targeted search was conducted across major databases, including PubMed, Scopus, Web of Science, and Google Scholar. Keywords used in various combinations included "nanotechnology," "nanomedicine," "nanoparticles," "diagnostics," "drug delivery," "therapeutics," and "biomedical applications." Only English-language articles were considered, and studies were selected based on their relevance to medical diagnostics and therapeutics, with a preference for original research, clinical trials, and high-impact reviews. Exclusion criteria included non-medical applications of nanotechnology, editorials, and articles lacking experimental or clinical data. After an initial screening of titles and abstracts, a full-text evaluation was conducted, and data were extracted regarding the types of nanomaterials, their mechanisms of action, clinical targets, and reported outcomes. Studies were grouped into diagnostic and therapeutic categories and analyzed for innovation, translational value, and scientific quality to provide a balanced and insightful synthesis of the current state of nanotechnology in healthcare.

NANOMEDICINE

The integration of nanotechnology into the medical domain has triggered a paradigm shift in how diseases are diagnosed, monitored, and treated, as illustrated in Figure 1. As the capabilities of nanomedicine continue to expand, they are redefining traditional healthcare models, offering innovative solutions with far-reaching impacts on patient outcomes.[17] The ongoing development of nanoscale drug delivery systems and diagnostic tools demonstrates the urgent need to further explore and implement these technologies in clinical settings.[28] Nanotechnology has enabled the evolution of drug therapy by introducing more precise and effective treatments. Areas such as oncology, cardiology, nephrology, and genetic medicine have witnessed transformative progress due to the application of nanoscale materials and engineered systems.[9] For example, gene therapy has leveraged nanoparticles to improve delivery efficiency, often utilizing viral vectors engineered at the nanoscale to transport therapeutic agents directly to targeted cells.[3] Smart devices such as ingestible sensors, nanobots, and responsive drug delivery systems are now capable of monitoring patient health in real time. These devices can provide critical feedback to healthcare professionals, ensuring the accurate administration of medications and enhancing the overall effectiveness of therapeutic regimens. The word "smart" refers to the capability of these devices to gather information intelligently and instantly.

POLYMERIC NANOPARTICLES

Are designed for inflammatory bowel disease (IBD) are primarily smart in nature. They can react to various stimuli, including reactive oxygen species, pH levels, specific ligands, magnetic fields, and the gut microbiome, enabling controlled drug release. By encapsulating the medication, they can safeguard it, minimize side effects, and specifically target certain cells. Smart nanoparticles have surfaced as a potential replacement for traditional nanoparticles in cancer treatment. In contrast to conventional nanoparticles, they can be activated by particular stimuli and deliver drugs accurately to targeted sites.[3,4,5] By replacing conventional diagnostic procedures with nanoparticle-enabled assays, medical practitioners can achieve higher accuracy at reduced costs. Nanoparticles are increasingly used as contrast agents or imaging enhancers, especially in identifying cancer biomarkers and tracking cellular changes in real-time. These particles can be fine-tuned to detect specific genetic mutations and cellular behaviours associated with tumour development.[4] Medical devices now often feature nanoscale surface coatings made from compounds such as titanium dioxide, silicon dioxide, zinc oxide, silver, and iron oxide. These coatings improve device performance by enhancing durability, biocompatibility, and resistance to microbial contamination.[5] Advancements in material science, particularly in nanosensors and nanostructured energy systems, are driving significant improvements in the design and performance of medical devices. These innovations underscore the growing importance of nanotechnology in medical engineering. Through collaborative efforts, scientists and engineers are developing next-generation medical technologies that integrate these cutting-edge materials, leading to smarter diagnostic tools, safer implantable devices, and more effective therapeutic systems.[16]

Nanotechnology applications in the medical field. CT: computed tomography, MRI: magnetic resonance imaging, PET: positron emission tomography, SPECT: single-photon emission tomography, US: ultrasound, and FI: fluorescence imaging.[7]

VARIOUS TYPES OF NANOPARTICLES THAT ARE USED IN MEDICAL APPLICATIONS

Nanoparticles are distinguished by their high surface-area-to-volume ratio, a characteristic that allows for superior drug loading capacity and enhanced circulation through the bloodstream. Their nanoscale size grants them unique physical and chemical properties, including tailored optical, magnetic, mechanical, and catalytic behaviors, making them ideal candidates for various biomedical applications.[8] The following are some of the significant technological benefits of nanoparticles as drug carriers: high stability (i.e., long shelf life); high carrier capacity (i.e., many drug molecules can be incorporated in the particle matrix); the feasibility of incorporating both hydrophilic and hydrophobic substances; and the feasibility of multiple routes of administration, including oral and inhalation. These carriers can also be developed to permit regulated (long-term) medication release from the matrix.[9] Nanoparticles can be engineered to respond to specific stimuli such as light, temperature, or magnetic fields. For instance, certain metal-based particles absorb light and convert it into heat, a feature that can be used to selectively destroy cancer cells, a process known as photothermal therapy.[40] Based on their chemical composition, as illustrated in Figure 2, nanoparticles used in medicine are generally categorized into three primary groups: organic, inorganic, and carbon-based nanomaterials.

ORGANIC NANOPARTICLES

They are composed of biologically derived substances such as proteins, lipids, carbohydrates, and biodegradable polymers.[1] These particles are often engineered to be smaller than 100 nanometers and are valued for their compatibility with human tissues, making them effective carriers for drug molecules and genetic material.[4]

WOUND TREATMENT AND INFECTION CONTROL

Significant progress has been made in tissue regeneration and wound healing through nanotechnology. Engineered nanomaterials can now assist the body in repairing damaged tissues by providing scaffolds that closely resemble the structure of natural cells.[17] This is particularly significant in reconstructive surgeries where traditional grafts or transplants may not suffice. Nanoparticles can be functionalized with specific ligands and imaging agents to selectively bind to diseased tissue, allowing for accurate identification of injuries and optimised surgical precision, which assists medical professionals in differentiating between healthy and affected regions, reducing the risk of further damage.[8]

ANTIMICROBIAL TREATMENTS

The antibacterial potential of nanomaterials is receiving growing attention as a promising strategy to combat the escalating challenge of antimicrobial resistance. Antimicrobial resistance mechanisms include active efflux pumps, restricted permeability of bacterial membranes, enzymatic degradation of antimicrobial agents, the formation of protective biofilms, altered antimicrobial targets, and the protection of bacterial sites of action from antimicrobials. Nanotechnology enables the development of highly effective antimicrobial agents and surfaces[54], as illustrated in Figure 3.

INORGANIC NANOPARTICLES

Encompass materials such as metal salts, metal oxides, and pure elemental metals. These particles are known for their chemical stability, water solubility, and biocompatibility. In comparison to organic NPs, they offer enhanced control over particle behavior and are less prone to degradation.[3]

MINIMISING CYTOTOXIC EFFECTS

All medications have side effects, although their magnitude and severity range from mild to severe. The majority of adverse effects are expected and are listed. However, the main issue is that some of the treatments' side effects are unknown or have not been observed, and the actual concern here is whether they will have a severe negative influence on the people who use them. The most crucial elements that may enhance the severity of the side effects are the kind of drug and the type of people using them.[6] A significant advantage of nanotechnology in cancer treatment is its capacity to precisely deliver drugs to malignant cells while sparing surrounding healthy tissues.[9]

NANOMEDICINE DIAGNOSTIC TECHNIQUE

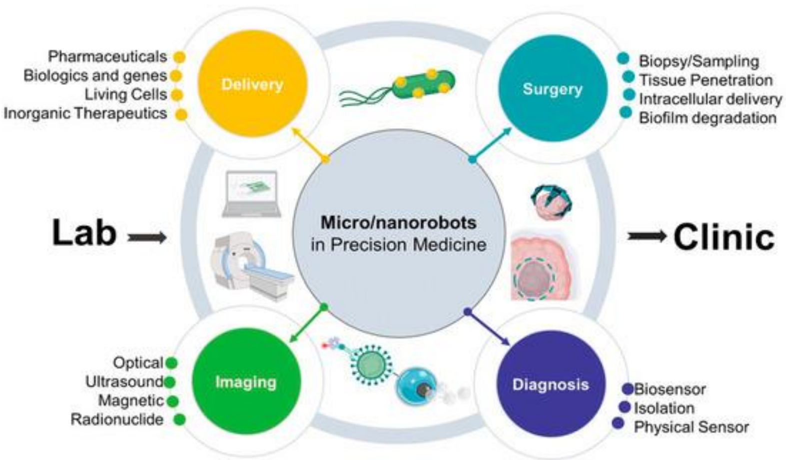
The diagnostic capabilities empowered by nanotechnology are rapidly reshaping how diseases are identified and monitored. Techniques employing gold nanorods, carbon nanotubes, and other nanosensors now allow for ultra-sensitive, cost-effective, and rapid detection of diseases at their earliest stages.[7] These innovations mimic natural biological behavior more closely than traditional prosthetics, supporting cellular growth and functionality in a more seamless way. Recent years have witnessed a leap in diagnostic imaging technologies such as MRI and CT scans. Yet, nanotechnology is pushing beyond the current limits of conventional tools by offering ultra-sensitive diagnostic techniques for both in vivo and in vitro applications.[7]

EMERGING FRONTIERS OF NANOTECHNOLOGY IN MODERN MEDICINE

Nanotechnology is redefining medical science through innovations in diagnostics, precision treatment, and advanced therapies.[9] Compact, portable systems now allow real-time analysis of minimal biological samples, drastically reducing the time required for diagnostics. As biosensor technologies evolve, their sensitivity and capability to process larger volumes of data will continue to enhance early disease detection.[10] Formulations using iron oxide particles and functional polymers have significantly improved imaging quality, even at lower dosages, thus reducing patient exposure to contrast agents while increasing the precision of diagnosis, especially in the identification of genetic disorders and malignancies.[11]

TARGETED DRUG DELIVERY

Advanced drug delivery mechanisms enabled by nanotechnology involve nanoscale carriers embedded with active pharmaceutical ingredients.[7,8] These carriers are tailored to reach specific tissues or organs, thereby maximizing drug impact and minimizing unwanted effects.[9] Metallic, organic, inorganic, and polymeric nanostructures, such as dendrimers, micelles, and liposomes, are commonly used in the creation of targeted drug delivery systems. These nanoparticles are specifically used to tag medicines with low solubility and absorption. However, the efficiency of these nanostructures as drug delivery vehicles varies with their size, shape, and other underlying biophysical/chemical properties.[10]



NANOZYME

Natural enzymes are well-known for their catalytic activity against certain substrates; yet, they require precise conditions to be stable under severe conditions such as high temperatures. To address this issue, scientists have developed immobilisation methods based on nano- and microscale materials. The combination of these materials in healthcare equipment mimics the properties of main biological environments. These nanomaterials can be enhanced using a variety of components, including artificial polymers, carbon-based nanoparticles, metal–organic frameworks, nanosized protein-based nano-delivery systems, lipid-based nanomaterials, and polysaccharide-based nanoparticles. As a result, nanozymes offer the advantages of natural enzymes in addition to better stability, simplicity of storage, and easy production.[98]

ENHANCING RADIATION THERAPY

Radiation treatment is being refined through the use of nanoparticles engineered to selectively accumulate in tumor tissues. These specialized particles can intensify the effects of radiation precisely at the cancer site, sparing surrounding healthy cells and reducing the harmful side effects commonly associated with conventional therapies.[12] One of the primary goals of integrating classical radiation therapy with nanotechnology is to enhance the difference in effects between cancerous and healthy cells, ensuring that only tumors are impacted by radiation treatment. Researchers are concentrating on specifically targeting cancer cells during radiation application and making radioresistant cancer cells more susceptible to standard radiation doses.

FUTURE AND EMERGING PROSPECTS

The evolving field of nanomedicine is poised to play a foundational role in the next generation of personalized healthcare, offering capabilities that extend from early disease forecasting to real-time health monitoring.[12] As research deepens, nanoscale materials are becoming integral to the design of ultra-sensitive diagnostic tools and molecular-level biomarkers that can detect multiple disease states at the earliest stages with exceptional accuracy and specificity. One of nanomedicine's key strengths lies in its ability to deliver targeted interventions.[14] Following an accurate diagnosis, nanoparticle-based systems can selectively attack diseased cells while sparing healthy tissues, minimizing collateral damage and side effects. Yet, the future holds even greater promise, particularly in enhancing drug payload capacity, improving release mechanisms, and refining the therapeutic capabilities of metallic nanoparticles.[15]

CHALLENGES AND LIMITATIONS

Despite its promising potential, nanomedicine faces several technical, economic, and safety-related hurdles that must be addressed before widespread clinical integration can occur. One of the most pressing issues lies in ensuring consistency in the production of nanomaterials. Achieving batch-to-batch reproducibility, maintaining stringent quality standards, and scaling up manufacturing processes without compromising precision remain formidable tasks for researchers and industry alike. Moreover, the high cost of developing nanomedical products continues to be a barrier, especially in the face of limited clarity about their long-term biological and ecological effects. Uncertainties regarding how nanoparticles interact with the environment and human physiology have raised red flags among regulatory bodies and investors. The pharmaceutical industry, in particular, has been hesitant to make significant financial commitments due to these unresolved risks and the slow pace of regulatory approvals. From a biological standpoint, the use of nanoparticles inside the body introduces a range of complications. These microscopic entities, due to their size and surface properties, can evade immune surveillance, bypass physiological defense systems, and accumulate in specific organs.

CONCLUSIONS

Nanotechnology is rapidly transforming modern healthcare by shifting the focus from reactive treatment to proactive health management. One of its core strengths lies in enabling precise therapeutic delivery, significantly lowering the risk of unintended side effects while improving overall treatment outcomes. Its precision-driven approach has shown immense promise in the management of complex diseases such as cancer, where accurate targeting is crucial. Among the most innovative advancements is the integration of nanorobotics within medicine, facilitating a wide spectrum of applications. These range from targeted drug transport and smart diagnostic systems to the development of next-generation vaccines and antimicrobial solutions. Additionally, nanotechnology is contributing to the evolution of wearable health monitoring devices and advanced imaging platforms. The synergy between conventional pharmaceutical therapies and nanotechnology is paving the way for a new era of combination treatments that can cross physiological barriers, such as the blood–brain barrier, and act directly on disease sites with heightened specificity. As a result, even long-standing drug classes are being revitalised through nanoscale delivery systems that enhance efficacy and reduce systemic toxicity. Ongoing advancements are also laying the groundwork for personalised medical strategies, where medications and diagnostic tools can be custom-designed based on an individual's unique biological profile.

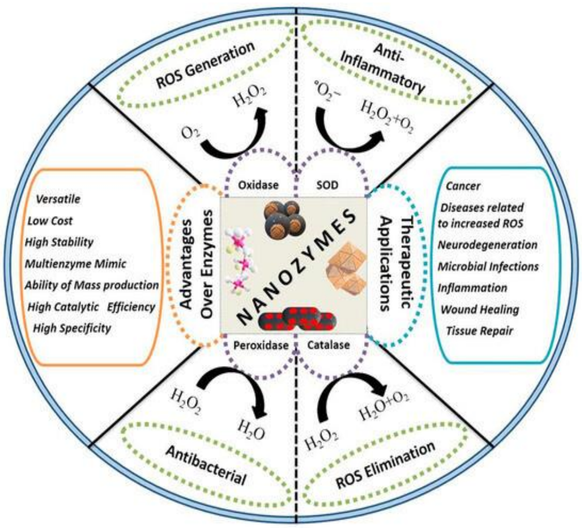


Figure 2: Medical applications of nanozymes.

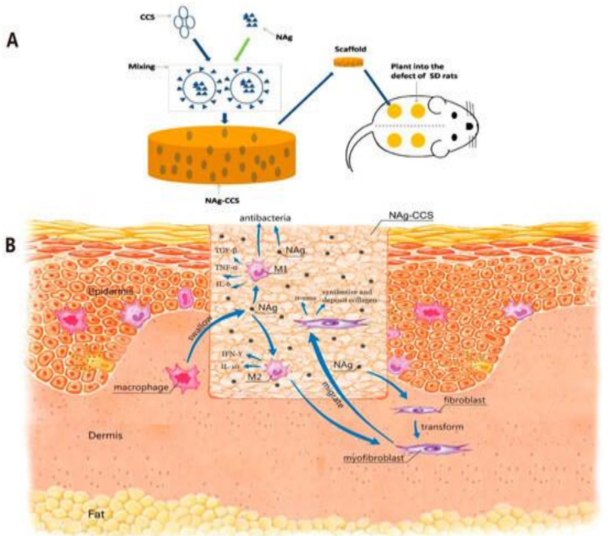


Figure 3: (A) A graphical representation of the NAg-CCS transplanted.

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