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Antimicrobial nanoparticles: a new horizon to combat multidrug-resistant bacteria

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Antimicrobial nanoparticles (NPs) exhibit revolutionary potential against infections due to their unique physicochemical properties that enhance antimicrobial activity. Antimicrobial NPs employ various mechanisms and pathways, including ROS generation, cell membrane disruption, DNA and protein damage, interference with metabolic pathways, and the electron transport chain, that eventually lead to microbial cell death. They are more beneficial than conventional antibiotics and have broad-spectrum efficacy with lower risk of resistance. Specifically, antibacterial NPs have a wide range of applications in various fields, such as food safety (e.g., antimicrobial packaging), water purification, healthcare (e.g., wound healing, coatings on medical devices), agriculture (e.g., disease management, plant protection), and industrial products (e.g., textiles, personal care items). Despite their promising potential, challenges such as toxicity, environmental impact, and regulatory limitations remain critical for their sustainable use. This review aims to provide the critical insight into various antibacterial NPs applications, mechanisms of action, and future scope, highlighting their potential prospects for safe and optimal use.

KEYWORDS

nanoparticle (NPs), multiple drug resistance (MDR), minimum inhibitory concentration (MIC), nanotherapeutics, reactive oxygen species (ROS)

1 Introduction

Types of nanoparticles with increasing multidrug-resistant (MDR) bacteria generate a serious concern in modern medicine, significantly reducing the efficacy of antibiotics. The major cause of MDR bacteria is the overuse of antibiotics; to combat such a problem, it is necessary to explore alternative strategies. Consequently, it is anticipated that if research on novel medications does not advance, it will be impossible to treat such antibiotic-resistant bacteria until 2050 (Bharadwaj et al., 2022; Ahmed et al., 2024; Almutairy, 2024).

Amid this serious concern, NPs have emerged as promising antimicrobial agents (Ogunsona et al., 2020; Yılmaz et al., 2023). The unique physicochemical properties of NPs, such as high surface-area-to-volume ratio, ability to disrupt bacterial cells, tuneable reactivity, etc., make them an effective antibacterial method. In general, traditional antibiotics work on target-specific molecular pathways, whereas NPs are known for their broad-spectrum antimicrobial activity via interaction with the bacterial cell membrane, adsorption through the cell wall, generation of reactive oxygen species, interference with intracellular components, and modulation of essential molecular pathways (Thapa and Choudhury, 2021; Shoudho et al., 2024; Ali et al., 2025).

Various NPs exhibit antimicrobial abilities, such as metallic NPs, carbon-based NPs, polymeric NPs, and hybrid NPs (Jessop et al., 2021; Tirkey et al., 2022; Bhattacharyya et al., 2023; Zhang et al., 2024; Shenasa et al., 2025; Zare et al., 2025). Metallic NPs such as silver (AgNPs) (Bruna et al., 2021; Sati et al., 2025), copper (CuNPs) (Ortega-Nieto et al., 2023; Banerjee et al., 2024; Bozhkov et al., 2024), and zinc oxide (ZnONPs) (Singh et al., 2018; Arun et al., 2020; Thakral et al., 2021; Eskani et al., 2023) have potent antibacterial properties and can disrupt bacterial cells by generating reactive oxygen species. Additionally, polymeric NPs and carbon-based NPs offer controlled drug release and biofilm penetration ability, which are crucial for treating chronic infections. Moreover, to improve biocompatibility and enhance target bacterial eradication, NPs can be modified accordingly, such as by modifying surface chemistry, which may influence the conjugation frequency and biochemical pathways (Habibullah et al., 2022; Shoudho et al., 2024). Furthermore, green synthesis NPs are proven effective antibacterial agents when compared to traditional methods; green-synthesised NPs are less harmful to the environment and use less energy. Large-scale applications are, however, constrained by differences in size, stability, and repeatability. With lower health and environmental concerns and cost-effectiveness, green synthesis offers a sustainable substitute for traditional chemical processes. For wider applications, more research on standardising procedures and enhancing yield and purity is essential (Ying et al., 2022; Banjara et al., 2024). As interest in employing smart nanoparticles to manage microbial illnesses has grown, research on nanomaterials with antimicrobial qualities has increased dramatically during the past decade. This demonstrates the field's widespread appeal as well as its room for further research (Hu et al., 2020; Dop et al., 2023; Chen et al., 2025; Qiao et al., 2022).

Despite their wide range of potential, the clinical application of nanoparticles (NPs) remains arbitrary due to concerns about cytotoxicity, possible resistance, and stability. NP optimisation for successful antibacterial applications requires further research (Składanowski et al., 2016; Li et al., 2018; Pulingam et al., 2021). Therefore, the development of safer and more effective antimicrobial agents requires detailed knowledge of the interaction of NPs with microbial systems at the molecular level. To combat resistance, understanding of toxicity reduction, dose optimisation, and synergistic usage with already available antibiotics is necessary. In light of this, this review aims to present a detailed analysis of the various NPs' modes of action, antibacterial effectiveness, obstacles to their clinical translation, and potential future uses in the fight against multidrug-resistant bacteria.

1.1 Metal-based NPs for antimicrobial action

Metallic NPs are well known for their unique antimicrobial activity, which makes them suitable for pharmaceuticals and healthcare sectors. However, not all NPs are effective against disease-causing pathogens (Bankier et al., 2019; Duval et al., 2019). Metallic NPs, derived from noble metals like gold, silver, and copper, have gained prominence in recent years due to their various benefits (Maruthupandy et al., 2017; Sharma et al., 2019; Karimadom and Kornweitz, 2021). These NPs are used in catalysis, composites, disease diagnosis, sensor technology, and optoelectronic labelling (Serna-Gallén and Mužina, 2024). Different methods, including electrochemical changes, chemical reduction, and photochemical reduction, are used for their preparation and stabilisation (Jamkhande et al., 2019). The use of metallic NPs is increasing worldwide in biomedicine and related disciplines. Various examples were reported of antibacterial NPs such as AgNPs, known for their antimicrobial activity against *Staphylococcus aureus* and *Pseudomonas aeruginosa* and its antimicrobial activity are significantly increased when it is used in combination with tungsten carbide and copper NPs (Bankier et al., 2019). Metallo-antimicrobials lower the likelihood of resistance development by providing potential multi-targeted ways to address antimicrobial resistance (AMR). To further their clinical translation, it is still imperative to improve their delivery and selectivity (Wang C et al., 2025). They provide a viable avenue for the development of targeted and multipurpose antibacterial treatments for oral health. The suggested hierarchical structure offers a useful starting point for directing further investigation and the logical development of next-generation anti-infective compounds (Qi et al., 2025). By improving medication delivery, reducing side effects, and specifically targeting various injured organ regions, they provide a potential new avenue for disease treatment. Their ability to serve several purposes provides a revolutionary method of treating many cardiovascular conditions (Haji, 2025). Below are more metallic NPs illustrated with their antibacterial activity.

1.1.1 Silver NPs (AgNPs): pathogen disruption via ROS

AgNPs provide exclusive optical, electronic, and chemical properties. The relationship between physicochemical activity and toxicity of silver NPs and their shapes, such as sheets (Zhang et al., 2013), mats (Abdelgawad et al., 2014), rods (Zhang and Yin, 2013), and beads (Nazari and Kashi, 2021), etc., is continuously explored for proper understanding of the antibacterial activity. The antibacterial property and the extent of its toxicity are largely affected by the size; the smaller the size of NPs, the higher the toxicity (Fredj et al., 2008; Zhou et al., 2012; Chernousova & Epple et al., 2013). The combination of polymer with metallic NPs provides modified optical activity and microelectronic and photoelectronic chemistry. AgNPs' antimicrobial activity is enhanced against carbapenemase and β-lactamase-producing *Enterobacteriaceae* specifically when used in combination with ciprofloxacin, gentamicin, ceftazidime, cefotaxime, and meropenem (Panáček et al., 2016).

AgNPs generate free radicals and reactive oxygen species (ROS) that trigger apoptosis, which kills cells and stops them from replicating. AgNPs infiltrate into cells and breach the cell wall because they are smaller than the bacteria. Additionally, it has been demonstrated that smaller NPs are more harmful than larger ones. AgNPs are also utilised in packaging to stop bacteria from destroying food items (Siddiqi et al., 2018).

Consequently, the preparation of AgNPs for antimicrobial activity has become an ongoing research focus. They can be prepared by various means, such as plants, microorganisms, marine organisms, etc. NP biosynthesis is currently recognised as a new field of study in nanoscience. Because of the numerous uses of AgNPs in nonlinear optics, spectrally selective coating for solar energy absorption, bio-labelling, intercalation materials for electrical batteries, optical receptors, catalysts in chemical reactions, and antibacterial materials in food and pharmaceutical production, biosynthesis of silver NPs is receiving more attention (Philip et al., 2011). Synthesis of NPs can be achieved by various methods, for example, physical, chemical, and biological methods (Samadi et al., 2010; Gholami-Shabani et al., 2014). For the synthesis of AgNPs, the physical method is based on laser burning, gas-phase deposition, ion sputtering, etc., but the size of NPs is quite larger than the NPs synthesised from chemical and biological methods. The NPs synthesised from chemical and physical methods are less environmentally friendly than biological methods. Quintero-Quiroz et al. synthesised silver NPs through chemical reduction and evaluated their antimicrobial activity against *Staphylococcus aureus* and *Escherichia coli* (Quintero-Quiroz et al., 2019). Maiti et al. synthesised silver NPs using an eco-friendly approach with *Lycopersicon esculentum* (red tomato) extract. And test its antimicrobial activity with a minimum inhibitory concentration (MIC) of AgNP of about 50 μg/mL (Maiti et al., 2014). The extract of *Lysiloma acapulcensis* can reduce silver to AgNPs, and these NPs show enhanced antimicrobial activity (Garibo et al., 2020). The AgNPs synthesised from the extract and the peel of *Annona muricata* show effective antimicrobial activity against *S. aureus, E. faecalis, E. coli, and C. albicans* in culture (González-Pedroza et al., 2024). AgNPs having strong antibacterial activity against both Gram-positive and Gram-negative bacteria, including those resistant to antibiotics, are produced biogenically. Additionally, Pernas-Pleite and colleagues' study demonstrated their synergistic effects with other antibiotics and proposed a number of processes, including the generation of ROS, that contribute to the death of bacteria (Pernas-Pleite et al., 2025). They also offer wound-healing efficacy, for example. Strong antibacterial efficacy against *S. aureus, E. coli,* and *P. aeruginosa* is demonstrated by AgNPs, which have an average size of 24.3 nm and are biocompatible with fibroblast cells. 90% wound re-epithelialisation and increased fibroblast production were encouraged by AgNP therapy *in vivo*, suggesting efficient bacterial control and tissue regeneration. These results prove the AgNPs' potential as a topical, scalable treatment for infected wounds (Baveloni et al., 2025). The antibacterial activity of positively charged quercetin-coated silver NPs (Que@AgNPs) against *S. aureus* and *E. coli* is greater than that of uncoated AgNPs, and this activity is further enhanced in complexes with lysozyme or γ-globulin. These proteins and Que@AgNPs interact through hydrophobic or electrostatic forces as well as static quenching, which alters the proteins' structural makeup and chemisorption kinetics (Li et al., 2025). *Bacillus vietnamensis*, which was isolated from marine soil, was used to synthesise AgNPs intracellularly. Bacterial nitrate reductase helped reduce Ag^+ to Ag^0. *Salmonella* sp., *Klebsiella* sp., *Escherichia coli,* and *Micrococcus flavus* were among the clinical pathogens against which the biosynthesised AgNPs had strong antibacterial action. These results demonstrate the potential of biologically produced, marine-derived AgNPs as strong, environmentally benign antibacterial agents with uses in biomedicine and nanobiotechnology (Aswini et al., 2025).

1.1.2 Gold NPs (AuNPs): targeted antiviral applications

AuNPs have become effective nanoplatforms in antiviral treatment because of their easy surface functionalisation and special physicochemical characteristics. With the continuous increase of various pathogens, the need of low toxic and tenable antibacterial agents is also increasing (Wang L et al., 2020). AuNP biogenesis has been extensively researched and documented. An active search for novel compounds with antibacterial capabilities or a new type of antibiotics with effective action is essential. Consequently, additional research is being done on the antibacterial properties of AuNPs functionalized with natural chemicals. AuNPs that have been functionalized with plant-derived bioactive chemicals or biosynthesized using plant extract seem to be helpful in medicinal approaches (Timoszyk and Grochowalska, 2022). Both NPs and ionic forms of gold show effective antibiotic activity, specifically Au in I&II form. These AuNPs are also used as a delivery vehicle for antibiotics (Zhang et al., 2015). Sathiyaraj et al. synthesized the gold NPs (PG-AuNPs) using the panchagavaya and evaluated the antibacterial activity against *Klebsiella pneumoniae, Escherichia coli,* and *Bacillus subtilis.* Their research concludes that there is more efficient activity against gram-negative bacteria than gram-positive bacteria (Sathiyaraj et al., 2021).

The gold NPs were prepared from the extract of *Galaxaura elongata* also effective against *K. pneumonia*e *and E. coli* (Abdel-Raouf et al., 2017). An envelope that may include proteins, lipids, phenolic acids, flavonoids, vitamins, and carbohydrates stabilizes the biosynthesized AuNPs. The stability and its interaction mechanism with pathogens are also determined by its coating (Timoszyk and Grochowalska, 2022). The coating of AuNPs with thiol and amine-tethered phenylboronic acids is potent coating agent for AuNPs and increases Gram bacteria selectivity (Wang L et al., 2020). In comparison to medium-chain (AHT) modified AuNPs, ultrasmall gold NPs modified with short (APT) and long (AUT) aminopropylthiol ligands shown greater antibacterial activity against *S. aureus* and *E. coli,* according to research by Yao and colleagues. This discrepancy was explained by increased membrane adsorption, which increased ROS production and membrane disruption (Yao et al., 2025). Similarly, a study, star-shaped gold NPs (AuNSTs) with an average size of 48 nm were synthesised. They exhibited intense absorption of visible light (maximum at 685 nm) and effective photocatalytic degradation of rhodamine B dye (up to 94% in 135 min at pH 9), which was ascribed to improved charge transfer and electrostatic interactions. Furthermore, with low MIC values and considerable inhibitory zones, AuNSTs demonstrated noteworthy antibacterial activity against *Staphylococcus aureus* and *Escherichia coli,* underscoring their potential for dual antimicrobial and environmental applications (El-Khawaga et al., 2025). Adding to this, 5-A-2MBI_Au gold NPs, shows strong antibacterial action against gram-negative bacteria resistant to carbapenem. The NPs exhibit oxidative stress disruption, ROS production, improved membrane permeability, and reduced MIC (Zhang et al., 2025).

1.1.3 Zinc oxide NPs (ZnONPs): photocatalytic pathogen control

ZnONPs effectively combat microbial infections by generating reactive oxygen species through photocatalysis, offering a sustainable approach to light-activated pathogen control. One of the biggest problems facing world healthcare is the emergence of microorganisms that are resistant to antibiotics. Using metal NPs and their oxides is a potential strategy for combating microbial resistance. Numerous investigations have shown that ZnONPs have excellent antibacterial activity against both gram-positive and gram-negative bacteria (Gudkov S. V. et al., 2021). ZnONPs and microparticles, created using chemical and physical techniques, exhibit strong antibacterial activity and are potent in combating *Staphylococcus aureus* and *Escherichia coli* due to their large specific surface area. ZnO hollow spheres also suppress bacterial growth, with *S. aureus* being more vulnerable to ZnO particles (Babayevska et al., 2022). Similarly, green synthesised ZnONPs from *Phlomis* leaf extract as a reducing agent are efficient against microbes. The characterisation by various techniques, including UV-Vis spectrophotometry, FTIR, XRD, DLS, zeta potential, and FESEM, of the ZnONPs showed a crystalline structure, no cytotoxicity on L929 normal cells, and significant antibacterial activity efficiently against *S. aureus* and *E. coli* (Alyamani et al., 2021). Similarly, ZnO NPs can be green synthesised from various sources such as *Ficus carica* latex (Al-darwesh et al., 2024), *Allium sativum* extract (Al-Badaii et al., 2024), *Vernicia fordii seed extract* (Chamaraja et al., 2023), *clove (Syzygium aromaticum)* (Elbagory et al., 2022), *Capparis spinosa* extract (Sezen et al., 2023), *Simarouba glauca* leaf extract (Prashanth et al., 2025), etc.

Furthermore, Riahi and colleagues report that the ZnONPs synthesised from the sol-gel technique can be an effective antibacterial agent against *Escherichia coli*, Klebsiella pneumoniae wild type, *Klebsiella pneumoniae*, methicillin-sensitive *Staphylococcus aureus* (MSSA), and methicillin-resistant *Staphylococcus aureus* (MRSA) (Riahi et al., 2023). If the various sources of obtained chitosan are used in the sol-gel synthesised ZnONPs as a capping agent, they show differential antibacterial activity against *Staphylococcus aureus*, *Listeria innocua*, *Salmonella typhimurium*, *Bacillus subtilis* and *Pseudomonas aeruginosa* (Ben Amor et al., 2022). Moreover, green synthesised ZnO NPs prepared from *plantain* peel extracts demonstrate effective antibacterial activity with an MIC value of about 100 μg/mL in the following sequence: *S. aureus, B. cereus, K. pneumoniae, S. enterica* (Imade et al., 2022). Hexagonal ZnONPs modified from the wet chemical method and decorated with Ag and Cu NPs combinedly meet the optical properties effective for long-lasting antibacterial activity (Geioushy et al., 2024). Similarly, ZnO NPs are effective against various microbes such as *Propionibacterium acnes* (Al-Momani et al., 2024), *Staphylococcus aureus*, *Escherichia coli*, *Pseudomonas aeruginosa* (Rezaei et al., 2024), *Klebsiella pneumoniae* (Al-Badaii et al., 2024), etc.

1.1.4 Copper oxide NPs (CuONPs)

CuONPs have gained significant attention in therapeutics because of their physicochemical properties, such as catalytic activity and chemical and physical nature. CuONPs can be synthesised from various methods such as vapour deposition, liquid phase, sol-colloidal, electrodeposition gel, etc. (Dörner et al., 2019; Ma et al., 2019; Faisala et al., 2022; Patel et al., 2022). However, the hazardous effect of these NPs remains a concern, and to address these limitations, green-synthesised CuONPs have been employed (Naz et al., 2020; Bouafia et al., 2020). Previous reports suggest that these NPs have antibacterial properties and are also effective against MDR bacteria such as *Staphylococcus aureus* as well as biofilm bacteria (Mohamed et al., 2021; El-Sherbiny et al., 2022). Various conjugations with these NPs are also effective as antibacterial agents, for instance. Ibne Shoukani and a colleague green synthesised the CuONPs using *Moringa oleifera* root extract and prepared a CuONP fabricated into a form of aspartic acid-ciprofloxacin-polyethylene glycol coated with copper oxide nanotherapeutics, and the formulation was called CIP-PEG-CuO, which shows enhanced antibacterial activity and completely eradicates *Staphylococcus aureus* from infected skin and shows efficient wound-healing properties (Ibne Shoukani et al., 2024a). Similarly, CuONPs conjugate with AuNPs showed effective MIC for *S. aureus, S. typhi,* and *E. faecalis*, i.e., 62.5 μg/mL, 62.5 μg/mL, and 31.25 μg/mL, respectively (Alghonaim et al., 2024). Similarly, Mosleh et al. report that Ag-doped CuONPs are effective against various human pathogens with an MIC of 100–120 μg/mL (Mosleh et al., 2024). Moreover, chitosan and curcumin-capped CuO nanostructures are effective against MDR microorganisms, and lipase-CuONPs show enhanced antibacterial activity (Elkattan et al., 2025; Handak et al., 2025). Recent reports also claim that these NPs are not only effective against bacteria but also inhibit viral infections (Jayaramudu and Kokkarachedu, 2024; Shehabeldine et al., 2025).

1.1.5 Other metal oxide NPs

Similarly, other metal oxide nanoparticles (MeO-NPs) have prospective uses in sensing, energy storage, information technology, medicine, and catalysis. Cell membrane destruction, metal/metal ion homeostasis disruption, reactive oxygen species generation, protein enzyme malfunction, genotoxicity, signal transduction blockage, and photokilling are some of the modes of action of certain MeO-NPs, which have potent antibacterial qualities. The synthesis techniques and variables that impact MeO-NPs' antibacterial processes, emphasising the possibility of an energy-efficient preparation process and the final structural morphology for effective antimicrobial qualities. However, due to its toxicity and potential usage as a substitute for conventional antibiotics in the eradication of infectious diseases, care is urged. (Jagadeeshan and Parsanathan, 2019). Advanced nanomaterial-based therapy is becoming necessary due to bacterial infections and antibiotic resistance. Because of their biocompatibility and adjustable characteristics, metal oxides such as TiO_2, MgO, and, CaO, show promise (Abou El Fadl et al., 2023).

For instance, biocompatible nanomaterials having a variety of biomedical uses are titanium dioxide nanoparticles (TiO_2-NPs). At 1,000 μg/mL, they generally show up to 94.6% 2,2-Diphenyl-1-picrylhydrazyl and 88.2% 2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid radical scavenging, demonstrating significant antioxidant activity. They typically have spherical, crystalline structures (10–50 nm). TiO_2-NPs have strong antibacterial action, outperforming gentamicin against *Escherichia coli* and *Enterococcus faecalis*, as well as greater antifungal activity in comparison to fluconazole. Additionally, they exhibit minimal haemolytic activity, selective cytotoxicity towards cancer cells while sparing normal cells, moderate wound healing, and over 90% inhibition of bacterial and fungal biofilms, making them promising multifunctional agents for tissue repair, cancer therapy, and infection control (Ghareeb et al., 2025). Similarly, research describes the use of magnesium oxide nanoparticles (nMgO) in a 3D-printed denture base resin to give antifungal action against *Candida albicans*. The nMgO-modified resin preserved mechanical strength, stability, and biocompatibility in accordance with ISO requirements while reducing fungal growth by up to 91% and preventing the formation of biofilms. These findings demonstrate that magnesium oxide (nMgO) is a secure and efficient antibacterial addition for dental prosthesis (Xue et al., 2025).

Iron oxide is one of the groundbreaking metal oxide NPs, its superparamagnetic forms, i.e., SPIONs, have low toxicity to eukaryotic cells and strong antimicrobial activity against both Gram-positive and Gram-negative bacteria and fungi (Gudkov S. V. et al., 2021). They can be produced chemically, environmentally, or biosynthetically, such as using plant extracts or β-cyclodextrin, and they can be used as antifungal agents, drug carriers, and imaging (Antony et al., 2020; Almutairi et al., 2023; Abedini et al., 2024). These NPs have the potential against multidrug-resistant pathogens like *Klebsiella pneumoniae* through improving bacterial inhibition via controlled drug release, magnetic hyperthermia, and antibiofilm activity (Álvarez et al., 2022; Kadhim and Aldujaili, 2025). They are eco-friendly NPs with diverse biomedical and environmental utility.

1.2 Carbon-based NPs for sensing and defense

The significant antibacterial activity of carbon-based nanomaterials stems from their remarkable physicochemical and structural features, as well as their comparatively high biocompatibility and ecologically benign nature. One of the most prevalent elements in the crust of the Earth is carbon. Diverse CNMs are produced by the diverse ways that carbon atoms link with one another to generate distinct allotropes of carbon. 0D fullerene, carbon dots (CDs), graphene quantum dots (GQDs), nanodiamonds (NDs), 1D carbon nanotubes (CNTs), 2D graphene and its variants, and graphitic carbon nitride (g-CN), nitrogen-rich graphene-like nanostructure, are among them. Sp2 hybridized carbon atoms make up the majority of fullerenes CNTs, and graphene (and its derivatives); NDs are primarily composed of sp3 hybridized carbon atoms; CDs and GQDs contain a mixture of sp2 and sp3 hybridized carbon along with defects and heteroatoms; and g-CN is made up of π-conjugated graphitic planes created by sp2 hybridization of carbon and nitrogen atoms (Georgakilas et al., 2015).

The previous report concludes that CNMs with varying dimensionalities exhibit notable changes in their antibacterial activity and mode of action when compared to CNMs with similar orbital hybridization of carbon atoms. Similarly, additional factors including lateral size, shape, number of layers, surface charge, the presence and kind of surface functional groups, and doping are discovered to affect the antibacterial activity of CNMs of a specific dimensionality (Zou et al., 2016; Al-Jumaili et al., 2017; Karahan et al., 2018). The particular preparation techniques also affect these physicochemical characteristics. CNMs with various physicochemical properties are made up of 60 sp2 carbon atoms grouped into a spherical shape using 20 hexagons and 12 pentagons (Qiao et al., 2007). The synthesis of GQDs and CDs, which are smaller than 20 nm and have thicknesses between 0.5 and 2 nm, can be done top-down by cleaving or breaking up a carbonaceous substance, or bottom-up by pyrolysing or carbonising tiny organic molecules (Sun et al., 2013). GQDs and CDs have many similar characteristics, such as high-intensity fluorescence and peroxidase-like activity, but can be distinguished from each other by their crystallinity, surface area, and number of layers. When compared with GQDs, CDs, which are composed of stacked multilayers, have lower crystallinity and smaller specific surface area (Zhu et al., 2015; Shen et al., 2012). This section discusses various antibacterial mechanisms in CNMs, focusing on their physicochemical properties. The bacterial outer membrane, crucial for cell shape, osmotic regulation, and infection control, can be damaged, leading to dysfunction and cytoplasmic leakage, resulting in bacteriostatic and bactericidal effects.

When exposed to *Escherichia coli*, 0D CNMs can break down the cell wall of bacteria, including carboxylated NDs, which have antibacterial properties (Chatterjee et al., 2015). Through hydrogen bonding and electrostatic interactions, positively charged CDs, such as spermidine CDs, can attach to peptidoglycans and cell membrane proteins, inhibiting membrane formation and generating synergistic membrane destabilisation (Jian et al., 2017).

Ravikumar and their colleagues' work offers a comprehensive grasp of graphene oxide's (GO) long-term antibacterial properties against *Staphylococcus aureus*. According to the research, GO uses a variety of processes, including first wrapping and trapping bacteria, then membrane penetration, and finally the generation of ROS, all of which contribute to oxidative stress, membrane leakage, and cell death. The development of these effects is validated by experimental methods such as protein analysis, ROS detection, live/dead labelling, and viability experiments. The extensive influence of GO on bacterial activities was further illustrated by proteomic data, which show notable alterations in proteins related to cell wall construction, oxidative stress management, virulence, and biofilm formation (Ravikumar et al., 2022). GO shows electrical and thermal conductivity, high mechanical strength, and outstanding biocompatibility. GO improves the characteristics of the scaffold when it is made sustainably from bio-waste materials and combined with calcium hydroxyapatite (HAp) and polycaprolactone (PCL) in a composite. In particular, GO promotes osteogenic differentiation and enhances the scaffold's antibacterial efficiency, which has been shown against *Staphylococcus aureus* and *Escherichia coli*. As such, it is an essential part of the scaffold's prospective uses in bone tissue regeneration and clinical medicine (Daulbayev et al., 2022). A durable GO-PEI-Ag nanocomposite with broad-spectrum antibacterial action against drug-resistant bacteria and fungi was synthesized which successfully inhibiting the development of biofilms while retaining minimal cytotoxicity with an effectiveness of >99% against Gram-negative bacteria and >95% against Gram-positive bacteria and fungus, the nanocomposite showed exceptional stability, long-term efficacy, and reusability. Its antibacterial method entails cytoplasmic leakage and damage to the integrity of cell membranes. These characteristics make GO−PEI−Ag a potential material for use in public health and biomedical applications, especially in the fight against resistant bacteria and biofilms (Zhao et al., 2018).

A sol-gel/ultrasound technique was used to successfully create the Ag_2S-MgO/GO nanocomposite. With peak performance under UV light, at pH 9 and a catalyst dosage of 1 g/L, it showed increased photocatalytic activity for RhB degradation. Better charge transfer and photocatalytic performance were made possible by the synergistic effects of MgO and Ag_2S NPs supported on GO, which were responsible for the increased degradation efficiency. The nanocomposite also demonstrated notable bactericidal qualities, underscoring its potential for use in antimicrobial and water treatment technologies (Wang H et al., 2020). Research suggests that GO disrupted *S. aureus* biofilm by 30%–70% at 100 μg/mL and killed 80% of intracellular bacteria at 200 μg/mL, dependent on actin polymerization. It enhances Mac-T cell viability below 250 μg/mL, with cytotoxicity only at higher doses, highlighting its antimicrobial potential and biocompatibility (Saeed et al., 2023). Carbon-based NPs fullerol (hydroxylated C60), two fullerenes, can generate ROS. In microbial growth media, fullerol produces superoxide and singlet oxygen. PVP/C60 produced these ROS more effectively. These characteristics imply that materials based on fullerenes might be useful in concentrating on particular contaminants or microbes that are susceptible to ROS, providing possible uses in water treatment (Brunet et al., 2009). Fullerenes, a promising nanomaterial because of their antibacterial and antioxidant qualities, fullerenes, a promising nanomaterial, have drawn interest as a possible treatment for acne vulgaris, a chronic skin disorder linked to Propionibacterium acnes. However, their usage in cosmeceuticals is limited due to their low water solubility. Glycine-fullerene conjugate (Gly-Ful), a water-soluble fullerene derivative, was created and refined to get around this. To treat acne topically, chitosan-modified Gly-Ful NPs (Chi-Gly-Ful NPs) were created. According to *in vitro* experiments, Chi-Gly-Ful NPs had antibacterial activity similar to streptomycin and successfully reduced the growth of *P. acnes* at 25–400 μM doses, The Chi-Gly-Ful NPs formulation showed no signs of cytotoxicity. According to these results, Chi-Gly-Ful NPs are a safe and efficient antibacterial agent that presents a promising new therapeutic strategy for treating acne vulgaris (Ghabdian et al., 2021). A silver-deposited fullerene (Ag(I)–C60) is an efficient antibacterial agent that acts through Ag^+ release and ROS generation under light (Pan et al., 2023). The pristine surface plasmonic electrons of AgNPs increase the activity of the fullerene (C60) molecule and exhibit great toxicity against pathogens and cancer cells in the AgNPs/endo-fullerene nanocomposite (Biswas et al., 2022). Additionally, CNTs have antibacterial action against a variety of pathogens, including *Candida albicans, Staphylococcus aureus, Klebsiella pneumoniae,* and *Pseudomonas aeruginosa.* Treatment with sodium dodecyl-benzenesulfonate (SDBS) improved CNT dispersion while maintaining their structural integrity and boosting antimicrobial activity. According to UV-Vis, FTIR, TEM, and FESEM investigations, multi-walled CNTs demonstrated higher antibacterial activity than double-walled CNTs, most likely as a result of stronger cell wall contacts (Saleemi et al., 2020). Significant antibacterial activity against Gram-positive, Gram-negative, and fungal strains is produced by the improved dispersion of DWCNTs and MWCNTs functionalised with SDBS, which enables efficient contact with microbial cells. MWCNTs exhibit greater performance in this regard (Mohammed et al., 2019).

1.3 Polymeric NPs for controlled agro-delivery

Polymeric NPs range in size from 1 to 1,000 nm. They are sometimes referred to as nanocapsules or nanospheres because of their ability to trap active compounds in their core or adsorb on their surface. They may serve as a flexible medication delivery method. Nanospheres are prepared by nanoprecipitation, solvent evaporation, emulsification/solvent diffusion, emulsification/reverse salting-out, and nanocapsules by nanoprecipitation (Zielińska et al., 2020). Polymeric NPs showed minimal cytotoxicity against mammalian liver cells and were shown to prevent the production of *S. aureus* biofilms. The interaction with cysteine as a model thiol indicates that the polymeric particles may interact with cellular thiols as a possible mechanism of action against bacterial cells (Dop et al., 2023).

Previous study highlights that positively charged clindamycin/positively charged PLGA-PEI NPs increase the adherence of methicillin-resistant *Staphylococcus aureus*, enhancing wound healing and antibacterial effectiveness (Hasan et al., 2019). Moreover, some cationic NPs with embedded silver provide efficient antibacterial activity one such example is silver NPs embedded Poly[2-(*tert*-butylaminoethyl) methacrylate] (PTBAM) and silver-embedded poly (methyl methacrylate) (PMMA) nanofibers in which silver embedded PTBAM shows enhanced bactericidal performance (Song et al., 2012). With MIC and minimum bactericidal concentration against *S. aureus* values of 0.39 and 6.25 μg/mL, respectively, polyurethane nanofibers loaded with clindamycin molecularly imprinted polymeric NPs (Clin-MIP) exhibit potent antibacterial action. It displays bactericidal action within 180 min of incubation *in vitro* and dramatically reduces the bacterial count from 1 × 108 to 39 × 101 CFU/mL *in vivo* (Elhabal et al., 2024). In order to reach the infection site, negatively charged NO-PE/PLL NPs effectively penetrated the airway mucus. PLL and colistin worked in concert, lowering the MIC of colistin from 2 to 0.5 μg/mL. By taking advantage of this synergistic antibacterial action and NO-mediated biofilm disruption, NO-PE/PLL NPs were able to achieve a 99.99 percent eradication rate against *P. aeruginosa* biofilms (Yu et al., 2024).

According to recent research, poly(amino acid)-based nanoparticles created by photoinduced electron/energy transfer–reversible addition fragmentation chain-transfer polymerisation has the potential to improve drug loading efficiency and antimicrobial activity by enabling tunable antibiotic release through regulated hydrophobic, hydrophilic, and hydrogen bonding interactions (Li et al., 2024). Similarly, spherical nanoparticles with uniform size, good cellular affinity, and pH-responsive targeted release were demonstrated by three-block poly(amino acid) polymers synthesised and characterised using sophisticated techniques, underscoring their biomedical potential for efficient drug delivery (Shen et al., 2023). Furthermore, *Staphylococcus* biofilm infections in mice were completely eradicated thanks to novel poly(d-amino acid) nanoparticles that target bacterial peptidoglycan and block intracellular metabolism. These nanoparticles also effectively disassemble biofilms, disrupt extracellular polymeric substances, and greatly increase the penetration and efficacy of encapsulated antibiotics (Feng et al., 2024).

All of these developments highlight the potential of amino acid-based nanomaterials as next-generation therapeutic approaches to treat disorders linked to biofilms and resistant bacterial infections. The physicochemical characteristics, including architecture, size, shape, charge, surface functionality, and adeptness of polymeric NPs, are responsible for the effective release of therapeutic cargo

TABLE 1 Represents the examples of antibacterial activity of polymeric nanoparticles (NPs) loaded with various peptide-based drugs, as well as intrinsic antimicrobial activity exhibited by unloaded polymeric NPs.

Nanoparticles	Microbes	Loaded drug/peptide	References
Polyacrylate nanocomposites with embedded metal oxide	*B.cereus*, *S.aureus*, *E. coli*, *H. pylori*, and *C. albicans*	i-buprofen	Sobh et al. (2025)
MCIP/(PEG–PCL)/PLL (NPs	*Pseudomonas aeruginosa*	Moxifloxacin	Chen et al. (2025)
PEG-PLGA NPs	*E. faecalis*	Ciprofloxacin	Ghawanmeh (2024)
Poly (amino acid) (PAA)	*S. aureus (MRSA)*	Rifampicin (Rif)	Li et al. (2024)
Poly(lactide-co-glycolide) (PLGA), polyethylene glycol (PEG) conjugate	*P. aeruginosa*	Antimicrobial peptide SET-M33	Cresti et al. (2023)
Sulfur-Polymer NPs	*S. aureus and Gram-negative P. aeruginosa.*	-	Dop et al. (2023)
Chitosan-coated polycaprolactone NPs	-	Azithromycin/Ciprofloxacin	Yassin et al. (2023)
CNMs (anocomposite antibacterial agent based on chitosan nanoparticles and AMP microcin J25)	*Tetracycline (Tet)-resistant E. coli*	Antimicrobial peptide MccJ25	Haitao et al. (2022)
Polyvinyl alcohol (PVA)/polyvinylpyrrolidone (PVP) blended with silver.	*E. coli and S. aureus*	-	Abd El-Kader et al. (2021)
Polymeric micelle (PLGA and dextran)	*Pseudomonas spp.*	Curcumin	Barros et al. (2021)
PBMA-*b*-(PDMAEMA-*r*-PPEGMA) (B*b*D*r*E), (PBMA-*r*-PDMAEMA)-*b*-PPEGMA (B*r*D*b*E), and PBMA-*r*-PDMAEMA-*r*-PPEGMA (B*r*D*r*E)	*P. aeruginosa,* and *S. aureus*	Baicalein (BA) and ciprofloxacin (CPX)	Guo et al. (2021)
Poly (lactic-co-glycolic acid) (PLGA) nanoparticles	*S. aureus*	-	Gheffar et al. (2021)
polycaprolactone (PCL)-based	*S. aureus* and *E. coli*	Cefotaxime	Javaid et al. (2021)
PLGA fiber mats	*S. aureus*, and *E. coli*	Ciprofloxacin	Barani et al. (2020)
PLGA/Mg	*S. epidermidis*	-	Ma et al. (2020)
PLGA-PEI, clindamycin-loaded PLGA NPs (Cly/PNPs)	*S. aureus* (MRSA)	Clindamycin	Hasan et al. (2019)
Chitosan-modified PLGA	*S. epidermidis*	Clarithromycin	Takahashi et al. (2015)

(Beach et al., 2024). Examples of such polymeric NPs are listed in Table 1.

1.4 Hybrid NPs for multi-functional protection

In recent years, research towards the analytical procedures and improving the effectiveness of NPs has been sparked by the growing use of NPs in therapeutics. New analytical problems can now be solved because of the development of hybrid NPs, which help to improve analytical methods even further. With their unique set of characteristics, hybrid NPs provide outstanding advantages in enhancing material performance for a variety of uses. There are various examples of hybrid antibacterial NPs, such as Fe_3O_4–Ag hybrid NPs, proven highly effective against *E. coli* (Ngo et al., 2016). Scientists have developed hybrid NPs by mixing various substrates with NPs, such as citric acid with quaternary ammonium cellulose derivatives demonstrate effective inhibition against *Escherichia coli* and *Staphylococcus aureus*. The tensile strength of the film was 47.2% higher when they were included in a polyvinyl alcohol matrix (Li J et al., 2023). To increase the antibacterial activity of polymyxins against a range of pathogens, the study reported a sophisticated delivery mechanism. With a poly (glutamic acid) shell and a silver core, hybrid core-shell NPs were created that showed no discernible macrophage absorption or cytotoxicity. *Pseudomonas aeruginosa* was examined after the NPs were placed onto composite materials using agarose hydrogel. The hybrid system of polymyxin B demonstrated a synergistic impact (Iudin et al., 2022). Cs/Ni/NiO hybrid NPs (HNPs) are a potential example of antibacterial and anticancer uses. The NPs showed high cytotoxicity against MCF-7 cancer cells and successfully inhibited *S. aureus* and *E. coli*. Notably, L929 cell lines demonstrated minimal toxicity to healthy cells in biocompatibility testing, indicating their potential for application in biomedicine. Although these results are promising, more investigation is required to see whether improving their structure might increase their antibacterial and anticancer efficacy (Karthikeyan et al., 2022). Hybrid NPs provide multifunctional antibacterial methods by combining many functional components (David et al., 2021). By using regulated release mechanisms, they improve target selectivity, biocompatibility, and ROS production (Wu et al., 2023; Tariq and Bokhari, 2020). By combining many processes into a single, adjustable nanoplatform, these NPs can overcome antimicrobial resistance by improving oxidative stress, site-specific activity, and cytotoxicity.

Furthermore, some antibacterial encapsulation in AuNPs with ZnO hybrid enhances antibacterial activity, and this composite also destroys excess antibiotics (Ahmed et al., 2022). Ag–ZnO nanohybrids can be prepared by green bioreduction method and enhanced antibacterial action against *Escherichia coli, Pseudomonas entomophila*, and *Bacillus oceanisediminis* at 100 µg/mL, 125 µg/mL, and 50 µg/mL, respectively (Mohapatra et al., 2023). Hybrid NPs can be modified in a variety of ways to improve their chemical and physical characteristics. For example, adding silver and titanium dioxide NPs to the polyvinyl alcohol (PVA) and sodium alginate (SA) matrix significantly improved its structural, thermal, and electrical properties, as demonstrated by several analytical methods. The materials' potential for use in semiconductors, energy storage, and food packaging is highlighted by their notable improvements in thermal stability, conductivity, and antibacterial activity. These results imply that these nanocomposites may be useful biomaterials with wide-ranging industrial applications (El Gohary et al., 2023). Adding to this, Mg/Pd hybrid NPs proved efficient against gram-positive, gram-negative, and fungal pathogens. In silico study also confirmed strong binding associations of the D-glucose cyclic 1, 2-ethanediylmercaptal pentaacetate molecule with the HuH-7 cancer cell line, EGFR tyrosine kinase inhibitor resistance, and Bcl2 gene target proteins; these results also suggest exciting opportunities to Significant anticancer activity (Kamaraj et al., 2025). Hybrid NPs can be used as versatile delivery vehicles. For example, Papain-loaded PLGA-phosphatidylcholine NPs were determined to be 77.5% efficient in drug encapsulation, which is about 28% more efficient than papain-loaded PLGA NPs (Sinha and Rupachandra, 2025).

1.5 Nanocomposites: mode of action

Researchers are focusing on developing novel materials from sustainable and biorenewable sources to address environmental concerns and depletion of fossil resources. Nanocomposites, made from biorenewable resources, offer benefits like high mechanical characteristics, thermal stability, and ease of production, benefiting various industries like food, biomedicine, and automotive (Ates et al., 2020). Increasing research on nanocomposite significantly focus on creating eco-friendly, nontoxic, biocompatible, and biobased fillers and composites. These materials are used in biosensors and biomedicine, particularly in microbiology as antibacterial agents (Warangkar et al., 2022). A study fabricated nanocomposites combining reduced graphene oxide (RGO) with metal oxides like silver oxide (AgO), nickel oxide (NiO), and zinc oxide (ZnO). The materials showed strong antibacterial and antifungal activities against pathogens like *Staphylococcus aureus, Escherichia coli,* and *Candida albicans,* with antibiofilm inhibition exceeding 90%. The nanocomposites also disrupted bacterial cell membranes, leading to cell death, highlighting their potential in combating resistant microbial strains (Elbasuney et al., 2023). Abd El-Fattah study presents an eco-friendly method for creating a multifunctional smart nanobiocomposite (NBC) made from ZnO, PIACSB, and TiO_2. The NBC was created by converting shrimp shells into polyimidazolium amphiphilic chitosan Schiff base (PIACSB), which was then used as an encapsulating and coating agent. The NBC demonstrated remarkable antimicrobial activity against *Staphylococcus aureus, Escherichia coli,* and *Pseudomonas aeruginosa*, and superior antibiofilm activity against ciprofloxacin (Abd El-Fattah et al., 2023). Nanocomposite can also be use to treat heavy metal pollution for instance Shewanella onesidensis metabolism is used to create bio-ZnS/CuS composites, which have broad-spectrum antibacterial properties and high visible light-driven photocatalytic activity. More than 95% of the heavy metal ions in wastewater are effectively recovered by the composites. Superior photocatalytic activity was revealed by the composite with a 1:9 Zn to Cu ratio, which achieved sterilisation rates of over 99.99% against *Escherichia coli* and 99.98% against *Staphylococcus aureus* (Ma et al., 2023). Various nanocomposite are used for environmentally friendly antibacterial fruit packing, for example; polylactic acid (PLA), in concert with nanofillers and antimicrobial compounds to increase mechanical strength and antibacterial effectiveness (Abdul Malek et al., 2025). Because of their nanoscale structure, which allows for targeted and sustained release, nanocomposites improve the stability and delivery of active substances (Singh and Agarwal, 2016). Their special physico-chemical characteristics enable them to interact closely with microbial cells. They work by producing ROS, rupturing cell membranes, interfering with DNA replication, and subsequently affecting metabolic pathways (Saravanan et al., 2023; Azadi et al., 2025). However, the broad usage of nanocomposites is hampered by constraints such possible toxicity risk, environmental adaptability, production costs, implementation of large-scale applications, and regulatory approval (Santhosh et al., 2021). Table 2, highlights the overview of various microbes' inhibition by various nanoparticles.

2 Mechanism of antibacterial action

2.1 ROS generation and membrane disruption

Based on existing research the antibacterial effect of NPs is primarily employed by the following mechanism; disruption of the bacterial cell wall and cell membrane; ROS generation; intracellular antibacterial actions (Wang et al., 2017). Since the plasma membrane and cell wall are vital barriers, hence making their interaction with nanomaterials is a key component of NPs antibacterial activity (Werner et al., 2018). NPs adsorption is an active process employed by endocytosis. The fate and cytotoxic effect of NPs are determined by the subsequent intracellular accumulation of NPs. Although it is well acknowledged that NPs have antibacterial properties, it is unclear how exactly they work to prevent microbes; in particular, it is thought that big NPs are unable to pass through cell walls. According to studies, the NPs may adsorb due to the increased membrane tension, resulting in mechanical deformation such as cell rupture and cell death. Based on a biophysical model that shows how NPs interact with membranes to cause membrane stretching and squeezing, which in turn facilitates NP adsorption (Linklater et al., 2020). Regardless of their surface functionalization, NPs smaller than 10 nm can passively pass through cellular membranes without seriously disrupting them (Werner et al., 2018; Lin et al., 2020; Burgess et al., 2020). Small NPs work by the formation of large irreversible pores so that they efficiently translocate from bacterial cell barriers. In order to effectively translocate from

TABLE 2 Overview of various NPs and the microbial pathogens they mitigate, highlighting their antimicrobial properties and potential applications in plant disease management.

NPs	Minimum concentration	Mode of action	Microbes' inhibition	References
CuONPs	1–10 μg/mL	ROS generation	*Streptococcus mutans* *Lacticaseibacillus casei* *Lactobacillus acidophilus*	Amiri et al. (2017)
CuONPs	100–1,000 μg/mL	ROS generation	*Candida albicans* *C. glabrata* *C. krusei*	Amiri et al. (2017)
Green synthesised ZnO NPs	0.025 mg mL^{-1}	Membrane disruption ROS generation	*Escherichia coli* *Staphylococcus aureus* *Klebsiella pneumonia* *Enterococcus faecalis*	Thi et al., 2020; Demissie et al., 2020
Superparamagnetic Iron Oxide NPs (SPIONs)	20 μg/mL		*Pseudomonas aeruginosa and Candida albicans*	Antony et al. (2020)
AgNPs	4–16 μg/mL	Hydrogen peroxide scavenging activity	*Escherichia coli* *Enterococcus faecalis* *Salmonella typhi*	Keshari et al. (2020)
Green synthesised nano copper	-	Disruption of bacterial cell membranes and oxidative stress induction via ROS generation	*E. coli,* *Proteus* sp. *Enterococcus* sp. *Klebsiella sp*	Wu et al. (2020)
SeNPs	82 μg. mL^{-1}–660 μg. mL^{-1}	Oxidative stress and disrupt bacterial membranes	*Escherichia coli and S. aureus*	Vahdati and Tohidi Moghadam (2020)
AuNPs/MOFs hybrid	-	Peroxidase-like activity toward H_2O_2 decomposition into toxic hydroxyl radicals (·OH).	*Escherichia coli S. aureus*	Hu et al. (2020)
Green synthesised AgNPs	0.11, 7.1 μg/mL	-	*S. aureus, E. faecalis, and P. aeruginosa,* *A. baumannii and E. coli*	Ebrahimzadeh et al. (2020)
GO/AgNPs and GO/CuONPs		ROS generation	*S. aureus* *E. coli*	Menazea and Ahmed (2020)
TiO_2 NP	1,000 μg mL^{-1}	ROS generation	*Escherichia coli,* *Proteus vulgaris,* *Pseudomonas aeruginosa, and* *Staphylococcus aureus*	Khashan et al. (2021)
Green synthesised AgNPs		-	*Streptococcus pneumoniae,* *Klebsiella pneumoniae and* *salmonella typhimurium*	Melkamu and Bitew (2021)
$Zn_{0.95}Ag_{0.05}O$ (ZnAgO) NPs	-	ROS generation and membrane disruption	*S. aureus and Escherichia coli*	Hojjati-Najafabadi et al. (2021)
AgNPs	100 μg/mL	Disrupting microbial cell membranes	*R. solanacearum* *M. incognita,* *F. oxysporum*	Khan et al. (2021)
Garcinia NPs	4 mg/mL, GNs combined with MV irradiation	Outer membrane (OM) disruption	*Escherichia coli*	Qiao et al. (2022)
Nickel oxide NPs	20 μg/mL	Release Ni^{2+} ions and generate reactive oxygen species (ROS)	*Gram-negative (Escherichia coli)*	Al-Zaqri et al. (2022)
ZnO NPs	0.2–1.4 mM.	Electrostatic interaction & membrane disruption By interfere with FtsZ protein	*Escherichia coli,* *Pseudomonas aeruginosa* *Staphylococcus aureus,* *Bacillus subtilis*	Mendes et al. (2022)
Antibiotic-loaded mesoporous silica NPs decorated with SPIONs	200 μg/mL	Magnetic hyperthermia via SPIONs under alternating magnetic field	*Escherichia coli biofilms*	Álvarez et al. (2022)

(Continued on following page)

TABLE 2 (*Continued*) Overview of various NPs and the microbial pathogens they mitigate, highlighting their antimicrobial properties and potential applications in plant disease management.

NPs	Minimum concentration	Mode of action	Microbes' inhibition	References
Phyto-fabricated chitosan, copper oxide, and chitosan-based CuONPs	62.5 µg/mL	Cu^{2+} ions and generating ROS and chitosan coating enhances nanoparticle stability, facilitates cell wall binding	*Acinetobacter baumannii*	Sarfraz et al. (2023)
Ciprofloxacin-loaded PEG-coated ZnO NPs	-	Releasing ciprofloxacin and Zn^{2+} ions, generating ROS	*S. aureus*	Ibne Shoukani et al. (2024b)
Polyvinyl alcohol (PVA) aerogel microsphere loaded with biogenic ZnONPs	12.5 U/mL	Zn^{2+} ions and generate ROS	*Pneumonia, P. aeruginosa and E. coli,*	Abdulrahman et al. (2024)
Polyvinyl alcohol/starch/chitosan films with NiO–CuO	160 to 0.156 µg/mL	Release metal ions and generate reactive oxygen species	*E. coli and S. aureus.*	Momtaz et al. (2024)
TiO_2 nanorod	10 mM	Release Ag^{+} ions and generate reactive oxygen species	*S. aureus*	Korcoban et al. (2025)

bacterial cell barriers, small NPs create enormous, irreversible holes. In the meantime, there are more and more reports about the antibacterial properties of NPs that are between 80 and 100 nm in size (Shaikh et al., 2019). After intruding into bacterial cell walls there is a requirement to cope with bacterial defense response, bacterial possess numerous defence responses and one of them is the oxidative stress response, although, the oxidative defence response is not that essential, but it is important for normal bacterial growth. ROS have a tremendous oxidation potential and seriously harm proteins, lipids, and nucleic acids. Numerous researchers are interested in ROS-based antimicrobials since they target numerous locations in bacteria (Vaishampayan and Grohmann, 2021). Various NPs such as AgNPs, ZnO NPs, and TiO_2 NPs respond through ROS generation, and target multiple cellular components by inducing lipid peroxidation in bacterial membranes, protein thiol group oxidation, disrupt cell integrity and enzymatic disfunctioning and leading to cell lysis. In defence to this, bacteria show various responses like, SoxRS and OxyR regulation (Méndez et al., 2022) which regulate antioxidant genes such as *sodA* (superoxide dismutase) (Giengkam et al., 2025), *katG* (Wan et al., 2021b), and *ahpC* (Xu et al., 2025).

In general, there are four forms of reactive oxygen species: hydrogen peroxide (H_2O_2), singlet oxygen (O_2), superoxide radical (O−2), and hydroxyl radical (·OH). Distinct NPs produce distinct NPs; for example, ZnNPs produce H_2O_2 and OH, whereas MgO and CaO NPs produce O-2. Meanwhile, CuONPs can create all four types of reactive oxygen. According to the literature, OH and O_2 may be more effective for immediate microbial death, whereas O−2 and H_2O_2 are known for less acute stress responses that are readily neutralised by endogenous antioxidants. Defects, reorganisation, and oxygen vacancies are the main sources of ROS generation. On the other hand, oxidation is preferred by the cells redox balance when ROS generation is high. Oxidative stress, which is caused by an out-of-balance condition, harms the separate parts of bacterial cells (Li et al., 2012; Malka et al., 2013; Peng et al., 2013). One such example is MnO_2 nanosheets, which show high antimicrobial properties by triggering ROS generation furthermore they also elevate ATPase activity and microbial membrane disruption which ultimately leading to cell death. 125 µg/mL concentration of these nanosheets may wipe out about 99% bacteria (Du et al., 2020). Additionally, Ag NPs on TiO_2 nanorods slow down the recombination rate of electrons-holes, and they demonstrated 90% killing efficacy against *Staphylococcus aureus* (gram-positive/cocci) and *Escherichia coli* (gram-negative/rods). The design of ROS responsive Ag decorated TiO_2 hybrid nanorods (HNRs) with dual functionalities of enhanced photodynamic therapy and antibacterial activity (Hou et al., 2022).

2.2 NPs against biofilms

Nanoantibacterial formulations accelerate protection from bacterial infections by various mechanisms, such as disrupting biofilms, damaging cell walls, and inducing oxidative stress. Antibiotics are frequently inadequate due to biofilm resistance to them and other antimicrobials. Metal oxide NPs are one of several biofilm-fighting tactics that have been developed as a result of advances in NPs manufacturing. These tactics deal with the functional and structural elements of drug resistance mechanisms and microbial biofilms. Various bacterial species may be treated using photodynamic therapy, quorum sensing, and nanotechnology to overcome resistance (Mishra et al., 2023). Focus should be on repurposing existing antimicrobial medications to enhance effectiveness, especially for persistent illnesses linked to biofilms. *S. aureus* and methicillin-resistant *S. aureus* are common sources of biofilm-associated illnesses. NPs could improve drug transport into biofilms, but mechanisms governing interactions remain unclear (Fulaz et al., 2020). For instance, Se@Ag@EGCG NPs demonstrated potent antibacterial activity against MDR, *S. aureus* and *E. coli* at 40 µg/mL through ROS overproduction. It also possesses efficient wound healing properties and low toxicity, which highlights its potential for ROS-mediated strategies for addressing antibiotic resistance (Yang et al., 2022). Similarly, in some AgNPs, the massive accumulation of ROS leads to antibacterial action (Pernas-Pleite et al., 2023; Li PP et al., 2023). Adding GO to Cu_2O significantly enhances photodynamic antibacterial efficiency and improves electron-hole separation and ROS

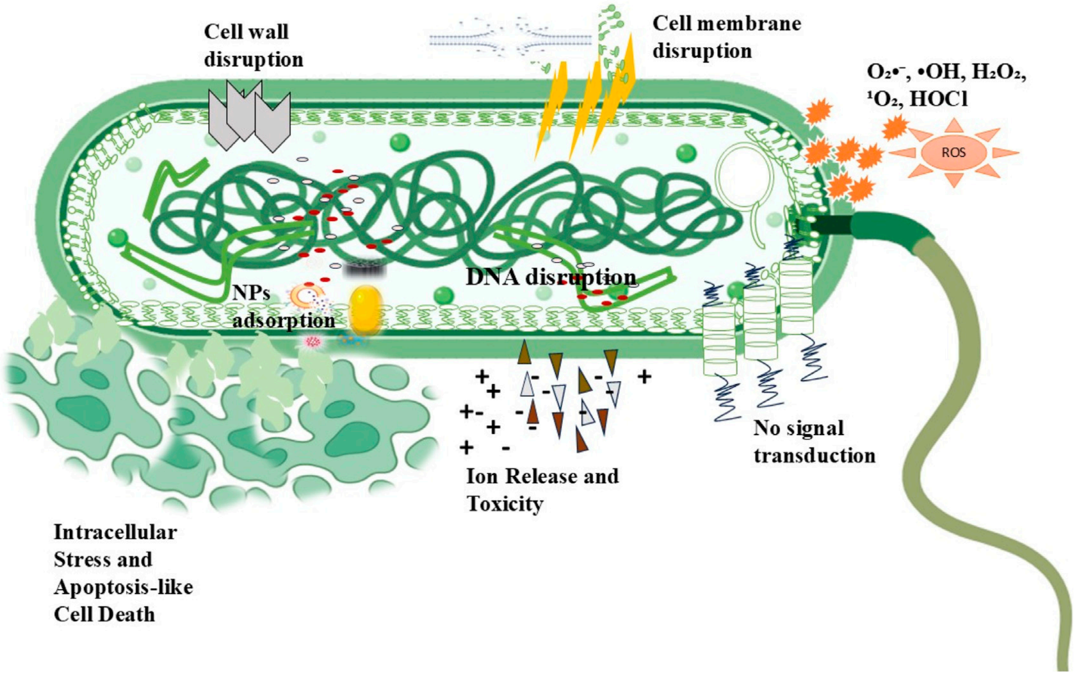

FIGURE 1
Diagrammatic illustration of the mechanism of action of NPs against bacteria. NPs interact with bacterial cells through multiple pathways, including: (i) breaking down the bacterial cell membrane, which allows intracellular contents to leak out; (ii) producing ROS, which causes oxidative stress and cellular damage; (iii) interacting with intracellular components like proteins and DNA, which inhibits replication and causes enzyme dysfunction; and (iv) interfering with electron transport and metabolic pathways, which ultimately results in bacterial cell death.

generation. The resulting PLLA/Cu_2O@rGO scaffold shows strong antibacterial activity (He et al., 2024). Successful synthesis of Ag, Cu, and Se NPs (50–100 nm) prepared by the DES-based method, ensuring stability and enhanced bioactivity against *S. aureus, E. coli,* and *C. albicans*. The NPs mediated ROS generation, leading to enzyme inactivation, metabolic disruption, and bacterial cell degradation. Additionally, Cu NPs from copper (II) acetate demonstrated significant antiviral activity, reducing virus titers of influenza A/H1N1, HCoV-OC43, and VSV by over 93.7%–99.96% (Długosz et al., 2025).

2.3 Stimuli-responsive NPs

NPs interact with the bacterial cell's basic components, such as DNA, lysosomes, ribosomes, and enzymes, leading to oxidative stress, heterogeneous alterations, changes in cell membrane permeability, electrolyte balance disorders, enzyme inhibition, protein deactivation, and changes in gene expression (Shrivastava et al., 2007; Yang et al., 2009; Xu et al., 2016). Figure 1 represent the mechanism of action of NPs against microbes.

According to a biophysical model, both Gram-positive and Gram-negative bacteria are impacted by the stretching and squeezing of membranes caused by NPs. AuNPs that are both hydrophilic and hydrophobic are created in order to investigate antibacterial processes. NPs induced membrane squeezing and tension are demonstrated in a microfluidic system; quasi-spherical NPs have stronger bactericidal activity (Linklater et al., 2020). For example, some metallic NPs dissolve close to the cell envelope in contact with bacteria, disrupting their cells and facilitating antibiotic activity (Bondarenko et al., 2018). The generation of ROS species in light by SA-CS@CuO/ZnO (sodium alginate (SA) and chitosan (CS)/CuONP and ZnONP) promotes improved antibacterial activity, which is another example of an antibacterial action mechanism. Differentially expressed genes that were mostly involved in membrane transport, cell wall and membrane formation, cellular antioxidant defence, and DNA repair mechanisms enable the generation of ROS, which in turn enhances antibacterial activity (Guan et al., 2021). Similarly, Bacitracin-AgNCs mechanism against *S. flexneri* by change in membrane permeability which lead to leakage of intracellular substances (Wang et al., 2021). After interacting through the cell membrane, various intracellular events are associated with antibacterial action, such as disruption of the electron transport chain, catalytic killing, cell cycle arrest, and bacterial DNA degradation (Xie et al., 2023). For instance, CuNPs may arrest bacterial cell division by destabilizing cell division proteins, FtsZ and FtsI (Ganesh et al., 2020). Furthermore, reports claim that the DI-SeNPs, actinomycetes-based AuNPs (Ac-AuNPs), possess antibacterial properties by cell cycle arrest (Ameen et al., 2025; Aati et al., 2025). Various mode of antimicrobial action of NPs are illustrated in Figure 1.

3 Application

Antibacterial NPs are multifunctional and used in various fields, including medicinal, healthcare, agriculture, plant disease management, food preservation and packaging, and personal hygiene products. In field of medicine, wound healing is an important application of antibacterial NPs. Various NPs used in wound healing, such as, lipid-based NPs (LBNs) (Motsoene et al., 2023), AgNPs (Chinnasamy et al., 2021), AuNPs (Boomi et al., 2020), LL37 and Serpin A1 encapsulated NPs (Fumakia and Ho, 2016), chitosan (Shao et al., 2019), etc.

3.1 Antibacterial NPs in healthcare

There is an immediate need for noble antimicrobial or antibiofilm surfaces and biomedical equipment that provide defence against planktonic infections, especially those caused by antibiotic-resistant strains, and biofilm development. Antibacterial NPs in healthcare have enhanced wound healing properties by reducing inflammation as well as regulating collagen deposition. Healthcare professionals are concerned about bacterial colonisation on surfaces, which results in biofilms that cause chronic illnesses. Some recently created nanotechnology-based biomaterials describe the fundamental techniques used to develop antibiofilm surfaces (Naik et al., 2015; Ramasamy and Lee, 2016). Pathogenic bacterial infection is one of the serious health concerns with high infection and lethality rates. Conventional antibiotics are not able to mitigate drug-resistant microbes. Nanosystem employment is a revolutionary approach to specifically target the infection location. Nanomedicine may increase the effectiveness of antibiotic administration. These nanocarriers improve stability, solubility, and half-life of antibiotics. NPs that react to pH changes in the environment or enzyme modifications to cause the release of antibiotics are being developed as passive and active targeting techniques (Yeh et al., 2020). One important method for enhancing medication bioavailability or targeted distribution at the site of action is polymeric NPs. Polymers are perfect for meeting the needs of each unique drug-delivery system because of their flexibility (Begines et al., 2020). NPs, such as Ag, Cu, Se, Ni, Mg, and Fe NPs, also play a vital role in agriculture, and they have all been thoroughly investigated for possible antifungal uses. Because of their potent antifungal qualities, AgNPs have been the subject of the most investigation. Other NPs with encouraging outcomes include Se, Ni, Mg, Pd, and Fe (Cruz-Luna et al., 2021).

3.2 Antibacterial NPs in healthcare

NPs have been extensively studied in plant disease management for sustainable agriculture (Kumar, 2020). For instance, Wohlmuth and colleagues' study of eight NPs against *Xanthomonas hortorum* pv. Carotae and the study against the seed-borne disease by *Xanthomonas hortorum* pv. carotae, which affects plants in the Apiaceae family, found that the three most effective NPs against a particular microbe were built of copper, silver, and silver/selenium composite. Copper-based NPs were shown to be the most effective when tested on infected carrot seedlings, causing a ten-fold reduction in the prevalence of Xhc (Wohlmuth et al., 2024). Whereas, SeNPs offer a more efficient and eco-friendlier alternative for boosting plant resistance while decreasing toxicity, especially at low dosages (Qin et al., 2025).

3.3 Antibacterial NPs in food packaging and preservation

Antimicrobial NPs are also employed as preservatives. By preventing microbial development, antibacterial NPs are also used in food packaging aid to prolong shelf life and guarantee food safety. By acting as active barriers, these clever NPs lower the chance of contamination and spoiling. Nanomaterials like: lipid NPs, nanoemulsion, nanoliposomes, nanosponges, graphene, mesoporous silica, copper, gold, titanium dioxide, magnesium oxide, zinc oxide, gelatine, alginate, cellulose, and nanofibers (Suvarna et al., 2022; Kumar et al., 2024). For instance, the Ta4C3Tx nanosheet as a template to create antibacterial bioplastic packaging that is strong, controlled, and long-lasting. The bioplastic CTa-Ag, which is based on nanocellulose, exhibits steady photothermal conversion efficiency, low oxygen permeability, and good mechanical qualities. New ideas for food packaging design are also made possible by its long-lasting antibacterial qualities and controlled release of antibacterial active chemicals (Wang X et al., 2024). For instant, a food packaging antibacterial nanocomposite film composed of NiO–CuONPs and polyvinyl alcohol/starch/chitosan (PVA/ST/CS) demonstrated no toxicity to fibroblast cells and higher antibacterial activity against Gram-positive bacteria. The film is a preferred material for food packaging because of the over 84% survival rate of these cells in contact with it (Momtaz et al., 2024). Furthermore, ZnO NPs at varying concentrations in a starch matrix are used in formation of biodegradable packaging solutions. The starch biofilms' mechanical qualities are improved by the NPs, which increases their strength and heat resistance. Additionally, the films offer UV protection and antimicrobial qualities (Dhiman et al., 2025). Moreover, the application of bio-based food packaging materials—more especially, biosynthesised ZnONPs, or ZnONPs—is investigated in Hashem and colleagues work. Superior antibacterial and antifungal qualities were demonstrated by the films, which were made with HPS/PVA, palmitic acid, and ZnONPs. Additionally, the films demonstrated biodegradability; after 4 weeks in soil, their biodegradability was around 85% (Hashem et al., 2023).

Nano emulsion is also one of the approaches of antibacterial NPs in food safety (Özogul et al., 2022; Gao et al., 2021; Kumar et al., 2024; Cui et al., 2025) such as, Gao and colleagues report that the strong antibacterial action against *Staphylococcus aureus* and *Escherichia coli* is demonstrated using cinamaldehyde nanoemulsion. 84% w/w deionised water, 10% w/w surfactant EL-90, and 6% w/w cinnamon aldehyde make up the ideal mixture. The droplet size of cinnamaldehyde nanoemulsion is uniformly tiny and steady. cinnamaldehyde nanoemulsion is efficient against these infections because of its lipophilic nature and ability to induce oxidative stress. The study offers a point of reference for upcoming food-grade preservative development (Gao et al., 2021).

3.4 Antibacterial NPs in water purification

To avoid harmful infections and extend the shelf life of medical devices, water purification systems, and food safety, antimicrobial coatings are crucial in medical applications. By creating protective shells on the material's surface, these coatings prevent the growth of microorganisms and guarantee both quality and safety. Commonly used metal-based coatings include copper, zinc, titanium dioxide, and silver-based coatings. However, excessive discharge of tainted water degrades water quality and has detrimental impacts on ecosystems. Water purifying techniques that are cost-effective, environmentally friendly, and sustainable are required. Ceramic filters work well with polydimethylsiloxane and polyurethane polymers (Goel and Arya, 2024; Kalakonda et al., 2024). One such example is Improved filtration velocity, efficient microbial elimination, and self-disinfecting potential are features of a 2D Ti3C2/Al2O3/Ag/Cu nanocomposite-modified filtration material with promising POU water treatment. The materials potential for real-world water treatment was demonstrated by the confirmation of its stability and antibacterial effectiveness (Jakubczak et al., 2021). Similarly, functionalised TiO_2 NPs in water purification membranes made of polyurethane and cellulose acetate. To initiate the membranes' photocatalytic activity against Methicillin-resistant *Staphylococcus aureus* and *Escherichia coli*, they were exposed to ultraviolet light. The membranes mechanical strength, water retention, thermal stability, and shape were all examined. According to the findings, these membranes may help purify water since they have strong antibacterial qualities (Ahmad et al., 2022).

Among various NPs, AgNPs are the most widely studied, primarily because of their strong antimicrobial activity at low concentrations. AgNPs work by releasing silver ions that disrupt bacterial cell membranes, generate ROS, and interfere with DNA replication, ultimately leading to bacterial cell death (Al-Rawajfeh et al., 2024). For instant, *Terminalia chebula* fruit extract synthesized AgNPs have distinct morphology and antibacterial properties for water purification. Under exposure to visible light, the AgNPs demonstrated catalytic capability in the degradation of commercial methylene dyes and effectiveness against *E. coli*. The biogenically produced TC-AgNPs show great promise for microbial control and long-term environmental restoration initiatives due to their remarkable capacity to break down organic contaminants and deactivate microorganisms (Kalakonda et al., 2024). Furthermore, for applications including water purification and ultrafast nitrophenol catalysis, a unique two-dimensional Ti3C2Tx MXene membrane enhanced with AgNW have reported. With AgNW optimisation, the membrane maintained a high bovine serum albumin rejection of 95.4% while demonstrating a water flow of up to 191.9 L/(m2 h). The M@A-12% membrane showed the highest recycling utilisation and catalytic reduction capabilities, with an antibacterial rate of more than 99% against *S. aureus* and *E. coli* (Qin et al., 2023). Similarly, in order to purify water, the study offers a 95% effective antibacterial sponge that has a high clearance ratio of bacterial corpses. The steady releasing feature of Ag^+ and the charge interaction of quaternary amine salts are responsible for the sponge's efficacy. A fresh approach to water purification without bacterial residue is provided by this creative technique (Yin et al., 2024).

As people's awareness of health and hygiene problems, has grown that needs more ecofriendly bioactive materials. Wearers are shielded from bacteria and fabrics from biodeterioration by bioactive coatings. There is continuous research on environmentally friendly production methods and quality requirements (El-Shamy et al., 2024). Researchers also assess how well thermoregulation-based smart fabrics and nanomaterials work as self-sanitizing face masks. It demonstrates how these masks can improve filtration efficiency by overcoming the drawbacks of traditional masks (Pattanaik et al., 2024). An overview of various applications offer by NPs is represented in Figure 2.

4 Challenges of widescale usage of antimicrobial NPs

The potential for environmental durability, cost-effectiveness, and industrial scalability also present difficulties (Mondal et al., 2024). Although, there has been great advancement, such as smart NPs that react to particular stimuli like light, bacterial enzymes, or pH changes, there are still challenges ahead (Zhang et al., 2023). With problems like cytotoxicity, oxidative stress, and the possibility of long-term environmental accumulation remaining unsolved, safety is still a top concern which is problematic for their real-world applications. Issues like uneven manufacturing, high prices, restricted scalability, and insufficient regulatory backing are also a major concern despite promising developments like hybrid nano-antibiotics, CRISPR-based carriers, and peptide-loaded systems (Xuan et al., 2023; Wang YL et al., 2024). Moving forward researchers must focus on creating biodegradable, biocompatible nanomaterials ideally developed through eco-friendly methods backed by strong safety testing, AI-guided design, and supportive public policies to truly bring these innovations from lab to life (Olawade et al., 2024; Yan et al., 2020). For safe biomedical uses and to reduce cytotoxic effects, NPs must be biocompatible. Their therapeutic potential can be increased while negative effects can be decreased by carefully designing and altering their surface to accommodate their flexibility (Wang YL et al., 2024).

5 Discussion

NP-based therapeutics, developed from nanotechnology, have improved therapeutic efficacy, reduced toxicity, and enable precise targeting. Since the 1980s, they have expanded the pharmaceutical market. However, developing comprehensive regulatory frameworks remains a challenge. This review analyses market-approved NPs therapeutics, highlighting the importance of adaptive pathways and supporting researchers in commercializing and clinical translating these therapeutics (Desai et al., 2025). Global public health is being threatened by antibiotic resistance. Although antimicrobial peptides (AMPs) are crucial for the innate immune response, they have drawbacks such as poor pharmacokinetic characteristics and cytotoxicity. By altering AMP delivery for accurate, regulated release at infection sites, delivery technologies such as hydrogels and NPs might overcome these difficulties. The purpose of this study is to provide light on how to get over translational obstacles and get AMPs medications closer to clinical use (Zheng et al., 2025) Notwithstanding these challenges, there is a lot of promise for infection control with nanotechnology (Ma and Poma, 2025). The future antibacterial NPs research is focused on the development of precise targeting, bioinspired designs, sustainable production processes, smart delivery systems, and AI-driven optimisation. Drug delivery methods based on

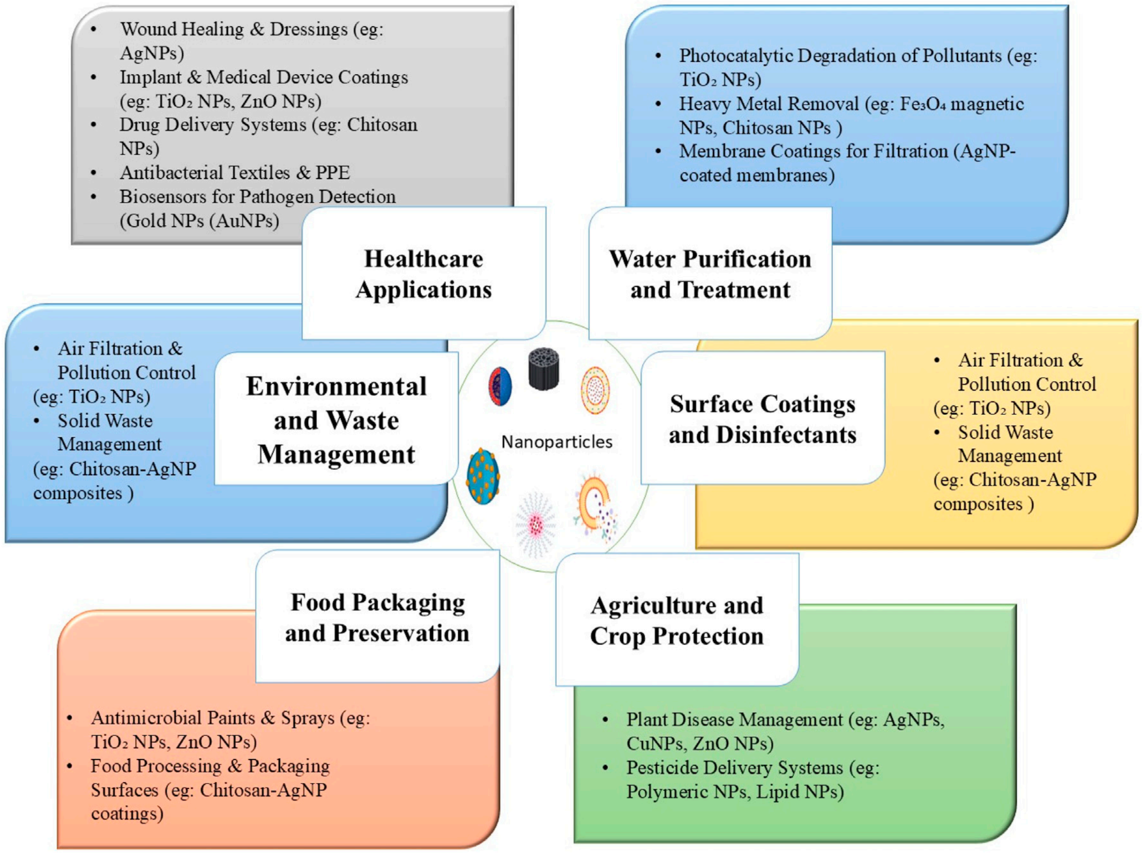

FIGURE 2
Diagrammatic illustration of the applications of antibacterial NPs: from healthcare to Agriculture, Enhancing Safety and Sustainability.

nanoparticles provide improved bioavailability, less side effects, and accurate targeting; yet, creating the ideal nanoparticles is still difficult. Predictive modelling speeds up the process of finding efficient formulations, while artificial intelligence (AI) offers strong tools like machine learning, neural networks, and optimisation algorithms to customise NP properties and enhance drug loading, targeting, and controlled release (Kapoor et al., 2024). Lipid nanoparticles (LNPs), such as amoxicillin-loaded LNPs for anti-Helicobacter pylori treatment, have also been optimised using AI-driven trial design, increasing stability, efficacy, and bioavailability with little chemical usage (Kumari et al., 2025). In a broader sense, AI facilitates the development of nanomaterials from design and synthesis to characterisation, allowing for quicker, data-driven advancements in biomedicine (Zhu et al., 2023).

6 Future perspectives

Antibacterial NPs became more common as the threat of MDR bacterial infection increased. Future studies on these NPs may concentrate on lowering toxicity while maintaining effective biocompatibility and specificity, as well as environmental biocompatibility (Dutt et al., 2024; Yaşayan et al., 2024; Khane et al., 2024). NPs should be specific stimuli-responsive to have an effective antimicrobial impact; this means that they can only work in reaction to certain stimuli, such as bacterial enzymes, pH variations, or outside influences like light and magnetic fields. The target-specific NPs will help reduce needless adverse effects (Cheeseman et al., 2020; Naskar and Kim, 2022; Zhang et al., 2023; Hao et al., 2024; Liu et al., 2024; Bera, 2024). For instance, copper sulfide (CuS) NPs show antibacterial properties and stimulate wound healing by utilizing photodynamic (PDT) and photothermal (PTT) strategies (Naskar and Kim, 2022). Similarly, lignin-based photodynamic nanoconjugates embedded in nanocomposite hydrogels utilize pH-triggered controlled release and may completely eradicate microbial populations upon laser exposure whereas Fe_3O_4 microbubbles (microbubble-based carriers embedded with Fe_3O_4 NPs) utilize a magnetic-targeted mechanism (Chandna et al., 2020; Lu et al., 2024).

The integration of NPs with antibiotics is another significant advancement that enhances the therapeutic horizon (Quiñones-Vico et al., 2024; Pisani et al., 2024; Costabile et al., 2024). Metal NPs loaded with antibiotics have already shown promising microbial resistance (Abdullah et al., 2024). Future research is also focused on optimizing hybrid nano-antibiotic systems for synergistic effects. Additionally, the encapsulation of antibiotics with polymeric NPs offers sustainable release with efficient penetration ability which reduces the dosage requirement and improves drug bioavailability (Ibraheem et al., 2022). For example, AgNPs are a promising tool for biomedical drug delivery due to their appropriate carrier property, the AgNPs loaded with ciprofloxacin prepared by chemical reduction and AgNPs loaded with vancomycin exhibit enhanced antibacterial ability (Ibraheem et al., 2022; Veriato et al., 2023).

The NPs may mimic a natural defence mechanism and can contribute to improving targeting efficacy, such as cell membrane-coated NPs and antimicrobial peptide-loaded NPs. The NPs may mimic a natural defence mechanism and can contribute to improving targeting efficacy, such as cell membrane-coated NPs and antimicrobial peptide-loaded NPs. These NPs may prevent the decomposition of the encapsulated drug due to their unique physicochemical property (Falciani et al., 2020; Ma et al., 2022; Wang et al., 2023; Omidian et al., 2025). One such example is chitosan NPs loaded with recombinant ll37 antimicrobial peptide with about 78% encapsulation efficiency and an average size of 127.12 nm, which provides enhanced stability and efficient antimicrobial activity (Fahimirad et al., 2021). Similarly, Nal-P-113-PEG-CSNPs formulation (Nal-P-113 loaded PEG-Chitosan NPs) effectively inhibited the growth of *Streptococcus gordonii*, *Porphyromonas gingivalis*, and *Fusobacterium nucleatum* with the MIC of 6 μg/mL, 23 μg/mL, and 31 μg/mL, respectively (Hu et al., 2021). Moreover, a study showed that the Cecropin-B peptide loaded-chitosan NPs are proven effective against MDR *Klebsiella pneumoniae* isolates (Okasha et al., 2023). Research based on CRISPR/Cas nanocarrier against microbes is also renowned (Wan et al., 2021a; Aziz et al., 2023). NPs have been extensively studied in the past decades, and their toxicity is a huge concern. Future studies are focused on developing less toxic biodegradable NPs (Remya et al., 2022; Wahab et al., 2024; Parvin et al., 2025). One of the most serious and difficult risks to human health is biofilm-associated illness, for which traditional antibiotics are ineffective. NPs are one of the newest therapeutic areas which show antibacterial activity, and it is also believed that the nanocarriers facilitate the effective penetration of biofilm by downregulating biofilm-related genes: ALS3, EFG1, ALS1, and HWP1, as well as inhibiting the bacterial defence mechanism. And the integration of both nanotechnology and the pharmaceutical would be a milestone for future therapeutics (Shkodenko et al., 2020; Campos et al., 2025). Studies are continuously exploring efficient antibacterial NPs, such as titanium dioxide NPs, AgNPs, chitosan NPs, etc. For instance, spherical-shaped ZnONPs with −21.9 zeta potential provide MICs of about 62 and 125 μg/mL against Gram-positive and Gram-negative bacteria. Additionally, at 125 μg/mL concentration, they may eradicate the biofilm-forming microorganisms (Masadeh et al., 2025; Wang P et al., 2025; Bano, 2025; Fakeeha et al., 2025). Regulatory obstacles, expenses, and public opinion are some of the difficulties in developing nanotechnology instruments for infection control, their clinical translation, and their possible influence on healthcare. By creating antimicrobial nanomaterials and medicinal nanocarriers, nanotechnology provides novel ways to fight infectious illnesses. It is essential to strike a balance between patient safety and quick clinical integration. Clinical translation is also impacted by high expenses and public opinion. Through processes including upregulating efflux pumps to release harmful ions or particles and creating biofilms that serve as chemical and physical barriers, bacteria can become resistant to NPs. By creating an extracellular matrix that restricts NPs penetration, lowers ROS transport, and sequesters metal ions, biofilm shielding greatly increases bacterial resistance to antimicrobial therapies based on NPs (Huang et al., 2022; Rajasekharan and Shemesh, 2022). Despite their promising applications, the antimicrobial action of NPs faces various limitations which hiders their environmental adaptability and clinical implementations (Nikzamir et al., 2021). More critical assessment of current constraints is necessary for the further development of antibacterial NPs (Mba and Nweze, 2021).

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