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Review Article

Role of nanotechnology in biomedical advances: a review of innovations and future directions

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Abstract:

Nanotechnology, a rapidly evolving field, enables the manipulation of materials at the nanoscale, transforming traditional manufacturing and reducing environmental impact through enhanced material efficiency. Recognizing the urgent need for advanced materials in biomedical applications motivates the exploration of nanobiotechnology for drug delivery, implant design, and disease diagnostics. This study hypothesizes that nanostructured materials, including liposomes, carbon nanotubes (CNTs), metallic and metal oxide nanoparticles (MONPs), and nanopatterned surfaces, can revolutionize biomedical technologies. Using a comprehensive review methodology, the study highlights the chemical and physical properties of these nanomaterials that enable their application in drug delivery systems, biosensing, bioimaging, and bone substitute implants. Our findings reveal that these materials not only enhance therapeutic efficacy but also provide avenues for safer and more efficient diagnostics, with implications for improved patient outcomes. These advancements emphasize the critical role of nanotechnology in addressing modern biomedical challenges while minimizing toxicity through insights from nanotoxicology studies.

Key words:
inorganic particles, liposomes, nanobiotechnology, nanopatterned surfaces

Apstrakt:

Uloga nanotehnologije u biomedicini: pregled inovacija i budućih pravaca

Nanotehnologija, kao brzo rastuće polje, omogućava manipulaciju materijalima na nanoskopskoj skali, transformišući tradicionalnu proizvodnju i smanjujući uticaj na životnu sredinu kroz poboljšanu efikasnost materijala. Prepoznavanje hitne potrebe za naprednim materijalima u biomedicini motiviše istraživanje nanobiotehnologije u isporuci lekova, dizajnu implantata i dijagnostici bolesti. Ova studija postavlja hipotezu da nanostrukturisani materijali, uključujući lipozome, ugljenične nanocevčice (CNTs), metalne i metal-oksidne nanočestice (MONPs), kao i nanostrukturisane površine, mogu značajno uticati na razvoj biomedicinskih tehnologija. Sveobuhvatnim pregledom literature, studija ističe hemijske i fizičke osobine ovih nanomaterijala koje omogućavaju njihovu primenu u sistemima za isporuku lekova, biosensingu, biomedicinkom snimanju i implantatima za zamenu kostiju. Naša sistematizacija otkriva da ovi materijali ne samo da poboljšavaju terapijsku efikasnost, već takođe nude mogućnosti za bezbedniju i efikasniju dijagnostiku, sa implikacijama za bolje ishode pacijenata. Ovi napreci naglašavaju ključnu ulogu nanotehnologije u rešavanju savremenih biomedicinskih izazova, uz minimizaciju toksičnosti kroz uvide dobijene nanotoksikološkim studijama.

Ključne reči:
neorganske čestice, lipozomi, nanobiotehnologija, nanostrukturisane površine

Introduction

Nanotechnology is the primary driver of economic expansion at all levels. Within the nanoscale range of 1 to 100 nm, intriguing phenomena such as mechanical, optical, electrical, magnetic, and a variety of other attributes can act very differently (Ebrahimi et al., 2024). A nanometer, or one billionth of a meter, is 80,000 times thinner than human hair. As a result, the nanometer domain includes sizes greater than a few atoms but less than the visible light wavelength. Nanotechnology is the manipulation of 100 nm or smaller materials in at least one dimension. The physical, chemical, colloidal, or biological characteristics differ significantly from those of the bulk material (Duman et al., 2024). Nanotechnology is the science and engineering of creating, synthesizing, describing, and applying materials and devices whose smallest functional organization in at least one dimension is on the nanoscale scale, or one billionth of a meter (Kumar et al., 2023). The dimensionality of the nanofiller determines the classification of nanocomposites. These can be categorized as zero-dimensional (nanoparticles, NPs), one-dimensional (nanofibers), two-dimensional (nanolayers), and three-dimensional (nanostructured networks) (Pande et al., 2024). Lamellar nanocomposites can be classified as either interspersed or removed. The number of polymer layers in the interlamellar space is predetermined in intercalated nanocomposites, and the polymer chains alternate with the inorganic layers in a predetermined compositional ratio. In exfoliated nanocomposites, the layers are more than 100 Å apart, and the number of polymer chains separating them fluctuates almost continually. Determining and altering the structure of materials and their interfaces at the atomic and nanoscales will enable the creation of novel materials and products. In the decades ahead, nanotechnology, along with wood and wood-based products, will have significant opportunities to enhance performance, expand utility, develop new product generations, and enter new market niches (Kumar et al., 2023).

Overview of nanotechnology in biomedical and material science

Nanotechnology is considered highly significant due to several key factors: (a) enhanced performance; (b) the emergence of novel phenomena and unique properties; (c) reduced consumption of materials, energy, and space; (d) an ideal scale for manufacturing precision; and (e) its ability to bridge the gap between living and non-living systems. Polymer nanocomposites are formed by integrating components with one or more nanoscale dimensions into a polymeric matrix. These nanoscale materials are commonly referred to in the literature as nanofillers, NPs, nanoscale building blocks, or nonreinforcements (Kumar et al., 2023; Santulli et al., 2024). Nanocomposites, a polymer type, are stiffer, stronger, more rigid, thermally stable, barrier-like, and flame-retardant than pure polymer matrix. Large surface area of these composites gives them unique properties that can be changed to produce materials with various biological traits and uses (**Fig. 1**). Nanotechnology-based products are increasingly useful in biomedicine, particularly

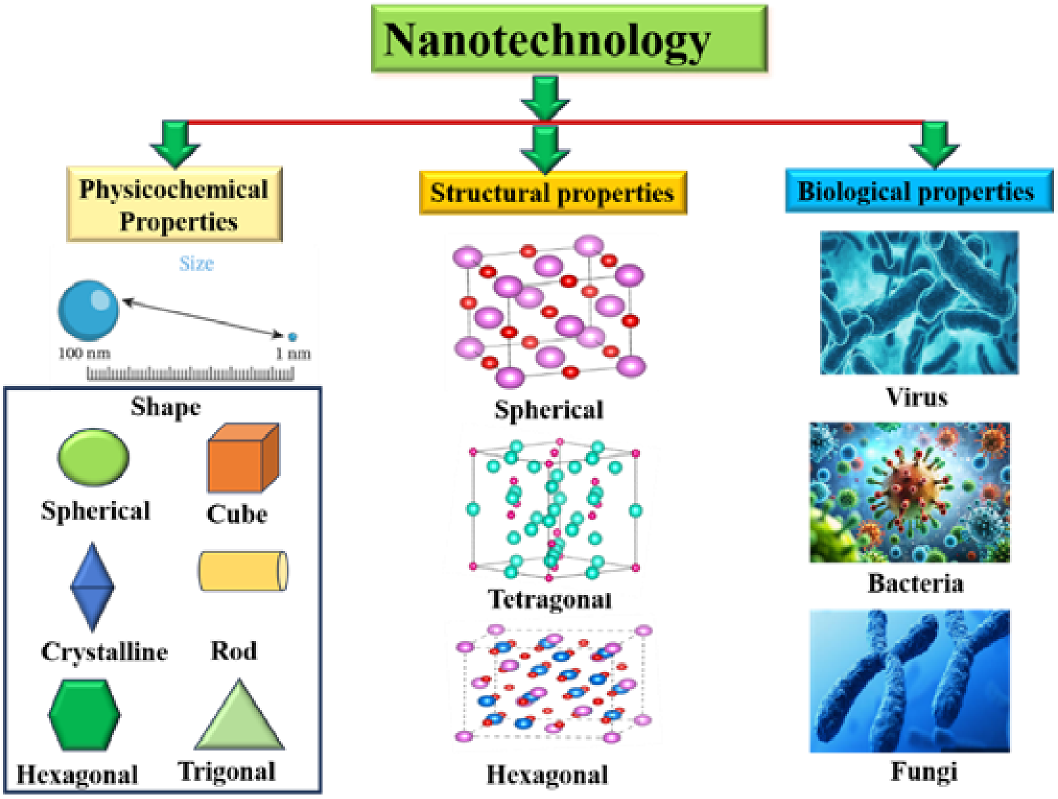

Fig. 1. Changes in material characteristics at the nanoscale and the benefits of integrating various nanotechnology materials

in prosthetics, implants, drug administration, and diagnosis (Balkrishna et al., 2021; Haleem et al., 2023). Common materials utilized in nanotechnology include metal oxide nanoparticles (MONPs), liposomes, metallic surfaces, and carbon nanotubes (CNTs). Properties of these materials such as surface chemistry, surface physics, surface thermodynamics, and toxicological effects influence the specific application of NMs (Bharathi et al., 2024). Designing nanostructures by adjusting their surface characteristics is one of the ways to acquire better results for various applications. Here, we focus on how medicine delivery systems, bone-replacing implants, biosensing and bioimaging devices, and diagnostics use inorganic (metal and metal oxide) and organic (CNTs and liposomes) NPs and nanopatterned flat surfaces. In connection with the toxicity of small particles, a novel field known as nanotoxicology is also investigated, which studies the surface effects caused by nanostructured materials (Rana et al., 2024).

Table 1. A variety of nanoparticles for different biomedical uses

Nanoparticle type	Biomedical applications	Mechanism
Au-NPs	Cancer therapy, drug delivery, imaging	Photothermal therapy, targeted drug delivery
Ag-NPs	Antibacterial agents, wound healing	Reactive oxygen species generation, cell membrane damage
Fe-NPs	Magnetic resonance imaging (MRI), targeted drug delivery, hyperthermia treatment	Magnetic properties, heat induction
Silica-NPs	Drug delivery, gene delivery, biosensors	High surface area, porous structure

Biomedical applications of metal oxide nanoparticles

MONPs are highly valued in the biomedical field due to their unique properties and versatility, as illustrated in **Fig. 2** and **Tab. 1**. They enhance imaging as MRI contrast agents, controlled drug release, and support cancer treatments through the use of photothermal, photodynamic, and magnetic hyperthermia treatments (Kimta et al., 2024). MONPs also have antibacterial properties for infection control and induce tissue engineering, encouraging bone and nerve repair (Thakur et al., 2024). Because of their anti-inflammatory and antioxidant qualities, they can be utilized to treat conditions linked to oxidative stress. In addition to being studied for blood cleansing, gene therapy, and as adjuvants in vaccines, MONPs have demonstrated promise in a number of medical uses (Kumar et al., 2024). MONPs have been used in the construction of numerous medical devices. Among the therapeutic and diagnostic uses of iron oxide's magnetic characteristics are magnetic particle imaging, photoacoustic imaging, magnetic particle hyperthermia (Thakur et al., 2024), magnetic particle imaging, and contrast agents for magnetic resonance imaging. The electrical structure of zinc oxide (ZnO) is useful for medical applications; for example, the intrinsic fluorescence of ZnO nanowires has been exploited to image cancer cells (Gupta et al., 2023). In particular, they exhibit enhanced water solubility, improved biocompatibility, and reduced cellular toxicity through surface functionalization. By modifying the ZnO surface with specific biomolecules, these nanostructures can be adapted for use in photosensitive biosensors. Additionally, the increased surface area of nanoparticles (NPs) facilitates rapid adsorption of plasma proteins, further influencing their biomedical potential (Sytu & Hahm, 2024). Consequently, the final application of NPs, as well as their interactions with other substances, is determined by their physical topography,

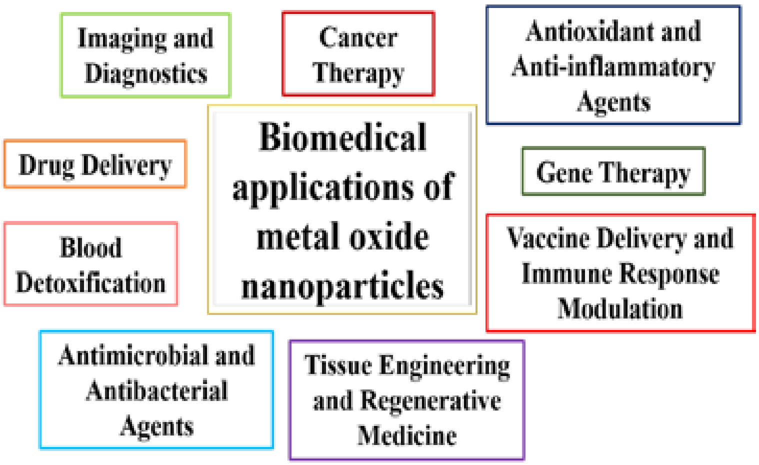

Fig. 2. Metal oxide nanoparticles as a versatile platform for various biomedical applications

chemical composition, and the interplay of these properties. Titanium oxide (TiO_2) has many biological applications. For instance, in bone-substituting materials, the biofluid first comes into contact with a thin layer of TiO_2 that spontaneously develops on the upper surface of metallic titanium (Shabib Akhtar et al., 2024) Zirconium oxide, which has recently been utilized for dental implants, is compatible with the same kind of hard tissues as titanium (Nikkerdar et al., 2024). Because of their strong optical absorption linked to the surface plasmon resonance of noble metals, MNPs are helpful for producing molecular contrast. Absorption and scattering in the visible and near-infrared spectrums have spurred the usage of materials containing metal nanoparticles in the sensing and diagnostic fields. Gold (Au NPs) can be deposited on appropriate substrates or added to substrate formulations to increase luminescence. The application of this technology is influenced by the particle's size and shape, which determine its absorption and scattering properties. Gold nanorods, which absorb in the near-infrared (700 nm to 2500 nm) (NIR), have been used to detect blood flow *in vivo* via photoacoustic imaging (Li et al., 2024). The literature contains examples of applications that use gold nanocages, nanoshells, and nanospheres. Sulfur-containing compounds have a strong chemical affinity and can be utilized to change the surface of gold nanoparticles. Modification of Au NPs with bio-specific compounds enhances their capacity to bind to specific tissues (Hossain et al., 2024). For example, cancer cells have been targeted *in vitro* using surface-labeled gold nanoshells, with optical microscopy confirming the results.

Carbon nanotubes

The physical and chemical properties of CNTs have motivated their application in various scientific domains. Surface modification and molecular functionalization with biological molecules have increased their use in nanobiotechnology by providing uniformly distributed samples suitable for physiological conditions. The primary biomedical applications of CNTs are listed in **Tab. 2**. In this case, nanotubes could be useful in medication delivery vehicles because of their nanoscale size, which allows them to move freely within the body. The bioavailability of methotrexate, a drug used

Table 2. The main biomedical uses of CNTs

Biomedical application	Details	References
Biosensing	Because of their high conductivity and surface functionality, CNTs are utilized in electrochemical biosensors to identify biomarkers.	Li et al., 2024
Drug delivery	By encapsulating medicinal substances and improving their absorption by particular cells, functionalized CNTs allow for tailored medication delivery.	Khan et al., 2024
Cancer therapy	CNTs are used in targeted therapy and cancer diagnosis, either as carriers for photothermal therapy or for direct medication delivery.	Maghimaa et al., 2024
Regenerative medicine	Because of their conductivity, CNTs are used as scaffolds in tissue engineering to encourage cell division and proliferation.	Parvin et al., 2024
Antibacterial therapy	By strengthening microbial inhibition, CNTs functionalized with antibacterial drugs are utilized to treat infections.	Jonathan & Agvini, 2024
Biomedical imaging	CNTs are used as contrast agents in bioimaging to improve visibility in diagnostic imaging.	Aher et al., 2024
Neurodegenerative disease	CNTs can pass across the blood-brain barrier, they are being researched for drug delivery systems that target Alzheimer's disease.	Al-Zharani et al., 2024
Wound healing	CNT-based materials encourage tissue regeneration and cell proliferation, which speeds up wound healing.	Elabbasy et al., 2024
Diagnostics	Through sophisticated biosensing platforms that identify illnesses early on, CNTs make precise diagnostics possible.	Acharya et al., 2024
Gene therapy	By aiding in the minimally harmful transfer of genetic material into cells, CNTs enable gene delivery.	Yazdani et al., 2024

to treat cancer, increases when it is administered following immobilization on the surface of a double-functionalized carbon nanotube (Maghimaa et al., 2024). An active substance can be bonded to the particle's surface or introduced to the tube to target and alter cell activity at the subcellular or molecular level. Biofunctionalized single- or multi-walled CNTs can also interact with DNA and penetrate different cellular barriers, which can be absorbed by a range of cells (Sonowal & Gautam, 2024).

Cells can absorb and interact with cationic CNTs complexed with plasmid DNA, making them suitable scaffolds for osteoblast proliferation and bone repair. Studies have shown that the toxicity of unmodified single- and multi-walled CNTs is concentration-dependent and that they can be safely used in osteoblast cells at concentrations up to 10–20 mg/mL (Mamidi et al., 2024). Synthesized CNTs disrupt bacterial function through a combination of oxidative and non-oxidative stress mechanisms, including cell wall penetration, reactive oxygen species (ROS) generation, and metal ion release. Oxidative stress results from the production of ROS such as superoxide anions, hydroxyl radicals, and hydrogen peroxide, which cause damage to cellular components, including lipids, proteins, and DNA. In contrast, non-oxidative stress involves mechanical disruption, where CNTs physically penetrate bacterial membranes, extract lipids, and adsorb essential biomolecules (Thakur et al., 2023). Their unique nanostructure enables CNTs to interact with and compromise the bacterial cell wall, weakening its integrity in both Gram-positive and Gram-negative bacteria. CNTs also enhance ROS generation through electron transfer reactions, further impairing cellular respiration and metabolism.

Metal-doped CNTs release toxic metal ions, which inhibit bacterial enzymes, disrupt membrane potential, and amplify antibacterial effects. Together, these multifaceted mechanisms make CNTs highly effective in combating bacterial infections. We have recently proposed using collagen-modified calcium carbonate nanotubes as a new generation of tubular structures for bone regeneration (Kumar et al., 2024).

Liposomes and nanobiotechnology

Bangham and Horne were the first to describe liposomes, the small synthetic lipid-bilayer spherical vesicles. Liposomes, a type of nanoparticle composed of lipid bilayers that encapsulate a range of chemicals, can be used to great advantage in drug administration, gene therapy, and nanobiotechnology applications (Kumar et al., 2024). Their ability to encapsulate both hydrophilic and hydrophobic molecules greatly facilitates targeting and controlling the release of medicinal medications. Liposomes are used in nanobiotechnology to deliver drugs directly to target cells or tissues, minimizing side effects and improving therapeutic efficacy, as seen in **Fig. 3.** Liposomes can have different properties by varying their size, composition, and surface charge. The stiffness and fluidity of the bilayer can also be

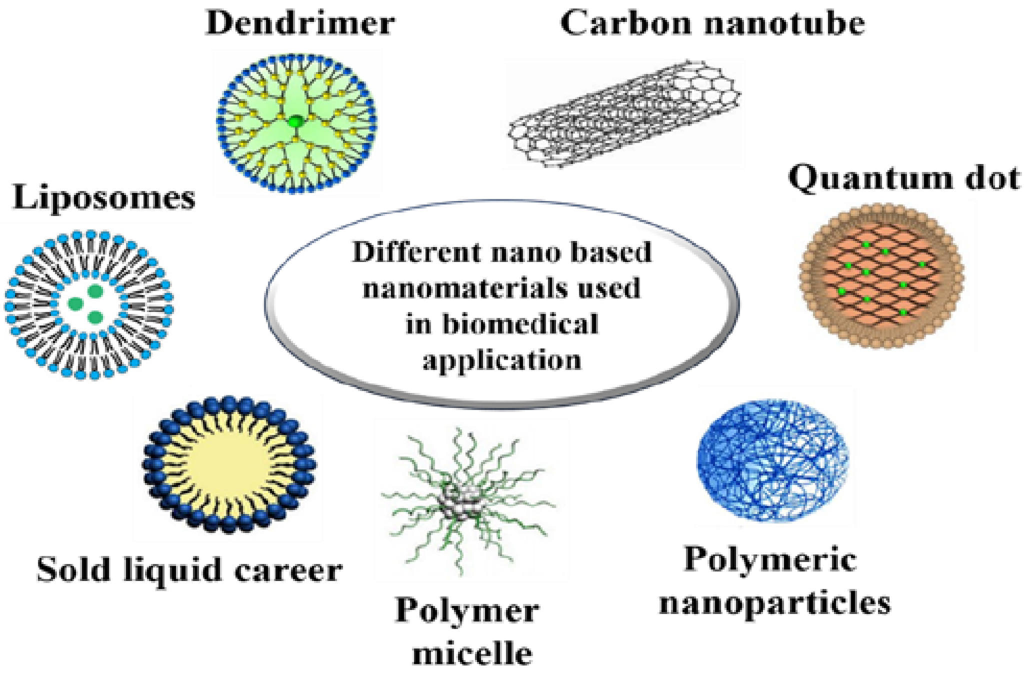

Fig. 3. Lipid based nanoparticles towards biomedical application

controlled by choosing specific lipids (Mitsuhashi et al., 2023). These artificial membrane models can be categorized based on their diameter. Small uniflagellar vesicles range from 20 to 100 nm, and large uniflagellar vesicles (LUVs) range from 200 to 1000 nm (Devi et al., 2024). The vesicles comprise a single lipid bilayer and an internal aqueous cavity. Liposomes can also be categorized based on the quantity of lipid bilayers they contain. Multiple concentric phospholipid bilayers intercalated with aqueous compartments make up multilamellar vesicles ranging in size from 400 to 3500 nm (Sulthana et al., 2024). Over the past 20 years, liposomes have been widely used for a number of applications, such as gene therapy, vaccines, and the administration of cancer medications. These vesicles can carry a range of bioactive compounds, such as antioxidants, antimicrobials, and anagenic proteins. These chemicals continue to operate once they are encapsulated. Moreover, materials with different solubility levels can be enclosed in the aqueous cavity or at the surface of lipid bilayers (Bakhshizadeh et al., 2024). Since liposomes are non-immunogenic, potentially non-toxic, and degradable in physiological conditions, it is possible that they could transport drugs with a low rate of disintegration and fewer adverse effects (Lee et al., 2024).

Nanotechnology in diagnostics

Nanotechnology has enormous benefit for diagnostics, particularly in imaging applications such as optical imaging and magnetic resonance imaging (MRI), where NPs are validated diagnostic tools (Thakhue et al., 2024). Quantum dots (QDs) are semiconductor nanocrystals used extensively in optical imaging because they are 100 times brighter than organic dyes (Palanisamy et al., 2024). The quantity of NPs in the cell's cytoplasm is essential for illuminating cells in deep tissues. Despite their effectiveness as tagging materials, QDs have drawbacks. More QDs are required to achieve sufficient brightness, which could pose toxicity concerns (Kumar et al., 2024). Moreover, the blinking behavior of biomolecules labeled with QDs may make tracking them more challenging. Consequently, the development of fluorescent NPs for *in vivo* imaging continues to be challenging. Silicon nanocrystals are more appealing than QDs because they are safe for cells and do not require a substantial surface coating to protect the nanocrystal core from the environment (Kumar et al., 2024).

Nanotechnology in therapeutics

Metallic nanoparticles (MNPs), known for their remarkable thermal conductivity, effectively transport the generated heat to the surrounding tissues (Thakhur et al., 2024). They are helpful in therapeutic applications due to their tendency to accumulate in tumors when administered intravenously (Kumar et al., 2024). CNTs, Au NPs, magnetic NPs, superparamagnetic Fe_2O_3 NPs (Kumar et al., 2024), and doped Fe_2O_3 NPs (Thakur & Kumar, 2024) are among the materials. MNPs, which produce heat and target tumor cells without harming healthy tissues, are activated by an alternating magnetic field. Superparamagnetic Fe_2O_3 NPs are especially effective heat generators and are highly localized in cancers (Kumar et al., 2024). Doped Fe_2O_3 NPs accelerate heat generation and selective absorption in a magnetic field. Additionally, superparamagnetic Fe_2O_3, graphene oxide, and doxorubicin-incorporated nanofibers have shown efficacy in promoting tissue regeneration and preventing breast cancer recurrence (Kumar et al., 2024). Electrospun fibers with NPs are also growing in popularity for postoperative care. Unlike magnetic NPs, Au NPs function by photothermal activation.

Drug delivery

Lipids are widely used as carriers for antiviral drugs because they are easily accessible, affordable, biodegradable, biocompatible, inert, non-toxic, and non-immunogenic (Satchanska et al., 2024). Their unique characteristics include better drug performance, controlled release, enhanced interface interactions, small size, large surface area, and high drug-loading capacity make them particularly helpful in drug delivery systems. Antisense oligonucleotide (ASO) drugs can block mRNA processing and translation, which is connected to a number of illnesses (Jawale & Kashikar, 2024). However, when administered freely, ASO therapies have limitations regarding biological stability, short circulation half-life, and low cellular absorption. NPs made of human serum albumin (HSA) cross-linked with glutaraldehyde and ASO significantly improves ASO cellular absorption. Confocal laser scanning microscope images indicate the presence of drug-loaded NPs in various cell types, including breast cancer cells (MDA-MB-468, MCF-7, and BT-474) and lung cancer cells (A549). MDA-MB-468 and MCF-7 cells exhibited the fastest absorption of NPs, which were detected at an incubation temperature of 37 °C after 24 hours (Aalhate et al., 2023).

Gene therapy

Gene therapy aims to replace or repair disease-causing genes by delivering healthy genes into target cells. Given that inflectionless NPs coupled to DNA have shown promise in transferring genes to stem cells, there are concerns with the widespread use of viral vectors for gene transfer, including the potential for cell damage. DNA-coupled NPs provide effective gene transfer to stem cells by shielding DNA from degradation and increasing cellular absorption. Surface changes to NPs ensure focused distribution. Once inside, they release DNA for integration or expression, providing a safer, non-viral therapeutic option for regenerative medicine and stem cell engineering (Alzahrani et al., 2023). By combining the benefits of gene therapy and photothermal therapy, surface-modified Au NPs carrying DNA have recently been demonstrated to aid in photoacoustic imaging (Song et al., 2024). Gene transfer is a novel treatment technique that involves inserting new genes into diseased cells or surrounding tissues to kill the cells, block the spread of cancer, or correct genetic flaws to restore normal cell function. One method, called gene-directed enzyme prodrug therapy, involves directing a gene for an enzyme not naturally present in the cancerous tissue to activate a prodrug that is subsequently administered. Genome editing will be a feasible cancer therapy option in the future thanks to new knowledge regarding nuclease activity and the creation of secure and efficient gene delivery vectors (Ramezani et al., 2023).

Nanotechnology for surface engineering of metallic implants

Nanotechnology is also being used in tissue and implant engineering. The material's capacity to enhance surface area and modify surface roughness at the nanometric scale should lead to improved biological responses from osteogenic cells and effective mechanical contact between tissue and implant. Titanium and its alloys are considered the most attractive materials for bone replacement applications (Rani et al., 2023). This metal finds extensive employment because of its superior mechanical properties, low surface reactivity, strong resistance to corrosion, and acceptable *in vitro* and *in vivo* biocompatibility. The live tissue heals in close proximity to the metal, even if there may be a thin fibrous layer separating the metallic implant from the bone, indicating a failure in the osteointegration process. The implant's surface needs to be changed to achieve good osteointegration and strengthen the bone-implant interface in this case (Bandyopadhyay et al., 2023). Changing the surface should just change the topography. However, the creation of nanoscale roughness and the addition of bioactive materials appear to be more viable strategies for biomedical applications. In the following subsections, we discuss which features of implant surfaces should be modified to enhance host tissue responses. We also describe the use of nanotechnology for implant surface engineering at the nanoscale. Modifying metallic surfaces improves the interface between implants and biological tissue in bone replacement applications. For orthopedic implants to be successful, bone tissue must form at the implant's surface (Zhang et al., 2024). To maximize implant attachment to the tissue, surface engineering alters properties, including topography, wettability, charge, and chemical composition. Clinical research indicates that when one goes away from the implant surface rather than toward it, the rate of bone growth rises (Thakur & Thakur, 2024).

Bio-inspired surface modifications

Adding bioactive minerals that mimic the structure of bone is one of the most common ways to modify the metallic surfaces of implants. Biomimetics is a preferred strategy since it predefines nanochemical and nanophysical structures. Calcium phosphate (CaP)-based coatings are often produced in biomaterials research, and their use in implants significantly affects the bone regeneration process (Furko et al., 2023). However, these methods are complex and need expensive equipment and very high temperatures. This method allows for the production of continuous CaP coatings with controlled surface topography despite the fact that it may need prolonged exposure times (Verma et al., 2023). Simulated bodily fluid is one of the most commonly used physiological solutions (SBF). SBF, composed of a supersaturated CaP solution replicating the pH and ionic composition of physiological fluids, is a frequently employed method for evaluating a material's bioactivity (Suchy et al., 2021).

Toxicology of nanomaterials

The toxicity of nanomaterials is influenced not only by the NPs but also by the solvents used to disperse them. NPs are frequently dissolved in solvents such as alcohol, which might influence their stability, bioavailability, and toxicity. As a result, the impact of the solvent must be carefully evaluated during toxicity studies since it may contribute to or affect the observed effects. Solvent interactions with biological systems, as well as possible cytotoxicity and changes in NPs behavior, can all substantially impact experimental results. To guarantee accurate and reliable results, comprehensive investigations should consider both the inherent toxicity of NPs and the function of solvents. NPs' toxicological effects are poorly understood despite their potential in biomedical applications. The toxicity of nanomaterials depends on a variety of criteria, including dosage and composition, as well as physicochemical properties like size, surface charge, roughness, crystalline structure, and shape.

Materials' physicochemical properties are influenced by their size. Consequently, the bulk material's toxicological behavior induces hazardous events peculiar to NPs. The word "nanotoxicology" has been used to better understand the physicochemical properties of NPs and their detrimental effects. Most nanotoxicological research is based on cell culture experiments (Motamedi and Tabatabaei, 2025). Numerous investigations have used fundamental biomimetic cell membrane models, like Langmuir monolayers and proteins *in vitro*. Verification *in vivo* experiments are necessary to forecast how nanomaterials will interact with biological systems, nevertheless, because the outcomes of *in vitro* tests might not accurately represent their effects in life. Even though multiple assays have been conducted, variable methodology has led to inaccurate toxicological results. For example, the conventional toxicological methodology, which considers exposure time and dosage, is not consistent with the toxicological consequences of nanomaterials. The selection of suitable dose measurements requires careful consideration.

Future of nanomedicine

Drug delivery and nanomedicine are rapidly growing topics with multiple clinical trials performed on 1,500 patients (Raj & Kaladhar, 2025). The diagnosis and treatment of illnesses like cancer have benefited immensely from nonmedical technologies. NPs can be used to precisely deliver drug dosages to diseased cells, including cancer cells, without changing the cells' normal physiology. However, the size of the NPs fluctuates, and more research is needed to ensure uniform consistency and drug loading and release capabilities. MNPs, including gold and silver, have shown potential for application in targeted removal techniques like radiation-based heat therapy. Despite its potential, nanomedicine's actual impact on healthcare is currently restricted because it is still in its infancy, and many crucial features are yet unknown. Future research should focus on understanding disease molecular markers and developing theoretical mathematical models for regulated medication release, technology evaluation, and therapeutic benefits. The future of drug delivery technology and nanomedicine appears promising, with a focus on increasingly complex and multidisciplinary approaches.

Challenges and opportunities

In biomedical applications, nanotechnology offers both great potential and formidable obstacles. Since NMs' interactions with biological systems can provide dangers that are not fully known, one of the main problems is ensuring their biocompatibility and minimizing their toxicity. Many high-precision methods used in laboratories are difficult to adapt for large-scale production while maintaining consistent quality, which makes the scaling and manufacturing of nanomaterials particularly challenging (Materon et al., 2021). Due to ethical and regulatory concerns, the absence of defined rules for the safety, testing, and approval of NMs continues to obstruct the broad use of nanotechnology in medicine. Overcoming the challenges of controlling the release of medicines to the intended location and attaining precise and efficient targeted medication delivery represent further challenges.

Notwithstanding these difficulties, nanotechnology presents fascinating prospects in the field of biomedicine. By providing extremely specialized drug delivery systems based on each patient's unique genetic profile, it has the potential to completely transform personalized medicine by enhancing therapeutic results and reducing side effects. Nanotechnology also holds potential for improving diagnostics because nanosensors and NPs can improve the sensitivity and specificity of detection tools, allowing for early illness identification and improved patient outcomes. Nanotechnology can potentially improve biosensing and bioimaging methods by offering high-resolution, real-time imaging for disease diagnosis and monitoring. Lastly, by providing continuous, real-time data that may be utilized to manage chronic illnesses and identify environmental risks, nanosensors have the potential to revolutionize environmental and health monitoring.

Conclusion

This study underscores the transformative potential of nanostructured materials in biomedical applications, demonstrating their ability to enhance drug delivery systems, biosensing, bioimaging, and bone substitute implants. Novel insights include the multifunctional role of CNTs, metallic and MONPs, and nanopatterned surfaces in improving therapeutic efficacy and diagnostic precision. These findings align with emerging trends in nanobiotechnology, addressing critical challenges in modern medicine while minimizing toxicity through nanotoxicology-guided approaches. However, limitations in the current approach must be acknowledged. The long-term biocompatibility and environmental impact of these nanomaterials remain areas of concern, necessitating further research to optimize safety profiles.

Additionally, scalability in synthesizing these nanostructures for industrial applications poses practical challenges. Future work should focus on refining functionalization techniques to improve selectivity and performance while ensuring sustainability. In conclusion, this work provides strong evidence for the promising role of nanostructured materials in advancing biomedical technologies, offering impactful solutions to pressing healthcare challenges. This field can pave the way for safer, more efficient, and widely applicable nanotechnological innovations by addressing the identified limitations.

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