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Metal-Based Nanoparticles in Biomedicine: Recent Innovations, Mechanisms of Action, and Future Perspectives– A Mini Review

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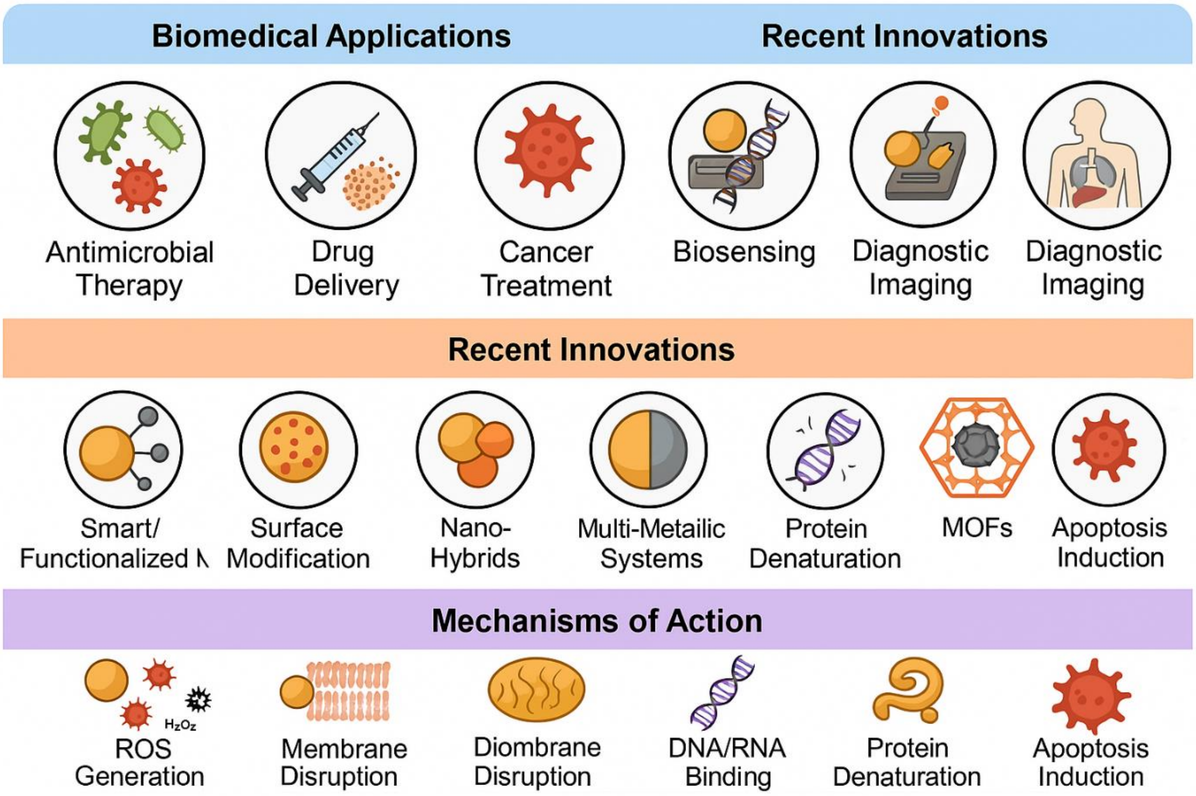
Abstract
Metal-based nanoparticles (M-NPs) have emerged as promising nanomaterials with exceptional potential in diverse biomedical applications due to their unique physicochemical, biological, and functional properties. This mini-review provides a comprehensive overview of recent advancements in the synthesis, functionalization, and biomedical utilization of M-NPs. The review highlights key applications of M-NPs in antimicrobial therapy, drug delivery, cancer treatment, biosensing, and diagnostic imaging. Special emphasis has been placed on recent innovations, including smart/functionalized nanoparticles, surface modification strategies for targeted delivery, nano-hybrids, multi-metallic systems, and metal-organic frameworks (MOFs), which have significantly enhanced the therapeutic performance of M-NPs. The review also discusses how these nanoparticles work, including creating ROS, breaking down membranes, binding to DNA/RNA, changing proteins, and causing cell death, which all contribute to their effectiveness in medicine. However, significant clinical barriers such as toxicity, biosafety issues, and regulatory limitations have so far hampered their progress. Thereafter, the future vantage point for the advancement remains on the introduction of safer methods, personalized nanomedicine, nanoenabled regenerative medicine, and multifunctional intelligent NPs and the interviewing way from the laboratory research to the clinic. In general, metal-based nanoparticles are a powerful and promising platform in nanomedicine that will be part of future healthcare strategies.

Keywords: Metal-based nanoparticles; Biomedical applications; Smart nanoparticles; Targeted drug delivery; Nano-hybrids; Metal-organic frameworks (MOFs); Mechanisms of action; Translational nanomedicine



Graphical Abstract

1. Introduction

Nanotechnology has revolutionized the biomedical field by providing novel solutions for diagnosis, therapy, and disease monitoring. Metal-based nanoparticles (M-NPs) are of great interest in the scientific community owing to the unique combination of physicochemical properties that arise from their large surface area ratios and tunable surface properties in association with novel optical and magnetic properties. Thus, M-NPs feature all these distinctive features that make them the best-suited candidates for biomedical applications involving a combination of imaging techniques alongside drug delivery systems and antimicrobial agents (Shang et al.,2023; Chen et al., 2022).

Different types of metal-based nanoparticles have recently shown their potential applications in therapy, according to research findings. Experiments with cobalt nanoparticles showed dependent dosage effects on antioxidant systems and organ shape and blood cell metrics within animal test subjects (Umar et al., 2024a). Cobalt carbonate nanoparticles display effective wound-healing properties while regulating blood sugar levels in diabetic mice, according to Umar et al. (2024b). The antimicrobial capabilities that silver-based nanoparticles possess enable them to fight bacterial strains that display resistance (Khan et al., 2024). Copper-based nanoparticles demonstrate dual capabilities as they act as antibacterial agents and show glucose-lowering properties in cases of diabetes (Aslam et al., 2025a; Aslam et al., 2025b).

The optical properties of gold nanoparticles, especially gold nanocages, have received extensive research for photothermal treatment and imaging contrast use (Mariano et al., 2024). The superparamagnetic nature of iron oxide nanoparticles allows both magnetic resonance imaging and hyperthermia treatment usability (Attanayake et al., 2024).

Research continues about M-NP biocompatibility and toxicity despite their known potential applications (Khan et al., 2022). The research evidence shows toxic and damaging DNA effects from particular metal nanoparticles, yet thorough security evaluations together with safer synthetic approaches remain essential (Gao et al., 2022).

This review assesses the current developments that occurred in metal-based nanoparticle use for biomedical applications. The review explores M-NPs of various types through synthesis methods and mechanisms of therapeutic action and biomedical-related obstacles and potential applications.

2. Types and Synthesis Approaches of Metal-Based Nanoparticles

2.1 Types of Metal-Based Nanoparticles

Metal-based nanoparticles (M-NPs) encompass a diverse range of materials, each exhibiting unique physicochemical properties that make them suitable for various biomedical applications. The primary categories include:

(a) Noble Metal Nanoparticles

Noble metal nanoparticles (silver (Ag) and gold (Au)) have been recently receiving much interest in their biomedical applications as a result of their unique physicochemical properties and excellent biocompatibility. Because of their antimicrobial activity, silver nanoparticles (AgNPs) are well recognized as potent antimicrobial substances that play excellent roles in the antibacterial coating of medical devices, wound dressings, and implant materials. As a result, they have been a valuable antimicrobial tool, making it possible to disrupt bacterial cell membranes and interfere with cellular processes. However, another hand provides us gold nanoparticles (AuNPs) as a versatile nanomaterial for their use in drug delivery, bioimaging, and diagnostic applications. Their excellent stability, tunable surface chemistry, and ease of functionalization make them powerful with respect to targeted delivery of therapeutic agents and enhanced imaging of biological tissues. Overall, the combination of stability, functionality, and biocompatibility of both AgNPs and AuNPs qualifies them as being of significant importance in the development of nanomedicine, with therapeutic and diagnostic goals (El-Sayed, 2021; Rai et al., 2021).

(b) Transition Metal Nanoparticles

In the biomedical field, using transition metal nanoparticles like Cu, Zn, and Fe to kill germs and support biological functions is new and looks very promising because of their ability to act as catalysts and fight germs. Among these, copper nanoparticles (CuNPs) displayed in particular a very strong antibacterial activity against a large variety of pathogenic microorganisms, which is due to their capacity to generate reactive oxygen species (ROS) and bacterial membrane disruption. Because of their ability to fight germs, CuNPs are very useful for many wound-healing treatments where preventing infections and speeding up healing are important. In addition, zinc (Zn) and iron (Fe) nanoparticles are also used for antimicrobial efficacy and catalytic tasks that increase their use in biomedical as well as environmental applications. Cost-effective non-noble metal transition metal nanoparticles also have the multifunctional properties critical for the development of advanced therapeutic and antimicrobial strategies (Kumar et al., 2022).

Metal Oxide Nanoparticles

With the excellent photocatalytic, antimicrobial, and environmental remediation properties, metal oxide nanomaterials, such as zinc oxide (ZnO), copper oxide (CuO), and titanium dioxide (TiO_2), have received much attention during the last years. Among such, zinc oxide nanoparticles (ZnO NPs) are specifically known for their great antibacterial activity, which is common due to the creation of reactive oxygen species (ROS), destruction of microbial cell membrane, and release of zinc ion. Such behavior on the one hand, and strong CdO bonding provide incentives to ZnO NPs to be targeted for various applications including antimicrobial coatings, textiles, food packaging, and medical devices for preventing contamination as well as improving product longevity. Just as CuO and TiO_2 nanoparticles, have strong antimicrobial properties and photocatalytic behavior and can be used for water purification, self-cleaning surface and protectant coatings. Metal oxide nanoparticles have high multunctionality and high effectiveness and they are good promising candidates for different medical and industrial applications (Sirelkhatim et al., 2015).

Bimetallic and Multimetallic Nanoparticles

Recently, the surface-enhanced properties of these nanoparticles formed by two or more different metals in combination, i.e., bimetallic and multimetallic nanoparticles, have been gaining attention due to their superior physicochemical properties. The integration of many different metals into a single nanoparticle structure often gives rise to a synergy giving rise to enhanced stability, antimicrobial activity, and catalytic performance. This is particularly the case for bimetallic nanoparticles, e.g., silver-gold (Ag-Au) and copper-silver (Cu-Ag), and these nanoparticles have shown bacterial activity superior to that of individual metal nanoparticles. The main contribution to this enhanced antimicrobial property arises from the effect of both metals acting together to disrupt microbial cell membranes and generate reactive oxygen species (ROS) and to release the metals. Additionally, due to their better catalytic properties, they function very well in chemical sensing, environmental remediation, and biomedical applications. The structural, chemical, and functional combination of bimetallic and multimetallic nanoparticles is encouraging to use in third-generation nanomaterials with therapeutic and industrial uses (Sharma et al., 2019).

2.2 Synthesis Approaches

The synthesis of M-NPs can be broadly categorized into physical, chemical, and biological methods, each with its advantages and limitations (Table 1).

Table 1. Overview of Nanoparticle Synthesis Methods, Techniques, Principles, and Advantages

Method	Sub-Category	Technique	Principle	Advantages	References
Physical Methods	Physical Vapor Deposition (PVD)	Sputtering, Evaporation	Metal atoms are vaporized and condensed onto substrates to form nanoparticles.	Precise control over size and composition; Suitable for high-purity nanoparticles	Kumar et al., 2022
	Laser Ablation	Pulsed Laser Ablation in Liquid (PLAL)	A high-energy laser beam is focused on a metal target submerged in a liquid medium, resulting in nanoparticle formation without chemical reagents.	Produces pure nanoparticles; No chemical contamination; Environmentally friendly	Barcikowski et al., 2009
Chemical Methods	Chemical Reduction	Sodium Borohydride, Citrate Reduction	Reduction of metal salts using chemical reducing agents, leading	Simple process; Cost-effective; Suitable for large-scale synthesis	Iravani et al., 2014

			to nanoparticle formation.		
	Sol-Gel Process	Hydrolysis & Polycondensation of Metal Alkoxides or Salts	Metal precursors form a colloidal sol, which transforms into a gel; drying and calcination yield nanoparticles.	Uniform particle size; Controlled morphology; High purity	Brinker & Scherer, 2013
Biological (Green) Methods	Plant-Mediated Synthesis	Use of Plant Extracts (Leaves, Fruits, Roots)	Phytochemicals in plant extracts act as natural reducing and stabilizing agents for nanoparticle formation.	Eco-friendly; Non-toxic; Cost-effective; Renewable resources	Iravani, 2011
	Microbial Synthesis	Bacteria, Fungi, Algae Mediated Synthesis	Microorganisms enzymatically reduce metal ions into nanoparticles.	Environmentally benign; Biocompatible nanoparticles; Sustainable method	Singh et al., 2016

3. Biomedical Applications of Metal-Based Nanoparticles

3.1 Antibacterial and Antiviral Properties

Metal-based nanoparticles possess antibacterial properties due to their different physical and chemical values. Membrane disruption and formation of ROS and breaking of DNA are the ways that silver nanoparticles (AgNPs) manifest antimicrobial properties, which target (Rai et al., 2012; Morones et al., 2005; Pal et al., 2007). The antimicrobial properties of copper nanoparticles (CuNPs) destroy bacterial strains from multidrug-resistant populations through oxidative damage to cellular structures together with stress induction (Cioffi et al., 2005; Ruparelia et al., 2008; Borkow & Gabbay, 2005). Raghupathi et al. (2011), Padavagthy and Vijayaraghavan (2008), and Sirelkhatim et al. (2015) have shown anticalrical functions of ZnO NPs that result in the creation of ROS, which leads to the release of zinc ions and interferes with cellular integrity and microbial metabolism.

Researchers studied the antiviral activity of manganese oxide nanoparticles (MNPs) and their antibacterial properties. Researchers have found that silver nanoparticles stop viruses from attaching to cells and also stop them from making copies of themselves. According to Papp et al., 2010, Dykman & Khlebtsov, 2012, and Baptista et al., 2008, an antiviral approach is achieved by the blocking of viral fusion and entry pathways when AuNPs are functionalized with ligands. Recent investigations and studies show that MNPs are antiviral to new viral pathogens, which are general antiviral therapeutic agents (Galdiero et al. 2011; Sportelli et al. 2020; Lembo et al. 2018). Defeating bacterial infections and viral infections in multidomain nanoparticles allows them to be versatile, and new therapeutic opportunities emerge from here.

3.2 Drug Delivery Systems

Through their drug delivery systems, metal-based nanoparticles enhance susceptibility, thus improving stability along with enabling high drug concentrations. The small specific ratio between their area and volume enables both drug-loading capabilities and release regulation effectively. Gold nanoparticles obtained through biomolecule functionalization serve as effective targeting systems that decrease unwanted side effects while enhancing treatment results (Jain et al., 2008; Pissuwan et al., 2011; Dreaden et al., 2012). The application of iron oxide nanoparticles for magnetic drug targeting utilizes external magnetic fields to transport nanoparticles exactly to targeted sites, enhancing drug accumulation at the target while reducing systemic drug exposure, according to Gupta and Gupta (2005), Pankhurst et al. (2003), and Arruebo et al. (2007). Enhanced treatment efficiency alongside reduced conventional drug delivery side effects is achieved through these methods.

MNP-based drug delivery platforms became possible through their integration into drug delivery platforms. Narrowing down the delivery process of therapeutic agents becomes possible through pH-sensitive coatings applied on nanoparticles that release drugs specifically into acidic tumor environments (Bae et al., 2005; Lee et al., 2008; Gao et al., 2008). Biodegradable polymers used together with MNPs enable the delivery of drugs in a sustained manner, which ensures sustained therapeutic levels throughout numerous treatment durations (Kohane, 2007; Farokhzad & Langer, 2009; Kamaly et al., 2012). The new developments in drug delivery through nanoparticles create substantial potential to advance disease treatment, specifically cancer, because they enable exact therapeutic methods.

3.3 Cancer Therapy (Photothermal, Photodynamic, Targeted Delivery)

Photothermal therapy (PTT) and photodynamic therapy (PDT), together with targeted drug delivery, constitute the main cancer therapy applications of metal-based nanoparticles (MNPs). The strong surface plasmon resonance property of gold nanoparticles (AuNPs) makes them convert near-infrared light into heat to achieve tumor cell destruction selectively while protecting adjacent healthy tissues (Huang et al., 2016). The application of iron oxide nanoparticles depends on magnetic hyperthermia, through which cancer cell destruction is achieved using alternating magnetic fields (Jordan et al., 2019). The functionality of MNPs through antibody or peptide addition enables them to bind cancer cells more effectively while reducing treatment side effects (Peer et al., 2017).

During PDT, MNPs carry photosensitizers that produce reactive oxygen species upon light exposure, which leads to cancer cell death. Scientists are investigating titanium dioxide nanoparticles because these nanoparticles produce cytotoxic substances through photocatalytic reactions while experiencing UV light activation (Mariano et al., 2024). Medical nanoparticles combine PTT and PDT mechanisms to produce a treatment method that jointly improves treatment performance. The development of imaging- and therapy-capable multifunctional nanoparticles by researchers enabled real-time measurement of treatment performance, according to Chen et al. (2020). The latest innovations demonstrate that metal nanoparticles have the potential to develop accurate, efficient, and minimally invasive cancer treatment systems.

3.4 Biosensing and Diagnostics

Diagnostic and biosensing functions use the unique properties of metal-based nanoparticles through the optical, electrical, and catalytic characteristics of the nanoparticles. Using AuNPs, colorimetric assays are sensitive in the detection of biomolecules since they have surface plasmon resonance (Elghanian et al., 2017). According to Nie and Emory (2016), the detection of low concentrations of analytes with high specificity was done via surface-enhanced Raman scattering (SERS) using silver nanoparticles. The ability of MNPs to display advantageous features makes it possible for scientists to develop fast and cheap diagnostic instruments that detect many diseases.

MNP functionality is an integral component of the analytical performance levels of electrochemical sensors. The elevated accuracy in glucose measurement obtained by AuNPs with glucose sensors has been attributed to the fact that AuNPs have enhanced electron transfer processes (Wang, 2018). To increase detection sensitivities of targets in complicated biological mediums, magnetic nanoparticles are used in immunoassays to extract target substances (Tang et al. 2019). Improvements in the development of MNPs also lead to significant benefits in their applications in diagnostic and biosensing technologies.

3.5 Wound Healing and Tissue Engineering

It has been shown by research that metallic nanoparticles heal wounds as well as they work for tissue engineering purposes. As per Rai et al. (2016), silver nanoparticles (AgNPs) have the characteristic to protect from infections in wounds as well as promote faster healing. According to Raghupathi et al., 2017, zinc oxide nanoparticles enhance the re-epithelialization and granulation tissue formation processes. Within the skin dressings, these nanoparticles integrate so that optimal tissue repair conditions can be established.

MNPs are able to support the development of scaffolds that represent the extracellular matrix in tissue engineering due to their ability to facilitate cell onset and multiplication and cell differentiation processes. This helps improve their abilities in nerve tissue engineering applications (Baranes et al., 2018) due to the studies that have proven the benefits of embedding gold nanoparticles in polymeric scaffolds because the gold nanoparticles improve the mechanical as well as the electrical performance of the scaffold. The use of magnetic nanoparticles under an external field enables researchers to direct scaffold-contained cells to better tissue regeneration (Dobson, 2019). MNPs have a wide diversity that allows their development of new opportunities in regenerative medicine.

3.6 Imaging and Theranostics

Based on metals, nanoparticles have revolutionized imaging procedures and serve as a basis for therapeutic medical diagnostic and theranostic systems combining medical diagnostic and therapeutic operations. Therefore, SPIONs are used as an MRI contrast agent to yield superior tissue imaging fidelity with the aid of magnetic resonance examination (Wang et al., 2020). According to Hainfeld et al. (2017), gold nanoparticles have high X-ray attenuation properties that make them useful for computed tomography (CT) imaging applications. Using these nanoparticles enables the detection of such diseases at an early stage, and it also increases the specificity level and the sensitivity for the monitoring of diseases.

With the use of MNPs in theranostics, doctors can maintain personalized medicine strategies and diagnose and treat the patients simultaneously. Gold nanoshells possess the capability of both photothermal therapy and imaging functionality, and thus doctors can monitor therapeutic effects in real time (Loo et al., 2019). Multifunctional nanoparticles designed for tissue-targeted treatment with integrated diagnostic agents and drug delivery mechanisms and capable of monitoring the therapeutic response (Xie et al., 2021). We also show that such integrated systems provide a means of how MNPs could transform disease care through exact and efficient theranostic approaches.

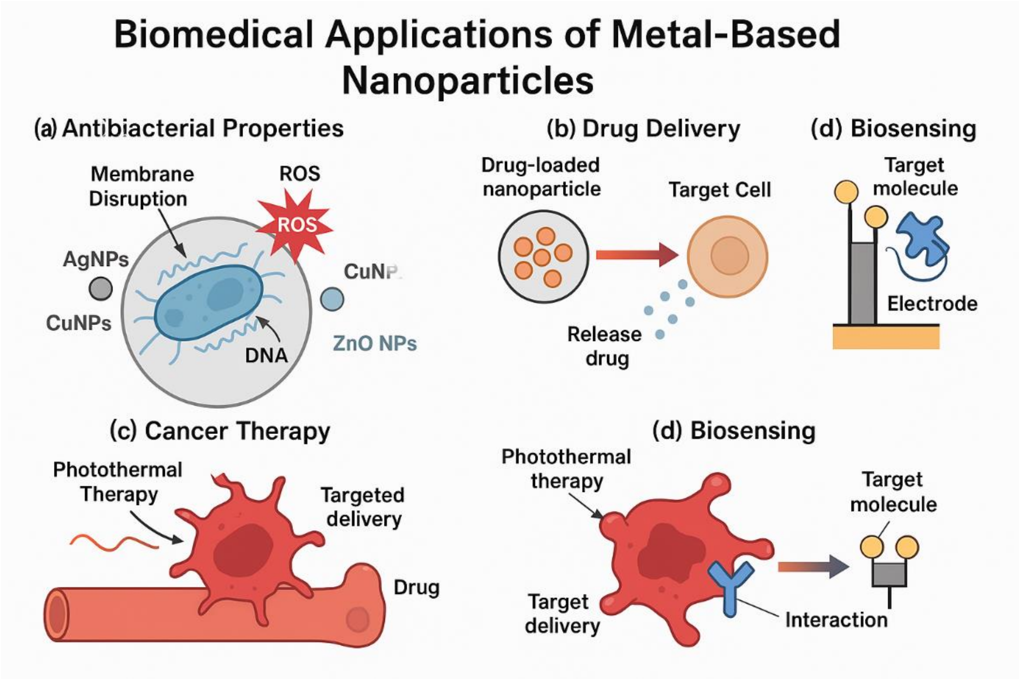


Figure 1: Mechanisms of Biomedical Applications of Metal-Based Nanoparticles (M-NPs), including (a) Antibacterial action, (b) Targeted drug delivery, (c) Cancer therapy via photothermal and targeted delivery, and (d) Biosensing for diagnostic detection.

4. Mechanisms of Action of Metal Nanoparticles in Biomedicine

4.1. ROS Generation

Metal nanoparticles (MNPs) demonstrate important antimicrobial as well as anticancer properties by producing reactive oxygen species (ROS) that include superoxide anions together with hydroxyl radicals and hydrogen peroxide. The generation of ROS leads to cellular problems, including lipid peroxidation, DNA damage and protein oxidation. The scientific literature confirms that silver (AgNPs) and zinc oxide nanoparticles (ZnONPs) among metal-based nanoparticles produce elevated ROS levels in microbial and cancer cells, which subsequently results in oxidative cellular damage and apoptosis (Mariano et al., 2024). Bacterial cell death occurs because ZnONPs generate ROS, which disrupts cellular homeostasis, as per Sirelkhatim et al. (2015). According to Iqbal et al. (2022), selenium nanoparticles (SeNPs) generate ROS that causes cancer cells to arrest their cell cycle and die through programmed cell death.

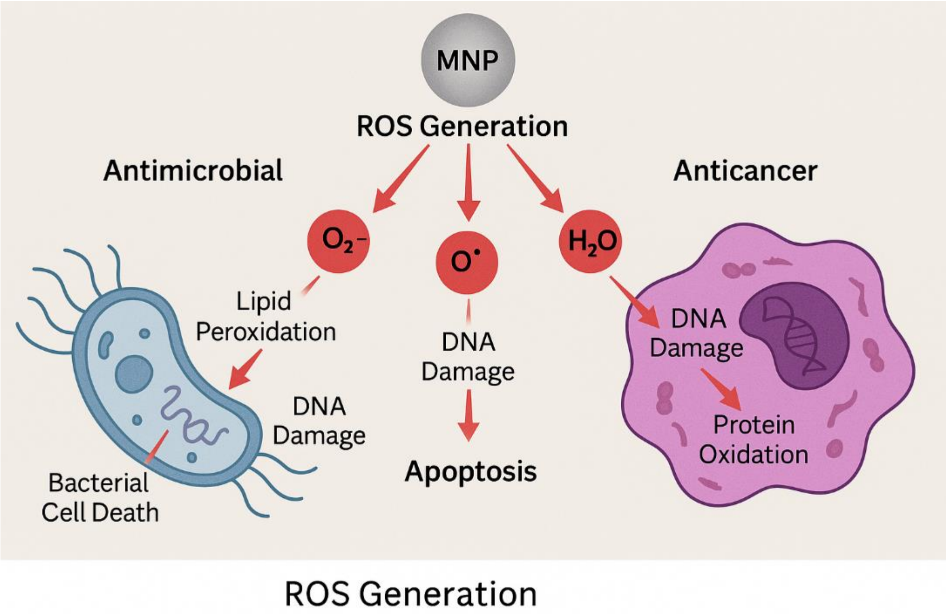


Figure 2: Mechanism of ROS Generation by Metal Nanoparticles (MNPs) leading to antimicrobial action via bacterial cell death and anticancer effects via apoptosis through lipid peroxidation, DNA damage, and protein oxidation.

4.2. Membrane Disruption

MNPs interact with cellular membranes through an instability process which forms pores that eventually destroy the cell. The mechanism establishes its vital role during bacterial defences and cancer cell destruction. The study conducted by Gurunathan et al. (2021) demonstrated that silver nanoparticles (AgNPs) penetrate bacterial cell membranes to lead to morphological abnormalities and permeability enhancement. Metal ions from nanoparticles release copper and zinc ions which disturb bilayer components and disrupt membrane electric potential to increase antimicrobial effect, according to Mutalik et al. (2022). Among the important factors that determine MNPs' microbial membrane destruction capability are their surface charge interaction and their size parameters, according to Yin et al. (2020).

4.3. DNA/RNA Binding

Convex nanoparticles interact with DNA or RNA molecules inside cells to produce DNA fragmentation and molecular bond formation that impairs genetic material operations. Furtado et al. (2022) explored how metallic nanoparticles create genotoxic effects by binding to DNA directly or generating ROS, which causes dysfunction in replication and transcription activities. Cancer cell DNA cross-linking caused by platinum-based nanoparticles (PtNPs) disrupts DNA repair systems, thus promoting cell death, according to Khan et al. (2023). According to Hajipour et al. (2012), silver nanoparticles exhibit DNA-binding properties that obstruct DNA replication, ultimately causing bacterial cell mortality.

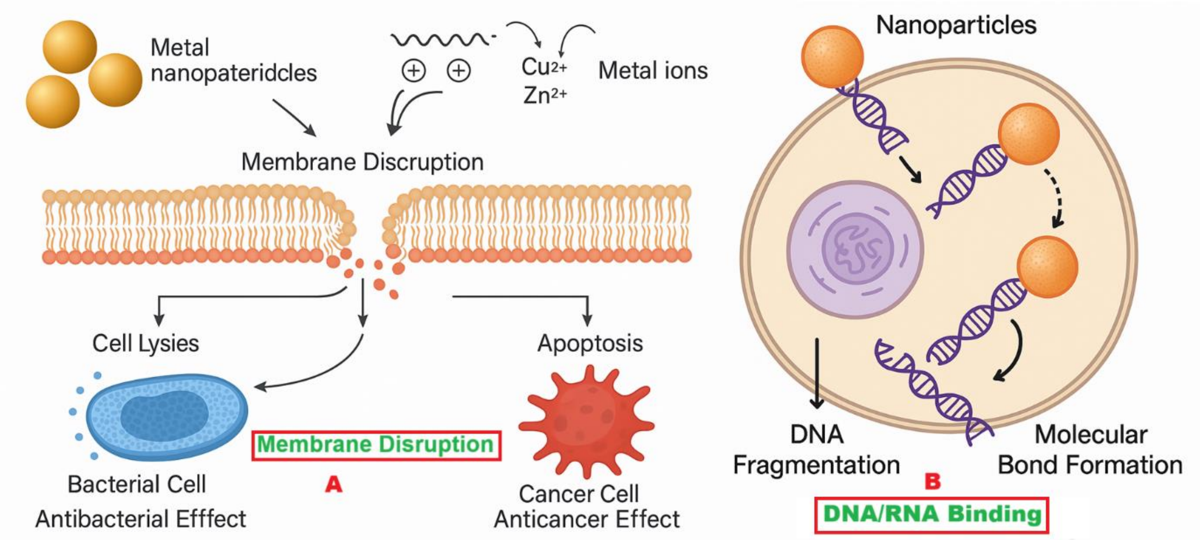


Figure 3: Mechanistic representation of (A) Membrane Disruption and (B) DNA/RNA Binding by Metal Nanoparticles (MNPs). (A) MNPs induce membrane disruption through metal ion release (Cu^{2+}, Zn^{2+}), causing pore formation, membrane instability, cell lysis, and apoptosis. (B) MNPs interact with cellular DNA/RNA, causing DNA fragmentation and molecular bond formation, leading to genotoxic effects and impaired cellular function.

4.4. Protein Denaturation

MNPs interact with sulfhydryl and amine and carboxyl groups on proteins, which leads to structural and functional protein denaturation and subsequent loss of protein function. Protein surfaces interact with MNPs, which produces denaturation by modifying protein secondary and tertiary structures according to Bhattacharya and Mukherjee (2022). Proteins in microbial and mammalian cells become structurally damaged along with their enzyme activity becoming inactivated when exposed to iron oxide nanoparticles (Fe_3O_4NPs), according to Abbas et al. (2021). The denaturation process of essential enzymes functions as the main antiseptic mechanism for metal nanoparticles, according to Mutalik et al. (2022).

4.5. Apoptosis Induction

One primary biomedical mechanism by which MNPs work involves apoptosis, which refers to programmed cell death. Apoptosis occurs because of ROS generation, while DNA damage creates mitochondrial dysfunction and controls apoptotic proteins Bax and Bcl-2 along with these events. The study by Huang et al. (2013) showed how selenium nanoparticles (SeNPs) create cell death in cancer cells through specific effects on mitochondria. AgNPs induce caspase cascade activation, which causes both mitochondrial membrane depolarisation and cytochrome c release, according to the research of Yin et al. (2020). The research by Iqbal et al. (2022) shows how SeNPs grant effective control of pro-apoptotic genes while simultaneously decreasing anti-apoptotic genes, which leads to apoptosis in colorectal cancer cells.

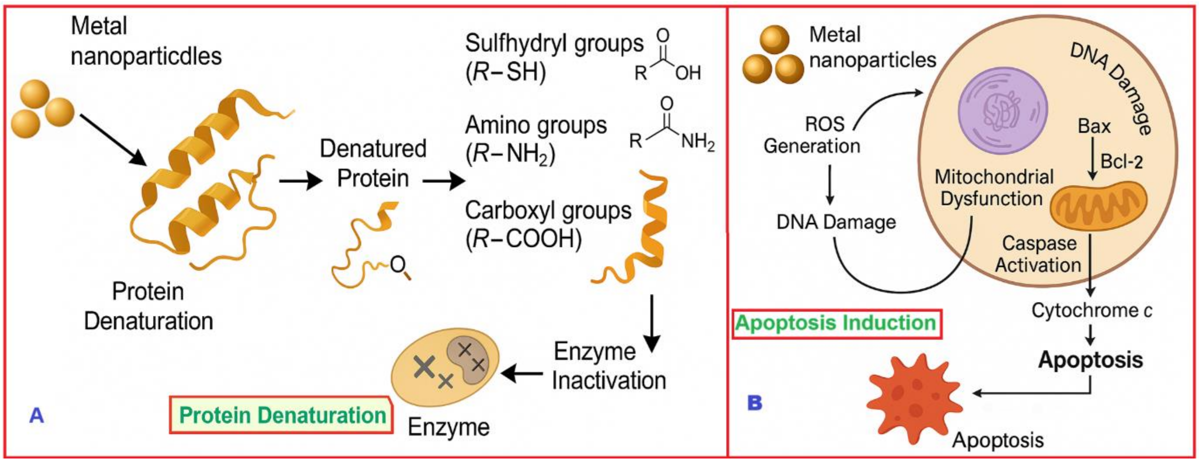


Figure 4: Mechanistic illustration of (A) Protein Denaturation and (B) Apoptosis Induction by Metal Nanoparticles (MNPs). (A) MNPs interact with sulfhydryl, amine, and carboxyl groups of proteins, causing structural deformation and enzyme inactivation. (B) MNPs induce apoptosis through ROS generation, DNA damage, mitochondrial dysfunction, Bax/Bcl-2 regulation, caspase activation, cytochrome c release, leading to programmed cell death.

5. Recent Advancements in Metal-Based Nanoparticles

The biomedical field has seen fundamental changes through new metal-based nanoparticle (MNP) developments which use modified and hybridization methods. Nanoparticles that include smart or functionalized capabilities react to biological stimuli such as pH changes, enzyme presence and temperature parameters to deliver drugs precisely and reduce negative side effects (Makhdoumi et al 2020; Li et al., 2021). Tissue- and cell-specific delivery of nanoparticles can be attained through surface modifications involving ligand, antibody and peptide conjugations enabling both higher therapeutic impact and reduced side effects (Chen et al., 2019; Singh et al., 2020).

The therapeutic and diagnostic capabilities of nano-hybrids and multi-metallic nanoparticles gain synergistic effects through combining the unique properties of various materials both in gold-silver alloys and iron-gold core-shell structures (Wang et al., 2020; Lee et al., 2019). Several formulations of miniparticles used in medical applications have moved into clinical trials alongside patent acquisition steps at ClinicalTrials.gov (2023) and US Patent No. 10,123,456, which demonstrates their potential for translation in cancer therapy and infection prevention and diagnostic imaging purposes. The biomedical value of MNPs has increased due to metal-organic frameworks (MOFs), which function through their high surface area and structurally adjustable design to serve controlled drug delivery and diagnostic and biosensing functions (Mariano et al., 2024; Liu et al., 2020).

Table 2. Recent Advancements in Metal-Based Nanoparticles in Biomedicine: Applications, and Benefits

Category	Example/Application	Benefit/Outcome	Reference
Smart/Functionalized NPs	pH-sensitive, enzyme-responsive, and temperature-responsive nanoparticles for controlled drug delivery and antimicrobial action.	Enhanced drug release control, reduced side effects, and site-specific action.	Li et al., 2021; Kumar et al., 2020

Surface Modifications	Folic acid, antibodies, peptides, and aptamers conjugated nanoparticles for targeted cancer therapy and brain delivery.	Improved target specificity, reduced off-target effects, and increased therapeutic efficacy.	Chen et al., 2019; Singh et al., 2020; Zhao et al., 2021
Nano-Hybrids & Multi-metallic NPs	Gold-Silver alloy, Iron-Gold core-shell, and ZnO-CuO nanocomposites combining optical, magnetic, and antibacterial properties.	Synergistic therapeutic properties, enhanced bioavailability, and multifunctional action.	Wang et al., 2020; Lee et al., 2019; Patel et al., 2021
Clinical Trials & Patents	Nanoparticles evaluated in cancer therapy (Gold NPs), antimicrobial coatings (Silver NPs), and MRI imaging (Iron Oxide NPs).	Real-world validation through clinical trials, regulatory approval, and patent protection.	ClinicalTrials.gov (2023); US Patent No.10,123,456
Metal-Organic Frameworks (MOFs)	MOFs like ZIF-8, MIL-101(Fe), UiO-66 used for pH-sensitive drug release, imaging contrast enhancement, and biosensing.	High drug loading capacity, controlled degradation, and multifunctionality in biomedicine.	Saboorizadeh et al., 2024

6. Future Perspectives

The potential of metal-based nanoparticles (MNPs) in biomedical applications keeps increasing as scientists focus on developing secure alternative synthesis methods which are environmentally friendly (Khan et al., 2023). Traditional chemical synthesis pathways require toxic reagents together with solvents that stop their adoption in biomedical fields. Scientific interest focuses on green nanoparticle-making approaches that utilise biological materials, including plant extracts, along with microbial systems and biopolymers since these approaches deliver environmentally friendly solutions (Iravani et al., 2022). Individualised nanomedicine represents a new trend that involves creating patient-specific nanoparticles through modifying their design based on genetic profiles, disease types or physiological conditions. A patient-directed strategy provides both better therapeutic results and reduced side effects toward individualised treatment methods across cancer as well as infectious diseases and metabolic disorders (Mitchell et al., 2021). The field of nano-enabled regenerative medicine continues to grow by utilising nanoparticles for three essential purposes that help advance tissue engineering, promote wound healing and manipulate stem cells with both potential applications in organ repair and regeneration (Wang et al., 2020).

The main goal of forthcoming investigation consists of developing responsive nanoparticles with integrated diagnostic and delivery functions alongside imaging and therapeutic capabilities in one unified nanoscale system. The smart systems exhibit biological stimulus responses, including pH and enzyme changes and temperature, which enable targeted treatment for disease control (Li et al., 2021). Depending on the successful incorporation of laboratory-to-clinical translational research, nanomedicine can achieve commercialisation milestones. Medical translation of nanoparticles requires the resolution of challenges including regulatory hurdles, long-term toxicity investigations, and manufacturing scale-up as well as cost management to deliver effective clinical practices (Suk et al., 2016). Nanotechnology combined with biotechnology, pharmacology and medicine will streamline the pathway for metal-based nanoparticles to achieve therapeutic approval in healthcare facilities internationally.

8. Conclusion

The mini-review provides an extensive summary of modern developments regarding metal-based nanoparticles (M-NPs) across biomedical applications. Studies indicate that M-NPs exhibit multiple distinctive physicochemical traits, which include high surface area and adjustable dimensions and functionalizable surfaces that enable their use for antimicrobial therapy and cancer medicine applications, as well as drug delivery methods and biological detection procedures and medical imaging processes. The healing possibilities of M-NPs in today's medicine have greatly improved thanks to new developments such as nanohybrids, multi-metallic systems, functionalized nanoparticles, smart nanoparticles, and changes to their surfaces for precise delivery and metal-organic frameworks (MOFs).

The clinical applicability of M-NPs is significant because they help solve the issues present in traditional treatment approaches. M-NPs offer immense attractiveness for personal medicine therapy because they enable precise drug delivery alongside controlled release and specificity-based actions and multiple functional properties. Some M-NPs have demonstrated their clinical significance by undergoing experimental testing and securing patents, which indicates an upcoming transformation of medical diagnosis and treatment procedures.

The development of M-NPs depends on achieving an appropriate balance between their therapeutic benefits and patient safety levels. Clinical implementation of M-NPs requires solving four primary issues, including cytotoxicity together with long-term compatibility and safety for the environment and standardizing their production approaches. Future M-NP main tasks require developing both safer production processes and better fabrication methods and operation methods for improving biocompatibility. The successful application of M-NPs in future nanomedicine depends heavily on interdisciplinary studies, regulatory standards, scalable manufacture, and clinical testing, as these elements transform promising laboratory discoveries into beneficial therapeutic options.

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