



Nanoparticles and Their Antimicrobial Activity: A Review Study

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Abstract

This review rigorously evaluates the antimicrobial characteristics of diverse nanoparticles (NPs) and their potential application in active food-packaging systems. The research concentrates on four principal categories: metallic nanoparticles (Ag, Cu, Au, Se), metal-oxide nanoparticles (ZnO, TiO₂, MgO, Fe₃O₄), carbon-based nanomaterials (graphene oxide, carbon nanotubes), and polymeric nanoparticles (chitosan, PLGA, PCL).

These nanomaterials demonstrate various antimicrobial mechanisms, such as the generation of reactive oxygen species (ROS), disruption of cell membranes, metabolic interference, and ion release that hinders DNA replication and protein synthesis. Silver nanoparticles exhibit remarkable broad-spectrum antimicrobial effectiveness; however, they pose cytotoxic risks at elevated concentrations.

Copper and zinc oxide nanoparticles are two other options that are cheaper and less toxic. Gold and selenium nanoparticles are showing promise in fighting pathogens that are resistant to many drugs. Magnesium and titanium oxides, on the other hand, are good for the environment. Adding these nanoparticles to biopolymer or synthetic matrices makes packaging films stronger, more resistant to damage, and better at fighting germs. But there are still problems with long-term toxicity, environmental accumulation, unclear regulations, and the ability to scale up production. This review emphasises the necessity for standardised synthesis, eco-friendly manufacturing methods, and thorough toxicological evaluations to enable the secure, widespread implementation of antimicrobial nanomaterials in food preservation and public health initiatives.

Keywords: Antimicrobial nanoparticles, Food packaging, Nanotechnology in food safety.

1. INTRODUCTION

The rise in food-borne diseases caused by pathogenic microorganisms has necessitated the development of new strategies to prevent microbial contamination without affecting the quality and safety of foodstuffs. Some food-borne pathogens, including *Escherichia coli*, *Salmonella* spp., and *Listeria monocytogenes*, are estimated to contribute to around 600 million illnesses and 420 000 deaths each year worldwide (World Health Organization, 2020). Thermal treatments or chemical preservatives often degrade sensory or nutritional quality, necessitating alternative strategies.

One approach involves the controlled introduction of antimicrobials into packaging materials to prevent microbial growth and extend shelf life—a strategy known as antimicrobial packaging. This approach relies on embedding antimicrobial agents as nanofillers within polymer matrices to create active packages that act directly against pathogens (Vanderroost et al., 2014). Nanoparticles are good antibacterial agents because they have a high surface area-to-volume ratio and small pore size. Nanoparticles that kill bacteria have smaller pores and a surface that holds more water than microscopic particles (Cha & Chinnan, 2004).

The composition of nanoparticles dictates their organic or inorganic status. Anbukkarasi et al. (2015) assert that metal and metal-oxide nanoparticles (NPs), such as AgNPs, CuNPs, ZnO NPs, and TiO₂ NPs, have significant antibacterial properties even in harsh environmental conditions. These nanomaterials disrupt bacterial cell membranes, modify intracellular dynamics, and produce reactive oxygen species, rendering them extensively antibacterial (Kim et al., 2007). NPs are stable and can be used in many ways, such as for food packaging, medical device coatings, water purification, and textile treatments (Prabhu et al., 2015).

Nanocomposites for food packaging have nanoparticles in either biopolymer or synthetic-polymer matrices. These solutions make the market more appealing by modifying the mechanical and barrier properties of packing materials and stopping the growth of bacteria (Emamifar et al., 2010a).

For example, silver nanoparticles entrapped in biodegradable films have shown remarkable inhibition towards *Listeria innocua* and *Escherichia coli* and, thus, play an important role in prolonging the shelf life of perishable items (Cano et al., 2016). Another example is zinc oxide nanoparticles, classified by the FDA as Generally Recognized as Safe (GRAS), which are capable of broad-spectrum antimicrobial and UV-protection effects, rendering them appropriate options for use in food-contact materials (Emami-Karvani & Chehrazhi, 2011).

Nonetheless, several limitations remain. The lack of uniform global regulation hinders safe application, as organisations such as ISO and NIOSH provide differing definitions

and recommendations (Esfanjani & Jafari, 2016). Concerns about potential human toxicity and environmental impact also call for further characterisation (Boholm & Arvidsson, 2016).

This review aims to critically survey metallic and inorganic nanoparticles, clarify their antimicrobial mechanisms, and evaluate their suitability for active food-packaging systems that enhance food safety and shelf life.

2. Categorization of Nanoparticles for Antimicrobial Activity

Antimicrobial nanoparticles are frequently categorised based on both their mode of action and chemical makeup. The four main categories are polymeric nanoparticles, carbon-based nanomaterials, metal-oxide nanoparticles, and metallic nanoparticles. Each group has distinct physicochemical characteristics and antimicrobial mechanisms that make it appropriate—and occasionally necessary—for uses ranging from water treatment and medical device coatings to food packaging.

2.1. Metal Nanoparticles for Antimicrobial Application

2.1.1. Silver Nanoparticles (AgNPs)

There is a lot of research on silver nanoparticles. Because they have a high surface area-to-volume ratio and are usually less than 10 nm in size, they are very good at killing bacteria (Kim et al., 2007). This enables robust interactions with bacterial membranes, resulting in biocidal effects (Duran et al., 2016).

Diffusing inward, adhering to membrane surfaces, and altering membrane permeability can damage DNA or proteins. They produce reactive oxygen species, including hydrogen peroxide (H_2O_2), hydroxyl radicals (OH), and superoxide anions (O_2^-), which induce oxidative stress (Chawengkijwanich & Hayata, 2008). AgNPs that are truncated or triangular have crystallographic planes that make them more reactive (Pal et al., 2007). The size, shape, and concentration of particles are all very important. Notably, AgNPs are more potent against Gram-negative bacteria because their thinner peptidoglycan layer and negatively charged outer membrane promote Ag^+ binding (Kim, 2007).

AgNPs have been embedded in polyvinyl alcohol, polylactic acid, and starch films. Such nanocomposites extend the shelf life of foods prone to *Escherichia coli* or *Listeria innocua* contamination without compromising sensory attributes (Cano et al., 2016). Nevertheless, high concentrations raise cytotoxic and genotoxic concerns, so safe dosage limits and long-term risks must be defined (Asare et al., 2012; Manke et al., 2013)

Research indicates substantial cytotoxic and genotoxic effects of AgNPs at concentrations surpassing 10 $\mu\text{g/mL}$ in vitro. Asare et al. (2012) noted DNA damage

and oxidative stress in testicular cells subjected to 10–50 µg/mL of AgNPs. Manke et al. (2013) also found that doses of 25 µg/mL or higher caused damage to mitochondria.

2.1.2. Copper Nanoparticles (CuNPs)

CuNPs are cheaper than noble-metal NPs and can be used for many things, such as preserving food and making medical devices (Ibrahim et al., 2008; Kalatehjari et al., 2015). They are economically and commercially feasible because copper is cheap and easy to get.

The antimicrobial action of CuNPs is based on the disruption of cellular processes. CuNPs can seriously affect enzymatic proteins and nucleic acids, thereby altering metabolic pathways and replication. The release of copper ions (Cu^+ and Cu^{2+}) binds to thiol groups (-SH) in proteins, inducing enzyme inactivation and oxidative stress. Furthermore, copper ions can catalyze Fenton-type reactions to produce ROS that attack lipophilic membranes, DNA, and organelles (Zhu et al., 2012). The morphology of CuNPs has a significant impact on antimicrobial activity: spherical particles are often inferior to blossom-like or polyhedral morphologies, partly because of higher ion release and surface reactivity (Xiong et al., 2015).

CuNPs have been incorporated into biopolymer composites (e.g., gelatin, chitosan, guar gum) to improve both antimicrobial and mechanical properties in food packaging (Arfat et al., 2017). Synergistic activity between CuNPs and natural antimicrobials such as lactic acid has been reported as an effective inhibitor of pathogens—including *Salmonella* spp. and *E. coli*—in drinking-water systems at lower concentrations (Ibrahim et al., 2008). Nevertheless, high-concentration cytotoxicity remains an issue; the controlled release and dosage of CuNPs should be further optimized for food safety.

CuNPs exhibit cytotoxicity at concentrations exceeding 20 µg/mL, primarily attributed to reactive oxygen species (ROS) generation and the disruption of enzymatic pathways (Ren et al., 2009). Apoptosis in mammalian cells is dose-dependent, which means that food-contact applications need controlled-release mechanisms and biocompatible coatings.

2.1.3. Gold Nanoparticles (AuNPs)

AuNPs have been extensively investigated *in vitro* and *in vivo* for antimicrobial activity, particularly in the face of rising resistance to conventional antibiotics. They are chemically stable and biocompatible, supporting biomedical and food applications (Syed et al., 2016).

Unlike silver or copper NPs, which act mainly through oxidative stress, AuNPs exert antimicrobial effects primarily via non-oxidative pathways. They attach to bacterial surfaces, disrupt electrochemical balance, and impair key metabolic functions—

notably ATP synthesis. AuNPs also hinder ribosomal-subunit formation, thereby obstructing protein synthesis and slowing cellular growth (Cui et al., 2012). Because their action is ROS-independent, AuNPs may impose less secondary oxidative damage on host cells, reducing cytotoxicity. Particle size and geometry are critical: spherical or rod-shaped AuNPs (5–50 nm) effectively inhibit *Pseudomonas aeruginosa*, *Staphylococcus aureus*, and *Klebsiella pneumoniae* (Syed et al., 2016).

AuNPs can be produced by green processes, such as reduction with plant extracts, yielding eco-friendly nanomaterials. In one study, extract-derived AuNPs displayed stronger antimicrobial action than gentamicin (Piruthiviraj et al., 2016). In food packaging, AuNPs incorporated into quinoa-based biofilms achieved > 99 % bacterial reduction while improving film transparency and barrier properties (Pagno et al., 2015). However, the high cost of gold limits large-scale use, even though AuNPs offer low toxicity and versatile functionalization for specialized applications.

2.1.4. Selenium Nanoparticles (SeNPs)

Selenium nanoparticles (SeNPs) have gained attention as antimicrobial agents offering dual antioxidant and antibacterial action with low toxicity (Tran & Webster, 2013).

Their antimicrobial mechanism involves regulated ROS production that damages microbial membranes, proteins, and DNA. Compared with AgNPs, SeNPs generate lower ROS levels, preferentially target bacterial cells, and exhibit reduced activity toward host cells (Huang et al., 2016). SeNPs can also intercalate into lipid bilayers, destabilizing membranes and causing leakage of intracellular contents. This multi-target mode improves efficacy against multidrug-resistant strains such as methicillin-resistant *Staphylococcus aureus* (MRSA), especially when SeNPs are surface-modified with bioactive moieties (e.g., quercetin) (Huang et al., 2016).

In biopolymer food packaging, SeNPs work as antioxidants and antibacterial agents. Multilayer polymers with SeNPs safeguarded hazelnuts and kept their quality by only releasing small amounts of nanoparticles (Vera et al., 2016). Toxicological studies indicate that SeNPs are less hazardous than heavy-metal nanoparticles, hence endorsing its application in food (Khiralla & El-Deeb, 2015). To improve antibacterial activity and lower cytotoxicity, particle size, surface modification, and release kinetics need to be fine-tuned.

2.1.5. Magnesium Oxide Nanoparticles (MgO NPs)

Magnesium-oxide nanoparticles (MgO NPs) have been extensively researched for antibacterial activities due to their broad efficacy, cost-effectiveness, and thermotolerance (Krishnamoorthy et al., 2012; Jin & He, 2011). Reactive oxygen species (ROS), such as hydroxyl radicals (OH) and superoxide ions (O_2^-), damage membranes and produce lipid peroxidation, which kills germs (Al-Hazmi & Javed,

2012). Oxygen vacancies on the surface make nanoparticles more reactive and more likely to stick to bacterial cell walls.

The thin peptidoglycan layer and high LPS concentration make electrostatic interactions with the positively charged MgO surface stronger. This makes MgO NPs more effective against Gram-negative bacteria (Krishnamoorthy et al., 2012). MgO NPs make biopolymer films more resistant to bacteria, more stable at high temperatures, and better at keeping things out. Nisin, MgO NPs, and mild heat destroy bacteria in milk (Mirhosseini, 2016). Smaller nanocubes with larger surface area are superior in killing germs (Vidic et al., 2013).

Research shows that MgO NPs are less harmful to cells than other metal NPs, hence they are safe to use in food preparation. The performance is affected by the size and shape of the particles. We need to do more research to find the optimal combinations and make sure they are safe for the environment.

2.2. Metal Oxide Nanoparticles Employed for Antimicrobial Purposes

Metal oxides are a major form of nanomaterial that is used to kill germs. They make reactive oxygen species (ROS) and directly affect the biological parts of germs. Iron oxide (Fe_2O_3), zinc oxide (ZnO), and titanium dioxide (TiO_2) are the three metal-oxide NPs that will be spoken about in this part. We may look at how they work to kill germs and what they are used for.

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2.2.1. Titanium Dioxide Nanoparticles (TiO_2 NPs)

Studies have concentrated on TiO_2 nanoparticles because of their antimicrobial properties in the presence of light. TiO_2 NPs generate reactive oxygen species (ROS), such as hydroxyl radicals ($\bullet\text{OH}$) and superoxide anions (O_2^-), upon exposure to ultraviolet radiation (Fujishima & Honda, 1972; Hashimoto et al., 2001). Reactive oxygen species (ROS) destroy bacterial cell membranes, proteins, and DNA, killing them (Thiruvengkatachari et al., 2008). The crystalline structure of TiO_2 nanoparticles affects how well they destroy germs. Anatase is better than rutile because it has a larger surface area and produces more ROS from UV-A rays (Thiruvengkatachari et al., 2008). TiO_2 NPs affect bacterial spores and vegetative cells with less UV radiation, making them work better (Molina et al., 2014). They are combined with polymers to create films and coatings for food packaging, medical equipment, and water treatment systems (Molina et al., 2014). TiO_2 NPs have problems since they need UV light to work well. Researchers have attempted to activate the visible spectrum by using silver, copper, or

hydrogen peroxide (Hou et al., 2015). Careful preparation is necessary to make sure that cells are safe and work well at high doses (Long et al., 2006).

2.2.2. Zinc Oxide Nanoparticles (ZnO NPs)

ZnO NPs are popular UV-free antibacterial metal oxides. This makes them appropriate for food packaging and biomedical coatings (Emami-Karvani & Chehrizi, 2011). Zinc oxide nanoparticles (ZnO NPs) are FDA-approved "Generally Recognised as Safe" (GRAS) for food-contact products and antimicrobial packaging (Espitia et al., 2012).

ZnO NPs act by two main mechanisms. First, they generate ROS (H_2O_2 , OH , O_2^-), producing oxidative stress that damages microbial membranes and metabolism (Sawai, 2003; Liu et al., 2008); hydrogen peroxide is particularly effective because it permeates bacterial membranes. Second, Zn^{2+} ions released from the NP surface bind to cell-wall and intracellular targets, disturbing enzyme activity, destabilizing the membrane, and inhibiting DNA replication (Atmaca et al., 1998; Xie et al., 2011).

Smaller ZnO particles promote higher ROS generation and ion release, thereby boosting efficacy against a wide range of pathogens such as *Escherichia coli*, *Listeria monocytogenes*, and *Salmonella* spp. (Jin et al., 2009; Xie et al., 2011). ZnO NPs have been incorporated into biopolymer films (cellulose, gelatin, chitosan) to create antimicrobial packaging that also enhances mechanical strength, thermal stability, and UV resistance (Jebel & Almasi, 2016).

Although ZnO is less cytotoxic than many metal-based NPs, ROS generation rises sharply at higher doses; pretreatment of human cells with $> 159 \mu\text{g mL}^{-1}$ ZnO NPs can induce oxidative damage. Therefore, careful control of particle size and loading is critical for safe food-contact applications (Espitia et al., 2012).

2.2.3 Iron Oxide Nanoparticles (Fe_3O_4 NPs)

Magnetite nanoparticles (Fe_3O_4 NPs), also called iron-oxide nanoparticles, are valued for their magnetic properties, antimicrobial activity, and magnetic recoverability through application of external fields to treated sites (Thiruvengkatachari et al., 2008; Dastjerdi & Montazer, 2010). These characteristics qualify Fe_3O_4 NPs for water-purification uses, food packaging, and biomedicine.

Reactive-oxygen species (OH , O_2^-) generated by Fe_3O_4 NPs play a crucial role in antimicrobial activity, damaging bacterial membranes, proteins, and nucleic acids (Dworniczek et al., 2016). Fe_3O_4 NPs also catalyse Fenton-like reactions with H_2O_2 , forming additional $\bullet\text{OH}$ that heightens oxidative stress and microbial killing (Dworniczek et al., 2016). Moreover, Fe_3O_4 NPs can attach to bacterial surfaces and disrupt membrane integrity through direct contact, inducing leakage of intracellular contents (Rincon & Pulgarin, 2007).

Surface functionalisation—for example, coating Fe_3O_4 NPs with biocompatible polymers such as poly (ethylene glycol) or chitosan—improves stability, enables controlled release, reduces toxicity risk, and enhances antimicrobial activity (Rincon & Pulgarin, 2007). Their magnetic behaviour allows site-specific delivery and high local concentration with minimal systemic exposure. Fe_3O_4 NPs have been incorporated into composite food-packaging films alongside Ag or Cu NPs to achieve synergistic effects (Dastjerdi & Montazer, 2010).

A key drawback is the tendency of Fe_3O_4 NPs to agglomerate, which limits surface reactivity and antimicrobial performance. Therefore, controlling particle size, surface modification, and dispersion stability is essential (Tran et al., 2010). Although Fe_3O_4 NPs show lower toxicity than many other metal-based NPs, comprehensive systemic toxicological evaluation is still required for food-contact applications.

2.3. Carbon-based Nanomaterials Used in Antimicrobial Applications

Carbon-based nanomaterials—graphene oxide (GO) and carbon nanotubes (CNTs)—are attractive antimicrobials because of their high surface area and tunable chemistry (Dastjerdi & Montazer, 2010). They inhibit microbes primarily through physical mechanisms; chemical interactions are secondary.

2.3.1. Graphene Oxide (GO)

Graphene oxide (GO) is a two-dimensional carbon nanomaterial enriched with oxygen-containing groups (hydroxyl, epoxide, carboxyl) that enhance hydrophilicity and interactions with microbial membranes (Akhavan & Ghaderi, 2010). Its principal antimicrobial mechanism is physical disruption: GO's sharp edges pierce the lipid bilayer, causing leakage of intracellular contents and cell death (Akhavan & Ghaderi, 2010). Thanks to its large surface area, GO can also adsorb microbial cells and separate them from nutrients, leading to starvation.

GO produces low-level ROS under light, adding oxidative stress to its mechanoporative damage and entrapment; together, these processes confer broad bactericidal activity (Liu et al., 2011). GO has been integrated into polymer matrices for antimicrobial food-packaging films, wound dressings, and water-filtration membranes, simultaneously improving microbial inhibition and the mechanical properties of host materials (Hu et al., 2010). A bottleneck is cytotoxicity toward mammalian cells at high concentrations, so GO content and surface chemistry must be tuned to balance antimicrobial efficacy with biocompatibility (El Achaby et al., 2017; Santos et al., 2012).

2.3.2. Carbon Nanotubes (CNTs)

Carbon nanotubes (CNTs) single-walled (SWCNTs) or multi-walled (MWCNTs) are cylindrical carbon structures with high mechanical strength, electrical conductivity, and aspect ratio (Dastjerdi & Montazer, 2010). Their antibacterial action is mechanical: CNTs puncture and destabilise bacterial membranes, leading to leakage of intracellular contents (Liu et al., 2009). Additional oxidative stress can arise when CNTs bearing oxygen-containing groups, or those exposed to light, generate ROS that damage lipids, proteins, and DNA (Vecitis et al., 2010).

Functionalising CNTs with hydrophilic groups, metals (e.g., silver), or polymers improves dispersion in aqueous media and intensifies interactions with bacterial membranes, thereby boosting biocidal activity (Aslan et al., 2010). CNTs are more effective against Gram-negative bacteria because their thinner peptidoglycan and outer membrane are more readily penetrated (Kang et al., 2008).

CNTs have been incorporated into antimicrobial coatings, filtration membranes, wound dressings, and food-packaging materials, enhancing mechanical strength, barrier performance, and thermal stability (Aslan et al., 2010). Nevertheless, potential cytotoxicity, especially at high concentrations or prolonged exposure, makes careful control of CNT concentration, purification, and surface modification essential for safety (Smart et al., 2006).

2.4. Polymeric Nanoparticles Used in Antimicrobial Applications

Polymeric nanoparticles can encapsulate, adsorb, or covalently bind antimicrobial agents, providing targeted and prolonged action suitable for food packaging, wound healing, and drug formulations (Esfanjani & Jafari, 2016).

2.4.1. Chitosan Nanoparticles

Chitosan nanoparticles (CNPs) are produced from chitin, a polysaccharide that possesses inherent antimicrobial activity against bacteria, fungi, and yeasts. Their mechanisms include electrostatic interaction between the positively charged amino groups of chitosan and the negatively charged bacterial cell wall, resulting in membrane damage and cellular-content leakage (Hosseinnejad & Jafari, 2016). CNPs also impede microbial metabolism by disrupting mRNA and protein synthesis and by chelating essential metal ions required for growth (Qi et al., 2004).

CNPs can encapsulate secondary antimicrobials—essential-oil compounds, peptides, or antibiotics—thereby potentiating efficacy and enabling controlled release (Hosseinnejad & Jafari, 2016). Incorporated into biodegradable films, they significantly prolong food shelf life and reduce spoilage (Dutta et al., 2009). Owing to

their low toxicity and biodegradability, CNPs are suitable for both food and medical applications (Qi et al., 2004).

2.4.2: Synthetic polymer nanoparticles (like PCL and PLGA)

Antimicrobial nanoparticles can also be synthesized from synthetic biodegradable polymers such as polycaprolactone (PCL) and poly (lactic-co-glycolic acid) (PLGA). Both polymers possess FDA approval for biomedical applications due to their differential degradation rates and biocompatibility (Danhier et al., 2012). They function as mechanisms for the controlled administration of medications employing the subsequent methods:

- a. Loading of antimicrobial agents (such as antibiotics, silver ions, and essential oils)
- b. Changing the surface with polymers or antibacterial peptides.
- c. Enzymes, pH, or temperature can cause the release of a stimulus (Makadia & Siegel, 2011).

For example, PLGA nanoparticles that contain antibiotics have antibacterial characteristics that last a long time. This means that people don't need to take increasing doses or develop resistance (Cherreddy et al., 2013).

According to Danhier et al. (2012), these carriers make labile antimicrobials more stable and easier for the body to use, stopping them from breaking down too soon before they reach their target.

2.4.3. Advantages and Challenges of Polymeric Nanoparticles

Polymeric nanocarriers offer controlled and targeted antimicrobial delivery, lower systemic toxicity than free drugs, facile surface functionalisation for multifunctionality, and complete biodegradability (Esfanjani & Jafari, 2016). Challenges include complex synthesis, batch-to-batch variability in release kinetics, and the need to confirm safety and biocompatibility at effective concentrations (Danhier et al., 2012). Additional research is required to optimise formulations and scale-up production for widespread use.

2.5. Comparative Analysis of Antimicrobial Nanoparticles

Table 1 summarises key parameters for the metallic, metal-oxide, and carbon-based nanoparticles discussed in Sections 2.1–2.3—minimum inhibitory-concentration (MIC) ranges, activity against Gram-positive and Gram-negative bacteria, ROS-generation capacity, mammalian-cell toxicity, and industrial-scale cost. Polymeric nanoparticles (Section 2.4) are excluded because their primary function—encapsulation and controlled release differs fundamentally from the direct antimicrobial modes of inorganic and carbon-based nanomaterials.

Table 1. Comparative Analysis of Antimicrobial Nanoparticles Based on Key Functional and Practical Parameters

Nanoparticle Type	MIC Range*	Activity Against Gram+/Gram- Bacteria	ROS Generation Potential	Cytotoxicity to Mammalian Cells	Cost & Industrial Scalability
AgNPs (Silver)	1–10 µg/mL	Strong against both; more effective on Gram–	High	High at >10 µg/mL	Expensive; limited scalability
CuNPs (Copper)	10–50 µg/mL	Broad-spectrum; effective on both types	High	Moderate to high	Moderate cost; scalable
ZnO NPs (Zinc Oxide)	25–100 µg/mL	Effective on both; especially Gram+	Moderate to high	Low to moderate	Low cost; highly scalable
AuNPs (Gold)	5–50 µg/mL	Broad but less ROS-dependent; Gram– preferred	Low to none	Low to moderate	Very expensive; low scalability
SeNPs (Selenium)	10–40 µg/mL	Effective; works on MDR strains	Moderate (controlled)	Low toxicity profile	Moderate cost; emerging scale
MgO NPs (Magnesium Oxide)	100–250 µg/mL	Preferentially Gram–; moderate on Gram+	Moderate	Low	Very low cost; easy to scale
TiO ₂ NPs (Titanium Dioxide)	Variable; UV-dependent	Broad-spectrum under UV; Gram+ > Gram–	Very high (UV-activated)	Low, but depends on UV dose	Low cost; scalable with limitations
GO (Graphene Oxide)	50–200 µg/mL	Broad-spectrum; more effective on Gram–	Low to moderate	Moderate at high concentrations	Moderate cost; scalable
CNTs (Carbon Nanotubes)	10–100 µg/mL	Broad-spectrum; more effective on Gram–	Low to moderate	Moderate to high at high concentrations	High cost; moderate scalability

Notes:

- *MIC values are approximate and context-dependent, varying with the target organism, formulation, and synthesis method (Kim et al., 2007; Emami-Karvani & Chehrizi, 2011; Akhavan & Ghaderi, 2010; Liu et al., 2009).

- Data for GO and CNTs are derived from studies evaluating their antimicrobial activity in aqueous suspensions or polymer composites (Hu et al., 2010; Vecitis et al., 2010).
- Polymeric nanoparticles (e.g., chitosan, PLGA) are not included due to their unique mechanisms, such as controlled release, which differ from the direct biocidal action of inorganic and carbon-based nanomaterials.
- This comparison looks at effectiveness, safety, and ease of use. AgNPs and CuNPs destroy bacteria, but they also hurt cells. But ZnO and MgO NPs are less expensive and safer. Nanomaterials are made of carbon. There are both physical and chemical processes involved in GO and CNTs. But they need to be focused correctly to avoid hurting cells. These insights help us choose nanomaterials for use in medical devices and food packaging because they are safe and work well.

3. Mechanisms of Antimicrobial Action

Biogenic metal nanoparticles affect how bacteria work by using physical, chemical, and ionic means, which makes them antibacterial. These are the things that happen: ROS production, membrane damage, metabolic disruption, and stopping DNA and protein synthesis. Gold (AuNPs), silver (AgNPs), zinc oxide (ZnO NPs), and copper (CuNPs) are all metals that kill microorganisms. Their unique and synchronized tactics are emphasized.

3.1. General Mechanisms of Antimicrobial Action

Metal nanoparticles induce oxidative stress by producing reactive oxygen species, including hydroxyl radicals ($\bullet\text{OH}$), superoxide anions (O_2^-), and hydrogen peroxide (H_2O_2). Stress destroys proteins, lipids, and DNA, which kills microbes (Das et al., 2017; Lemire, 2013). When exposed to light or oxygen, wide-surface nanoparticles catalyze more reactions, generating ROS.

Nanoparticles physically break down the plasma membrane of microbes, modifying how permeable and potential it is. This interaction can cause structural problems that let things leak out of cells and break them down (Sondi & Salopek-Sondi, 2004).

Electrostatic attraction between positively charged nanoparticles and negatively charged cell membranes enhances adhesion and subsequent membrane destruction (Shrivastava et al., 2007).

Penetration of nanoparticles releases metal ions, further contributing to antimicrobial activity. These ions react with sensitive cellular targets.g., thiol groups ($-\text{SH}$) in proteins, inhibiting enzymatic activity, or phosphorus- and sulfur-containing bases in DNA, thereby disorganising replication and transcription (Prabhu & Poulouse, 2012;

Kim et al., 2009). The concurrent action of these mechanisms diminishes the likelihood of resistance development by attacking multiple cellular pathways.

Important Insight. Even though AgNPs are very effective, their MIC values can vary up to one log from study to study. This is mostly because of the way they are made and the coating on their surfaces. According to comparative trials, PVP-coated AgNPs need doses that are about 40% higher than those of citrate-stabilized AgNPs to get the same log-reduction (Kim et al., 2007). Standardising surface chemistry is crucial for converting laboratory effectiveness into commercial packaging.

3.2. Specific Mechanisms of Key Metal Nanoparticles

3.2.1. Silver Nanoparticles (AgNPs)

Silver nanoparticles (AgNPs) exhibit a broad spectrum of antimicrobial activity via multiple mechanisms, summarised, which show AgNP interactions with bacterial constituents. AgNPs attach to the bacterial cell membrane, causing structural damage, increased permeability, and leakage of cellular contents that kill the cell (Sondi & Salopek-Sondi, 2004). This effect is augmented by electrostatic interactions between positively charged AgNPs and negatively charged membranes (Shrivastava et al., 2007).

After entry, AgNPs interfere with DNA replication and protein production. Released Ag⁺ binds to thiol groups in respiratory enzymes, leading to bioenergetic dysfunction and ATP depletion (Prabhu & Poulouse, 2012; Du et al., 2012). AgNPs also generate ROS, promoting oxidative stress that damages mitochondria, proteins, and the electron-transport chain (Das et al., 2017). Figure 1 illustrates these mechanisms:

- Inhibition of DNA replication
- Damage to cellular proteins and leakage
- Mitochondrial dysfunction
- Membrane destruction
- Direct nanoparticle entry
- Disruption of the electron-transport chain

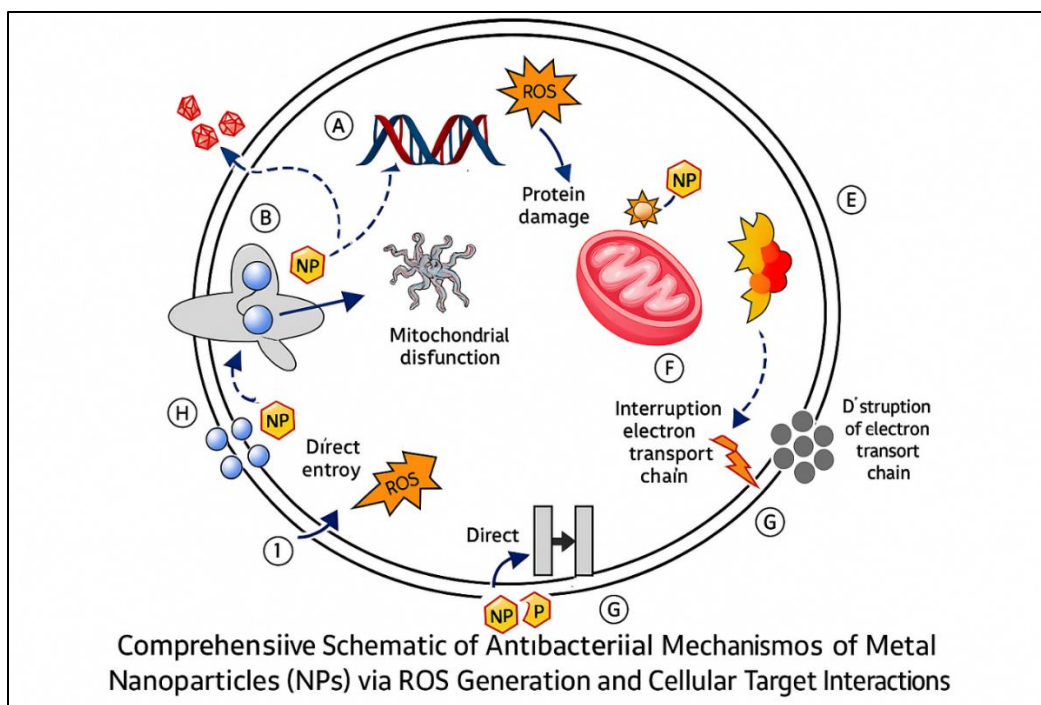


Figure (1): Comprehensive Schematic of Antibacterial Mechanisms of Metal Nanoparticles (NPs) via ROS Generation and Cellular Target Interactions

3.2.2 Gold Nanoparticles (AuNPs)

Most bactericidal mechanisms of AuNPs are non-oxidative, setting them apart from ROS-mediated NPs. Bacterial energy production is disrupted because AuNPs block F-type ATP synthase, decreasing the proton-motive force and ATP levels (Cui et al., 2012; Zharova & Vinogradov, 2004). AuNPs also suppress protein synthesis by inhibiting binding of tRNA to ribosomal subunits, arresting translation and causing cell death (Cui et al., 2012). These mechanisms act against multidrug-resistant Gram-negative organisms.

In fungi, AuNPs target plasma-membrane proton pumps (H^+ -ATPase), altering ion and pH homeostasis, interfering with metabolism, and leading to cell death (Ahtyngad et al., 2013). schematically illustrates AuNP interaction with fungal cell walls and membranes, showing pump inhibition and membrane rupture. Reduced ROS formation underlies the high biocompatibility of AuNPs compared with other metal nanoparticles (Cui et al., 2012).

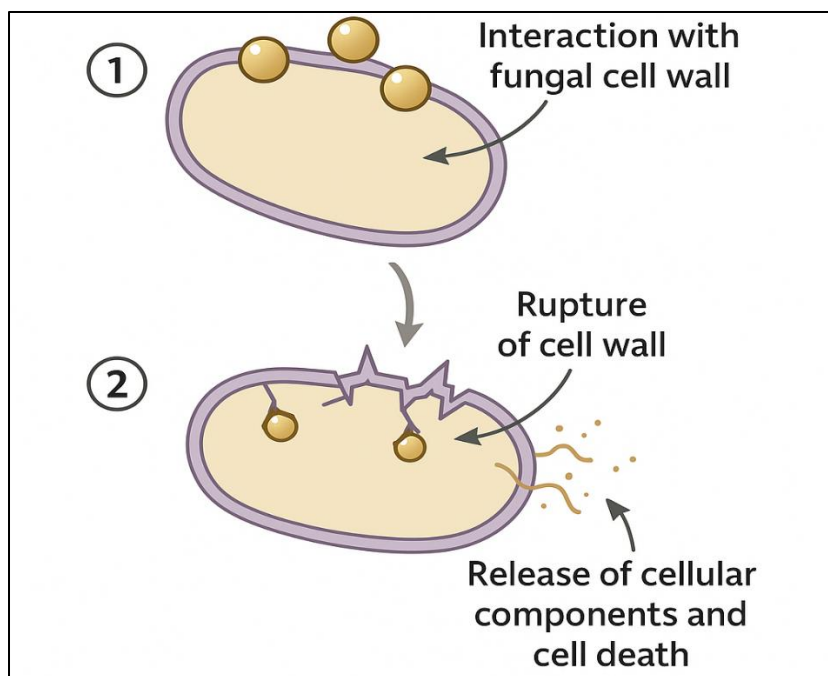


Figure (2): Schematic Representation of the Antifungal Mechanism of Action of Gold Nanoparticles (AuNPs) on Fungal Cell Walls and Membranes

3.2.3. Zinc Oxide Nanoparticles (ZnO NPs)

ZnO NPs exhibit both oxidative and ionic antimicrobial mechanisms. Under UV or visible light, they generate ROS (H_2O_2 , $\bullet\text{OH}$, O_2^-), which oxidise lipids, proteins, and DNA (Sawai, 2003; Liu et al., 2008). Concurrently, Zn^{2+} ions released from the particle surface bind to cell-wall components and intracellular enzymes, destabilising membranes, inhibiting metabolic activity, and blocking DNA replication (Atmaca et al., 1998; Xie et al., 2011). Reduced particle size increases surface reactivity and ion release, enhancing efficacy against pathogens such as *E. coli*, *Listeria monocytogenes*, and *Salmonella* spp.

3.2.4 Copper Nanoparticles (CuNPs)

CuNPs act through both chemical and physical pathways. Cu^{2+} -mediated ROS production damages DNA, proteins, and lipids (Shende et al., 2015; Ren et al., 2009). Cu^{2+} also binds sulfhydryl groups ($-\text{SH}$) of enzymes, inactivating them and disrupting vital functions. Local changes in pH and conductivity further destabilise microbial membranes, causing leakage of intracellular components (Ren et al., 2009). Direct contact between CuNPs and cell envelopes—especially the thinner wall of Gram-negative bacteria—amplifies membrane damage (Xiong et al., 2015). Together, ROS generation, ionic toxicity, and membrane disruption provide broad-spectrum activity.

3.3. Importance of Multifaceted Mechanisms

Metal-nanoparticle antimicrobial action combines oxidation, membrane damage, metabolic interference, and ion release. Simultaneous inhibition of several cellular processes increases efficacy and lowers the risk of resistance compared with most conventional antibiotics, which usually target a single pathway. This multifaceted nature makes nanoparticles attractive for food packaging, medical devices, and other antimicrobial applications.

4. CONCLUSION

This review highlights the potential of metallic, metal-oxide, carbon-based, and polymeric nanoparticles for incorporation into food-packaging structures. Their modes of action include ROS generation, membrane disruption, and inhibition of DNA replication and protein synthesis. Silver nanoparticles (AgNPs) show outstanding efficacy but require careful dose control owing to cytotoxicity at high concentrations. Copper (CuNPs) and zinc-oxide (ZnO NPs) provide cost-effective, less-toxic alternatives; ZnO is already GRAS-listed for food contact. Gold (AuNPs) and selenium (SeNPs) offer advantages against multidrug-resistant strains, while magnesium-oxide (MgO NPs) and titanium-dioxide (TiO₂ NPs) have niche environmental applications. Carbonaceous nanomaterials (GO, CNTs) act by physical disruption, whereas polymeric nanoparticles (e.g., chitosan, PLGA) enable sustained antimicrobial release.

Embedding these nanoparticles in biopolymer or synthetic matrices can improve food safety and extend shelf life, helping to mitigate food-borne disease worldwide. The remaining challenges include comprehensive toxicological assessment, scalable green synthesis, and harmonised regulation. Addressing these issues will pave the way for safe, widespread use of nanoparticles as sustainable, potent antimicrobial solutions in food preservation and beyond.

4.1. Restrictions and Future Obstacles

Nanoparticles have been shown to work well in antimicrobial applications, but there are still some problems that make it hard for them to be used widely. To begin with, toxicity to human cells is still a big worry, especially when silver, copper, and carbon-based nanomaterials are present in large amounts. Regulatory bodies still do not have unified safety limits for long-term exposure to materials that meet food.

Second, the ability of things to build up in the environment and break down raises questions about their long-term effects on the environment. Metal-based nanoparticles may remain in ecosystems, impacting microbial flora and aquatic organisms.

Third, scalability and cost are problems that make it hard to use these in industry. ZnO and MgO are not too expensive, but nanoparticles made of noble metals like gold and silver are still too expensive for everyday use.

Fourth, there is not enough standardisation and reproducibility in the process of making nanoparticles. Differences in size, shape, surface coating, and aggregation state can have a big effect on how well an antimicrobial works, making it hard to compare studies.

Finally, microbial resistance to nanoparticles is a growing worry. Adaptive responses to extended nanoparticle exposure are infrequent but documented, necessitating strategies that integrate nanomaterials with alternative antimicrobials to mitigate resistance development.

Future research should focus on biocompatible formulations, environmentally friendly synthesis methods, and thorough toxicological evaluations to strike a balance between effectiveness and safety. To make sure that antimicrobial nanoparticles can be safely used in real-world applications, there needs to be a coordinated regulatory framework.

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