Antibacterial/Magnetic Iron Oxide Nanoparticles: A Comprehensive Review of Synthesis Methods, Doping Effects, Antibacterial Properties, and Applications in Medical and Food Industries

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Editor's note: Magnetic nanoparticles are gaining attention as effective solutions to the growing problem of multidrug-resistant bacteria. In this systematic review, Hosseinzadeh provided a detailed overview of recent studies on the effects of various dopants on the antibacterial mechanisms of magnetic nanoparticles. These dopants boosted the antibacterial activity of these nanoparticles for a variety of applications in clinical, food, and environmental fields, such as drug delivery systems, coatings for implants, wound healing, and antimicrobial packaging.

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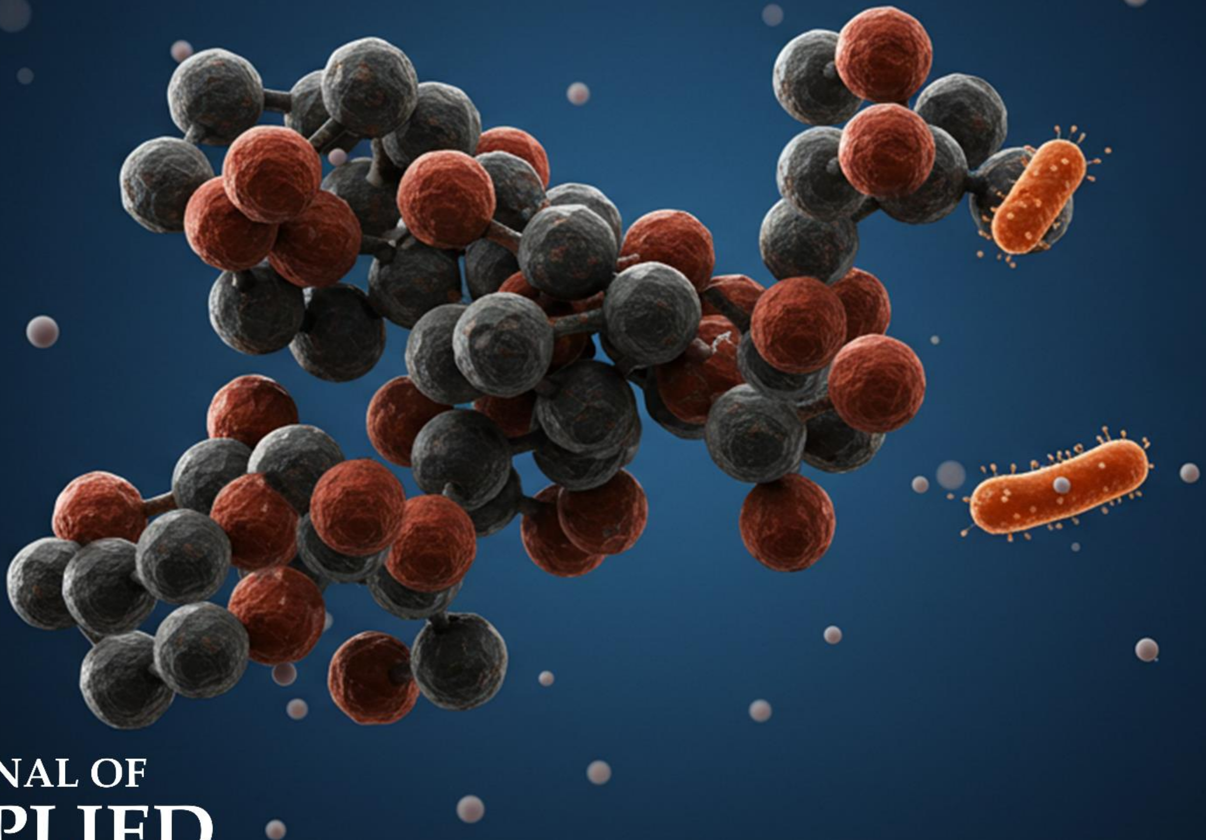

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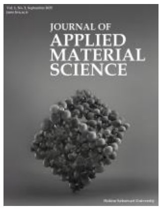

Review

Antibacterial/Magnetic Iron Oxide Nanoparticles: A Comprehensive Review of Synthesis Methods, Doping Effects, Antibacterial Properties, and Applications in Medical and Food Industries

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Abstract

The alarming rise of multidrug-resistant (MDR) bacteria has necessitated the development of innovative antimicrobial strategies beyond traditional antibiotics. Magnetic nanoparticles (MNPs) have emerged as promising candidates due to their unique physicochemical properties, including high surface area, superparamagnetism, and facile surface modification. This review explores the multi-faceted antibacterial mechanisms of MNPs, including membrane disruption, reactive oxygen species (ROS) generation, metal ion release, biofilm penetration, intracellular uptake, and hyperthermia-induced bacterial eradication. These mechanisms operate synergistically, allowing MNPs to combat a broad spectrum of bacterial pathogens, including biofilm-associated and drug-resistant strains. The incorporation of antibacterial dopants such as silver (Ag^+), zinc (Zn^{2+}), copper (Cu^{2+}), cobalt (Co^{2+}), and manganese (Mn^{2+}) into MNPs further enhances their antimicrobial activity by promoting ROS generation, enzymatic inhibition, and DNA damage, while also improving magnetic and catalytic performance. Surface functionalization further enables targeted delivery, biocompatibility, and multi-functionality for therapeutic and diagnostic applications. MNPs hold significant promise in clinical, food safety, and environmental contexts, particularly for applications such as drug delivery, implant coatings, wound healing, and antimicrobial packaging. Their ability to combine physical, chemical, and biological antibacterial mechanisms positions MNPs as a versatile platform for next-generation antimicrobial technologies aimed at overcoming the global antibiotic resistance crisis.

Keywords: Magnetic nanoparticles; Antibacterial dopants; Antibacterial mechanisms; Medical applications; Food industry.

1. Introduction

The rapid and widespread emergence of antibiotic-resistant microorganisms has become a critical global health concern, threatening the effectiveness of conventional antimicrobial therapies and posing serious challenges to the management of infectious diseases. The overuse and misuse of antibiotics in clinical, agricultural, and industrial settings have accelerated the

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evolution of multidrug-resistant (MDR) bacterial strains, leading to increased morbidity, mortality, and healthcare costs worldwide [1, 2]. This alarming situation necessitates the urgent development of novel antimicrobial agents and alternative strategies that can effectively overcome bacterial mechanisms of resistance while minimizing adverse effects on human health and the environment [3, 4].

Nanotechnology has emerged as a transformative field offering innovative solutions to this problem, with magnetic nanoparticles standing out as up-and-coming candidates due to their unique and tunable physicochemical properties. Characterized by their nanoscale dimensions, including a high surface area-to-volume ratio, superparamagnetic behavior, and facile surface modification, MNPs offer a multifunctional platform for targeted antimicrobial interventions [5, 6]. Their nanoscale size enables intimate interaction with microbial cells, allowing for enhanced adhesion, penetration, and disruption of bacterial membranes [7]. Furthermore, the intrinsic magnetic properties of these nanoparticles facilitate their manipulation by external magnetic fields, enabling targeted delivery, controlled localization, and stimulus-responsive activation, critical features for precision antimicrobial therapies [8, 9].

The antibacterial activity of MNPs arises from a combination of physicochemical and biochemical mechanisms. These include the generation of reactive oxygen species (ROS), which induce oxidative stress and damage vital cellular components such as lipids, proteins, and nucleic acids, direct disruption of the bacterial cell membrane integrity leading to leakage of intracellular contents, release of metal ions that interfere with enzymatic functions and genetic material, and intracellular uptake that disrupts metabolic pathways and gene expression [10-13]. This multifaceted mode of action not only enhances antimicrobial potency but also reduces the risk of resistance development, making MNPs effective against a broad spectrum of bacterial pathogens, including drug-resistant strains and biofilm-forming communities.

Beyond their antimicrobial efficacy, MNPs exhibit remarkable versatility, extending their utility across various biomedical and industrial applications [14-17]. In the medical field, they have been extensively studied as vectors for targeted drug delivery, enhancing the therapeutic index of antibiotics and other antimicrobial agents by localizing treatment to infected tissues while sparing healthy cells [18]. Additionally, MNPs serve as contrast agents in magnetic resonance imaging (MRI), improving diagnostic accuracy [19]. Their ability to generate localized heat under alternating magnetic fields, known as magnetic hyperthermia, provides a non-invasive approach to eradicate infections and tumors [20]. Moreover, MNPs are incorporated into advanced wound dressings and tissue engineering scaffolds to promote healing and prevent infection simultaneously, addressing two critical aspects of wound management [21, 22].

In the food industry, MNPs are gaining traction as active components in packaging materials designed to inhibit microbial contamination and extend the shelf life of perishable products. They are employed in preservation technologies and incorporated into nanosensors capable of detecting microbial spoilage and contamination in real time, thereby enhancing food safety and quality control. The magnetic properties of MNPs also enable their recovery and reuse, offering sustainable solutions for food processing and packaging [23, 24]. An exciting emerging application of MNPs lies in their capacity to serve as carriers and stabilizers for enzymes. The immobilization of enzymes on the surface of magnetic nanoparticles enhances their enzymatic stability, activity, and reusability, which is highly advantageous for industrial biocatalysis, environmental remediation, and biosensing applications [25]. This multi-functionality positions MNPs not only as antimicrobial agents but also as integral components in biotechnological and environmental innovations.

Given their broad spectrum of functions and potential impact, magnetic nanoparticles represent a dynamic and rapidly evolving area of research at the intersection of nanotechnology, microbiology, medicine, and food science. This review aims to provide a comprehensive overview of the current state-of-the-art in the synthesis, surface functionalization, antibacterial mechanisms, and practical applications of MNPs in medical and food sectors. By highlighting recent advancements and identifying existing challenges and future perspectives, we seek to underscore the critical role of magnetic nanoparticles as multifunctional tools in addressing microbial threats and enhancing human health and food security in the era of escalating antimicrobial resistance.

2. Synthesis methods of antibacterial magnetic nanoparticles

The synthesis of magnetic nanoparticles (MNPs) with effective antibacterial properties is a fundamental and decisive step in their development, as it directly influences critical attributes such as particle size, shape (morphology), magnetic characteristics, surface chemistry, stability, and ultimately their interaction with biological systems [26, 27]. These physicochemical properties govern not only the antimicrobial efficacy of MNPs but also their biocompatibility, toxicity profile, and functionality in complex environments such as human tissues or food matrices [28].

Over the years, researchers have developed and optimized a wide range of synthesis techniques aimed at producing MNPs with tailored properties to meet the demands of specific biomedical, pharmaceutical, and food-related applications (Table 1). These synthesis methods are generally classified into three main categories: physical, chemical, and biological approaches. Each category offers distinct advantages and limitations concerning control over nanoparticle characteristics, scalability, cost-effectiveness, environmental impact, and the ability to incorporate functional elements such as antibacterial dopants or surface coatings.

Physical methods encompass top-down approaches such as ball milling, laser ablation, and physical vapour deposition, which typically involve the mechanical or physical breakdown of bulk materials into nano-sized particles. These methods allow for the production of MNPs without the use of chemical reagents, reducing contamination risks. However, they often yield particles with broad size distributions and irregular shapes, which can affect reproducibility and biological activity [29].

Chemical methods are among the most widely employed techniques due to their ability to control nanoparticle size, composition, and surface properties precisely [27]. These methods include co-precipitation, thermal decomposition, hydrothermal/solvothermal synthesis, microemulsion, and sol-gel processes. The co-precipitation method is favored for its simplicity and scalability, where iron salts are chemically precipitated in alkaline media to form iron oxide nanoparticles. Thermal decomposition provides highly uniform and crystalline MNPs by decomposing organometallic precursors at elevated temperatures in organic solvents. Chemical methods also facilitate the doping of MNPs with antibacterial metal ions (e.g., silver, copper, zinc) and the functionalization of nanoparticle surfaces with polymers, ligands, or antimicrobial agents to enhance stability, biocompatibility, and targeted action.

Table 1. Comparison of magnetic nanoparticle synthesis methods

Synthesis method	Common materials/precursors	Advantages	Disadvantages	Particle control	Antibacterial enhancement
Co-precipitation	$FeCl_2$, $FeCl_3$, NH_4OH or NaOH	Simple, low-cost, scalable	Poor size control, possible agglomeration	Moderate	Can be doped with Ag^+, Cu^{2+}, Zn^{2+}
Thermal decomposition	Iron oleate, $Fe(acac)_3$ in organic solvents	High monodispersity, good crystallinity	Expensive, toxic solvents, not eco-friendly	Excellent	Precise shape and surface control
Hydrothermal/solvothermal	$FeCl_3$, organic solvents, surfactants	Good control over shape and crystallinity, high purity	Requires high temperature/pressure equipment	Good	Suitable for doping and surface functionalization
Green-synthesis	Fe salts + plant extracts, bacteria, fungi	Eco-friendly, biocompatible, cost-effective	Less control over size/shape, slower reactions	Low to moderate	Natural capping agents enhance antibacterial activity
Microemulsion	Fe salts + surfactants in oil/water emulsions	Produces uniform particles, tunable size	Complex system, low yield	Good	Allows for multi-metallic compositions
Sol–gel	Metal alkoxides (e.g., TEOS, $Fe(NO_3)_3$)	High purity, good chemical homogeneity	Time-consuming, requires calcination	Moderate	Easily combined with silica or antibacterial agents

Biological synthesis methods have recently gained traction as environmentally friendly and sustainable alternatives. These green-synthesis approaches utilize biological entities such as bacteria, fungi, plant extracts, and enzymes to mediate the reduction and stabilization of metal ions into magnetic nanoparticles [30]. Biological methods often produce biocompatible MNPs with intrinsic surface functional groups that can enhance interaction with microbial cells and reduce toxicity. Moreover, they avoid the use of hazardous chemicals and high energy inputs, aligning with green chemistry principles [31]. However, challenges remain regarding the control of particle uniformity and large-scale production [32].

The choice of synthesis method is closely linked to the intended application of the MNPs. For biomedical uses such as targeted drug delivery, imaging, or hyperthermia, strict control over particle size and surface chemistry is essential to ensure biocompatibility and functional performance [33]. In food-related applications, synthesis routes that prioritize safety, non-toxicity, and environmental sustainability are especially desirable. Therefore, the diverse synthesis methodologies available for magnetic nanoparticles provide a versatile toolbox for designing MNPs with optimized antibacterial properties and tailored functionalities.

Continuous advancements in synthesis techniques, including hybrid methods that combine physical, chemical, and biological processes, are expanding the potential of MNPs in combating microbial threats across the medical and food industries. In this section, we will review several widely utilized chemical synthesis methods for magnetic nanostructures, critically evaluating and comparing their respective advantages and limitations.

2.1. Co-precipitation

Among the various chemical synthesis methods for magnetic nanoparticles, co-precipitation is one of the most commonly employed techniques due to its inherent simplicity, cost-effectiveness, and scalability for large-scale production. This method involves the simultaneous precipitation of divalent and trivalent metal ions, typically iron (II) (Fe^{2+}) and iron (III) (Fe^{3+}) salts, from aqueous solutions in the presence of a base, commonly sodium hydroxide (NaOH) or ammonium hydroxide (NH_4OH). Under controlled alkaline conditions, these ions react to form magnetite (Fe_3O_4) or, through subsequent oxidation, maghemite (γ-Fe_2O_3) nanoparticles.

The co-precipitation process offers several advantages. First, it allows for relatively straightforward control over nanoparticle size and composition by adjusting parameters such as pH, temperature, ionic strength, and the Fe^{2+}/Fe^{3+} molar ratio. These factors influence nucleation and growth kinetics, enabling the synthesis of nanoparticles typically ranging from 5 to 20 nanometers in diameter. Second, the aqueous nature of the process makes it environmentally friendly and compatible with a broad range of functionalization strategies post-synthesis.

Despite these benefits, co-precipitation has some inherent limitations. The nanoparticles produced often tend to aggregate due to their high surface energy and magnetic dipole interactions. This aggregation can reduce colloidal stability and limit their effective surface area, which is critical for antibacterial activity and other biomedical functions. Moreover, controlling the phase purity and oxidation state of the nanoparticles can be challenging, as incomplete oxidation or over-oxidation may lead to mixed phases that affect magnetic properties and biological performance. Careful optimization of reaction conditions and use of inert atmospheres during synthesis can mitigate these issues.

The co-precipitation method remains a versatile and practical method for producing magnetic nanoparticles with antibacterial properties, particularly when followed by appropriate surface engineering. Its ease of operation and adaptability make it a preferred choice for both research and industrial-scale production of MNPs tailored for medical and food-related applications [34, 35].

2.2. Thermal decomposition

Thermal decomposition is a widely utilized chemical synthesis method that provides superior control over the size uniformity, crystallinity, and morphology of magnetic nanoparticles. This approach involves the high-temperature decomposition of metal-organic precursors, such as metal acetylacetonates or metal carbonyls, in the presence of organic solvents and surfactants or stabilizing agents. The elevated temperatures, typically ranging from 200 °C to 350 °C, facilitate the controlled nucleation and growth of nanoparticles, resulting in highly monodisperse and crystalline structures with narrow size distributions.

Compared to simpler aqueous-based methods like co-precipitation, thermal decomposition offers enhanced precision in tuning nanoparticle properties, including size, shape, and magnetic behavior, by carefully adjusting reaction parameters such as temperature, precursor concentration, and surfactant type. This level of control is particularly important for biomedical applications where consistency in nanoparticle characteristics directly influences their performance and safety profile. For instance, in targeted drug delivery, uniform particle size ensures predictable biodistribution and cellular uptake, while in magnetic resonance imaging (MRI), high crystallinity and size uniformity enhance contrast efficiency.

Despite these advantages, thermal decomposition is inherently more complex, requiring specialized equipment, organic solvents, and inert atmospheric conditions to prevent premature oxidation or contamination. Moreover, the process tends to be more costly and less environmentally friendly due to the use of organic solvents and high energy input. Nevertheless, the high-quality nanoparticles produced via thermal decomposition are highly sought after in advanced biomedical research and clinical applications, where their reproducibility and functional performance are critical [36, 37].

2.3. Hydrothermal and solvothermal synthesis

Hydrothermal and solvothermal synthesis are versatile chemical methods that utilize reactions conducted in sealed autoclaves under elevated temperatures and pressures to produce magnetic nanoparticles with controlled size, crystallinity, and morphology. In hydrothermal synthesis, aqueous solvents are employed, whereas solvothermal methods use non-aqueous organic solvents, allowing a broader range of reaction conditions and product characteristics. These high-pressure, high-temperature environments facilitate enhanced solubility and reactivity of precursors, promoting the formation of highly crystalline nanoparticles with uniform size distributions.

By carefully adjusting key synthesis parameters such as temperature, reaction duration, solvent type and composition, and precursor concentration, researchers can precisely tailor the physicochemical properties of magnetic nanoparticles to meet specific application requirements. One of the significant advantages of hydrothermal and solvothermal methods is their ability to synthesize nanoparticles with diverse morphologies, including spheres, rods, plates, and phase purity, which directly influence magnetic properties and antibacterial efficacy. Additionally, these methods often yield nanoparticles with superior crystallinity compared to conventional co-precipitation, resulting in enhanced magnetic behavior desirable for biomedical imaging, drug delivery, and hyperthermia treatments. However, the requirement for specialized high-pressure equipment and longer reaction times can limit the scalability and increase production costs. Despite these challenges, hydrothermal and solvothermal syntheses remain valuable tools in producing high-quality magnetic nanoparticles for both medical and food industry applications, where precise control over nanoparticle characteristics is essential [38, 39].

2.4. Green-synthesis methods

Green-synthesis methods have emerged as a sustainable and environmentally friendly alternative for producing MNPs, avoiding the use of toxic chemicals and harsh reaction conditions typically associated with conventional chemical techniques. These approaches harness biological entities such as plant extracts, bacteria, fungi, or algae, which act simultaneously as reducing, capping, and stabilizing agents during the synthesis process. The biomolecules present in these natural sources, such as polyphenols, flavonoids, terpenoids, proteins, and enzymes, not only facilitate the reduction of metal ions but also impart surface functional groups that can enhance the biological activity and biocompatibility of the resulting nanoparticles. Plant-mediated synthesis is particularly attractive due to its simplicity, scalability, and the wide availability of plant resources.

Extracts from leaves, roots, or fruits can efficiently mediate nanoparticle formation under mild conditions, eliminating the need for high temperatures, pressures, or toxic solvents. Microbial synthesis using bacteria or fungi offers another promising route, providing precise control over nanoparticle nucleation and growth through enzymatic and metabolic pathways. One of the most noteworthy features of green-synthesized MNPs is their surface bio-functionalization. The natural capping agents not only stabilize the nanoparticles but can also enhance their antibacterial activity by facilitating better interaction with microbial cell membranes or promoting ROS generation. Moreover, the improved biocompatibility of these particles makes them suitable candidates for various biomedical applications, including wound healing, targeted drug delivery, and biosensing.

In the food industry, green-synthesized MNPs have shown potential in the development of biodegradable antimicrobial packaging, active food coatings, and nano-sensors for spoilage detection. Their non-toxic nature and natural origin make them particularly suited for applications requiring human or environmental safety. Despite their advantages, green-synthesis methods may face challenges such as batch-to-batch variability, lower reaction yields, and limited control over particle size and morphology. Nevertheless, persistent research is focused on optimizing these parameters to expand the applicability of green-synthesized MNPs in both medical and food-related domains [40-42].

3. Antibacterial mechanisms of magnetic nanoparticles

Magnetic nanoparticles, particularly those doped with antibacterial ions or functionalized with bioactive agents, exhibit potent antimicrobial activity through multiple synergistic mechanisms [43]. These mechanisms operate at the molecular and cellular levels and vary depending on the nanoparticle's chemical composition, size, surface functionalization, and the type of bacterial strain (i.e., gram-positive vs. gram-negative). The following is a detailed overview of the principal antibacterial mechanisms by which magnetic nanoparticles inactivate or destroy bacterial cells.

3.1. Disruption of bacterial cell membrane integrity

One of the most prominent and direct antibacterial mechanisms of magnetic nanoparticles involves the disruption of the bacterial cell membrane, a critical structural component essential for maintaining cellular integrity and homeostasis. Owing to their nanoscale dimensions and high surface-area-to-volume ratio, MNPs exhibit unique physicochemical properties that facilitate close interaction with bacterial cells. Notably, their surface charge enables strong electrostatic interactions with the negatively charged components of bacterial cell walls, such as lipopolysaccharides in Gram-negative bacteria and teichoic acids in Gram-positive species.

Upon approaching the bacterial surface, MNPs can adsorb and penetrate the outer structures of the cell envelope. This interaction is often driven by electrostatic attraction and can result in the insertion of nanoparticles into the lipid bilayer. Such insertion disrupts the membrane's structural integrity, leading to several downstream effects: destabilization of the lipid matrix, formation of nanoscale pores, and leakage of vital intracellular components, including proteins, ions, and nucleic acids. These events compromise membrane function and induce increased permeability, creating an osmotic imbalance that ultimately culminates in bacterial cell lysis. Furthermore, the antibacterial efficacy of MNPs can be significantly enhanced through surface modification or doping with antimicrobial metal ions such as silver (Ag^+) or copper (Cu^{2+}). These dopants facilitate additional modes of action, including the generation of ROS, catalytic oxidative stress, and direct interactions with membrane proteins and phospholipids, further weakening the cell envelope. Collectively, these synergistic effects make MNPs, particularly when functionalized, highly effective agents against a broad spectrum of bacterial pathogens [44-46].

3.2. Generation of reactive oxygen species (ROS)

A central antibacterial mechanism of magnetic nanoparticles is the induction of oxidative stress through the generation of ROS. These include highly reactive molecules such as hydroxyl radicals ($OH^\bullet$), superoxide anions ($O_2^{\bullet-}$), and hydrogen peroxide (H_2O_2), which can interact destructively with essential biomolecules within bacterial cells, leading to structural and functional damage. ROS generation by MNPs occurs primarily through Fenton and Fenton-like reactions, in which ferrous (Fe^{2+}) and ferric (Fe^{3+}) ions catalyze the decomposition of hydrogen peroxide into reactive radicals. The presence of redox-active dopants such as copper (Cu^{2+}) or manganese (Mn^{2+}) can further enhance this process by facilitating electron transfer reactions that intensify ROS production. Additionally, in certain composite or semiconductor-modified MNPs, exposure to ultraviolet or visible light induces photo-activation, resulting in the formation of electron-hole pairs. These photo-induced charges subsequently react with molecular oxygen and water to generate ROS through a series of redox reactions. Once formed, these reactive species readily diffuse into bacterial cells, where they initiate a cascade of oxidative damage.

Lipid peroxidation compromises the integrity and fluidity of the cell membrane, leading to increased permeability, disruption of ion gradients, and eventual cell lysis. Proteins are also targeted, undergoing oxidative modifications that result in loss of enzymatic activity and breakdown of metabolic pathways. Furthermore, ROS can cause significant genotoxic effects by introducing strand breaks, base modifications, and oxidative lesions in DNA, thereby impairing replication and transcription processes. This oxidative mechanism is particularly effective under aerobic conditions, where sufficient oxygen is available to sustain the redox cycles involved in ROS generation. As a result, MNP-induced oxidative stress contributes to a broad-spectrum antibacterial effect that is non-specific, making it highly effective against diverse classes of bacterial pathogens. Moreover, this mode of action often works synergistically with other antibacterial mechanisms of MNPs, such as membrane disruption and metal ion toxicity, thereby enhancing their overall antimicrobial efficacy [47, 48].

3.3. Metal ion release and intracellular toxicity

Another important antibacterial mechanism of magnetic nanoparticles, particularly those doped with biologically active metal ions such as silver (Ag^+), zinc (Zn^{2+}), or copper (Cu^{2+}), is their ability to act as reservoirs for controlled and sustained ion release. When these doped MNPs come into contact with aqueous environments or bacterial cells, the embedded metal ions are gradually released into the surrounding medium. This release is often facilitated by factors such as local pH, redox conditions, or the presence of cellular metabolites, allowing for a regulated exposure that enhances antimicrobial efficacy while minimizing off-target toxicity. Once liberated, these metal ions can readily penetrate bacterial membranes and accumulate within the intracellular environment, where they exert toxic effects through multiple molecular pathways. A key mode of action involves the binding of metal ions to thiol (-SH) groups in bacterial proteins and enzymes. This interaction leads to conformational changes or inactivation of critical metabolic enzymes, disrupting processes such as nutrient metabolism, redox homeostasis, and stress response systems. Furthermore, metal ions can directly interfere with genetic processes by interacting with nucleic acids, thereby impairing DNA replication, transcription, and protein synthesis. These interactions not only hinder bacterial proliferation but may also induce genotoxic stress and mutagenesis.

In addition to enzymatic and genetic disruption, metal ions are known to interfere with cellular energy production. They can impair the function of membrane-bound proteins involved in the electron transport chain, leading to a collapse in proton motive force and a significant reduction in ATP synthesis. This energy depletion compromises the cell's ability to maintain homeostasis and repair damage, ultimately contributing to cellular dysfunction and death. This ion-mediated toxicity is particularly valuable in combating antibiotic-resistant bacterial strains, as it operates through mechanisms distinct from those targeted by conventional antibiotics. By supplementing the physical effects of membrane disruption and the oxidative stress induced by reactive oxygen species, metal ion release provides a multifaceted antibacterial strategy that enhances the overall potency of MNP-based antimicrobial systems [49-51].

3.4. Biofilm penetration and inhibition

Bacterial biofilms represent a significant challenge in antimicrobial therapy due to their highly structured, multicellular architecture and protective extracellular polymeric matrix, which confer enhanced resistance to conventional antibiotics and host immune responses. These biofilms, commonly found on implanted medical devices, chronic wound surfaces, and mucosal tissues, create a physical and chemical barrier that limits the diffusion of antimicrobial agents and promotes the persistence of bacterial infections.

Magnetic nanoparticles, owing to their unique physicochemical properties and external controllability, offer a promising strategy for biofilm disruption and eradication. One of the most distinctive advantages of

MNPs is their responsiveness to external magnetic fields, which enables their targeted and magnetically guided transport deep into dense biofilm structures. This targeted penetration allows MNPs to overcome diffusion limitations that typically hinder conventional treatments. Once within the biofilm, MNPs can be engineered to generate ROS in situ, particularly upon exposure to light or in the presence of catalytic metal ions.

The localized production of ROS within the biofilm microenvironment facilitates the oxidative degradation of the extracellular polymeric substances (EPS) that form the scaffold of the biofilm matrix. This degradation weakens the physical integrity of the biofilm and increases its permeability, rendering the embedded bacterial cells more susceptible to antimicrobial action. Furthermore, MNPs can be functionalized to carry or co-deliver biofilm-disrupting agents, such as dispersin B, DNase, or surfactants, which enzymatically or chemically break down matrix components like extracellular DNA, polysaccharides, and proteins. This multifunctional approach not only enhances the penetration and dispersion of biofilms but also aids in the prevention of biofilm reformation. By combining physical penetration, chemical degradation, and potential therapeutic delivery, MNPs provide a versatile and effective platform for targeting biofilm-associated infections. Their applicability is particularly relevant in the management of chronic infections related to indwelling medical devices and poorly healing wounds, where traditional antibiotics often fail to achieve sufficient therapeutic outcomes [44, 52, 53].

3.5. Intracellular uptake and metabolic interference

Beyond their extracellular actions, magnetic nanoparticles also exert potent intracellular effects following their uptake by bacterial cells. Although bacteria lack the classical endocytic machinery found in eukaryotic cells, various studies suggest that MNPs can enter bacterial cytoplasm through mechanisms resembling endocytosis or via direct penetration facilitated by membrane disruption, especially in the presence of nanoparticle surface modifications that enhance cellular adhesion and translocation. Once internalized, MNPs interact with key intracellular components, initiating a cascade of cytotoxic events that compromise bacterial viability.

A primary mode of intracellular toxicity involves the disturbance of redox homeostasis. Internalized MNPs can catalyze the generation of ROS within the cytosol, intensifying oxidative stress beyond the cell's capacity for detoxification.

This intracellular ROS accumulation leads to widespread damage to nucleic acids, proteins, and membrane structures from within the cell itself. In addition to oxidative stress, MNPs can interfere directly with ribosomal function, disrupting the process of protein translation. By hindering the synthesis of essential enzymes and structural proteins, MNPs severely limit the bacteria's ability to grow, replicate, and respond to environmental stressors. Moreover, exposure to internalized nanoparticles has been shown to alter gene expression profiles and modulate the activity of critical metabolic enzymes. Such interference with the regulation of genes involved in cell division, repair mechanisms, and energy metabolism can push bacterial cells into a state of metabolic arrest or apoptosis-like death.

The cytosolic presence of MNPs, therefore, introduces a multilayered form of metabolic interference that complements their extracellular actions. This intracellular mechanism becomes particularly powerful when MNPs are used as carriers for antibiotics or bioactive polymers. By delivering therapeutic agents directly into the bacterial cytoplasm, MNPs bypass external resistance mechanisms and maximize the intracellular drug concentration, thereby enhancing overall antibacterial efficacy. This integrated strategy makes MNPs valuable tools in combating resistant bacterial strains and persistent infections [48, 54].

3.6. Photo-thermal and magnetic hyperthermia effects

In addition to their intrinsic chemical and biological activities, MNPs can be engineered to respond to external physical stimuli, enabling localized thermal therapy as an auxiliary antibacterial strategy. Specifically, when exposed to alternating magnetic fields (AMFs), certain MNPs undergo magnetic relaxation processes that result in the generation of localized heat, a phenomenon known as magnetic hyperthermia.

Similarly, MNPs modified with photo-thermal agents or possessing intrinsic optical absorption capabilities can convert near-infrared (NIR) light or laser irradiation into

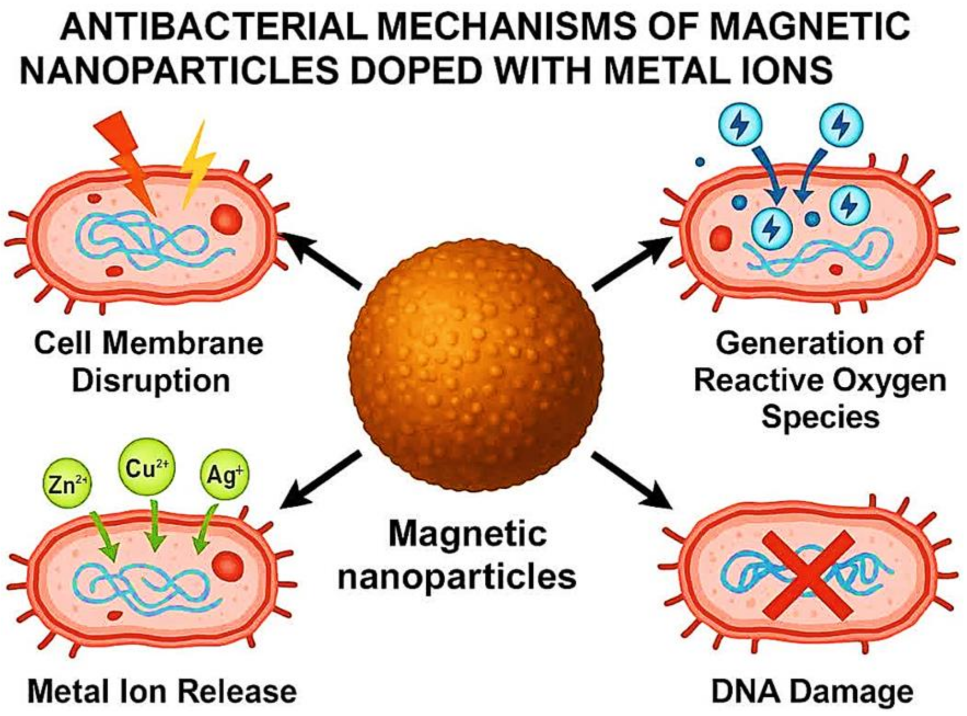

Figure 1. Schematic representation of the antibacterial mechanisms of magnetic nanoparticles.

heat through non-radiative decay, producing a photo-thermal effect. The mild, localized elevation of temperature in the range of approximately 42–50 °C, while not damaging to surrounding healthy tissue, is sufficient to exert bactericidal effects. This thermal energy can denature bacterial proteins, destabilize cellular membranes, and impair essential enzymatic functions, leading to irreversible damage and cell death. Moreover, hyperthermia has been shown to enhance the efficacy of other antibacterial mechanisms, such as ROS-mediated oxidative stress and antibiotic action.

By increasing bacterial membrane permeability and disrupting repair pathways, heat treatment can facilitate the intracellular uptake of drugs and potentiate their effects, thereby overcoming common resistance mechanisms. The capacity for spatially controlled activation through external stimuli makes this approach particularly attractive for non-invasive and site-specific antibacterial therapies. This is especially valuable in the treatment of deep-seated infections or biofilm-associated infections on implanted medical devices, where conventional systemic antibiotics often fail to achieve therapeutic concentrations. Thus, photo-thermal and magnetic hyperthermia strategies represent a promising extension of MNP functionality, contributing to the development of responsive, multimodal, and highly effective antimicrobial platforms [55-57].

In conclusion, the antibacterial activity of magnetic nanoparticles arises from a combination of physical, chemical, and biochemical interactions. Their multi-target action makes them effective even against multidrug-resistant (MDR) bacterial strains. By tuning the particle design through doping, surface modification, or external activation, MNPs can be adapted to specific medical or food-related antibacterial challenges. These diverse mechanisms make MNPs one of the most promising candidates for next-generation antimicrobial technologies. Figure 1 illustrates a schematic representation of the antibacterial mechanisms exhibited by magnetic nanoparticles.

4. Antibacterial dopants in magnetic nanoparticles: Properties and applications

To enhance antibacterial efficacy and tune magnetic features, researchers have focused on incorporating other functional metal ions into the iron oxide lattice.

The substitution of iron ions with metals such as silver (Ag^+), zinc (Zn^{2+}), copper (Cu^{2+}), cobalt (Co^{2+}), or manganese (Mn^{2+}) can significantly alter the surface reactivity, redox potential, and ion release profile of the nanoparticles. These dopant ions not only increase the oxidative stress generated upon interaction with microbial cells but also disrupt key cellular processes such as membrane integrity, enzyme activity, and DNA replication [58, 59].

The modified particles thus exhibit multifaceted antimicrobial actions that are often more potent than their undoped counterparts. For instance, Ag-doped Fe_3O_4 nanoparticles have been shown to possess synergistic antimicrobial capabilities, whereby silver ions confer strong bactericidal effects while the iron oxide core maintains magnetic properties necessary for targeted delivery and post-use recovery. Beyond bulk composition, the surface chemistry of MNPs plays a crucial role in their colloidal stability, interaction with bacterial membranes, and compatibility with biological environments [18].

Surface functionalization, often performed post-synthesis, enables the introduction of stabilizing or bioactive agents such as polymers, surfactants, biopolymers, or small molecules. These modifications serve to improve dispersion in aqueous or biological media, prevent nanoparticle agglomeration, and increase specificity toward microbial targets [60]. Moreover, tailored surface coatings can facilitate the loading of therapeutic agents, enzymes, or fluorescent markers, thus transforming MNPs into multifunctional platforms capable of simultaneous bacterial eradication, diagnostics, and therapeutic delivery. In medical applications and food safety, the ability to fine-tune the chemical composition and surface characteristics of MNPs is of paramount importance. In clinical contexts, such engineered nanoparticles are being explored for use in targeted drug delivery, wound healing, implant coatings, and theranostic systems that combine antimicrobial activity with imaging functionalities.

In the food sector, compositionally optimized MNPs are being integrated into smart packaging materials, active coatings, and biosensors for contamination monitoring [61]. Ultimately, the convergence of compositional engineering and surface functionalization allows for the rational design of advanced MNPs with enhanced antibacterial efficiency, improved safety profiles, and increased versatility across diverse application domains.

Doped-magnetic nanoparticles, particularly iron oxides, with antibacterial metal ions are a common strategy to enhance their antimicrobial efficacy while preserving or tuning their magnetic properties. These dopants not only contribute directly to bacterial cell disruption but also modulate surface reactivity, oxidative stress generation, and biocompatibility. The following is a detailed overview of the most prominent antibacterial dopants, their roles, and application relevance in medical and food-related fields.

4.1. Silver (Ag^+)

Silver ions (Ag^+), as a functional dopant in magnetic nanoparticles, are recognized as one of the most potent and broad-spectrum antimicrobial agents, with mechanisms of action that include disruption of bacterial membranes, interference with DNA replication, and the induction of oxidative stress through ROS generation [62, 63].

In the context of magnetic nanoparticles, Ag^+ is often doped onto or incorporated into iron oxide cores such as Fe_3O_4 (magnetite) or γ-Fe_2O_3 (maghemite), effectively combining the intrinsic magnetic responsiveness of these cores with the potent antibacterial properties of silver. This integration enables the design of multifunctional nanostructures capable of both diagnostic and therapeutic applications. From a biomedical standpoint, silver-doped MNPs have shown great promise in a range of clinical applications. They are widely employed as antimicrobial coatings on medical implants, catheters, and surgical tools to prevent bacterial colonization and biofilm formation.

In wound management, Ag^+-functionalized MNPs are incorporated into hydrogels and advanced wound dressings to accelerate healing while providing localized antibacterial protection. Additionally, their ability to serve as both imaging agents (e.g., magnetic resonance imaging contrast enhancers) and therapeutic agents positions them as effective components in theranostic platforms aimed at simultaneously detecting and treating localized infections [64-66].

In the field of food safety, silver-doped MNPs have also demonstrated utility as active components in antimicrobial packaging materials, which inhibit

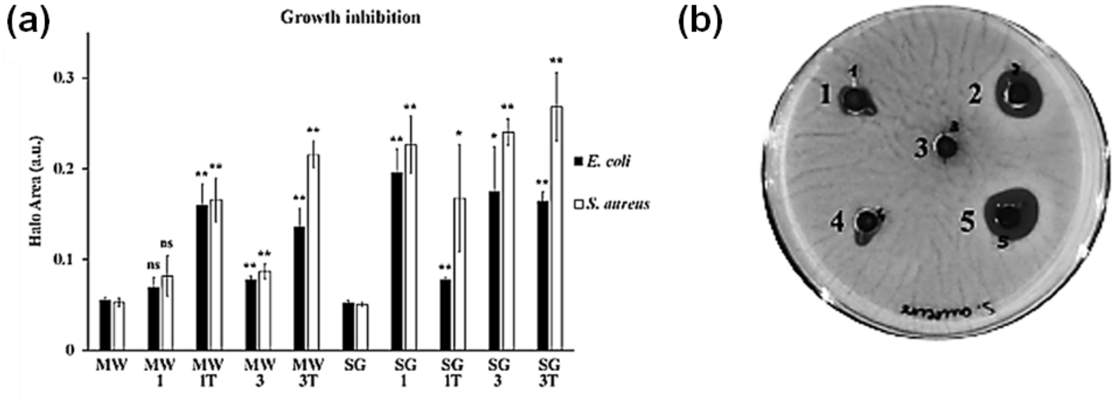

Figure 2. Investigation of the silver dopant effect on the antibacterial activity (a) of $MgFe_2O_4$ nanoparticles against *S. aureus* and *E. coli* bacteria and growth inhibition properties (b) against *S. aureus*. Reprinted/adapted with permission from Ref. [69]. 2021, MDPI.

microbial growth and extend shelf life. Moreover, they are applied as surface disinfectants and antimicrobial coatings in food processing environments, where microbial contamination poses a serious threat to public health [67, 68].

While silver doping may lead to a slight reduction in the overall magnetic saturation of iron oxide nanoparticles, this trade-off is generally acceptable given the substantial enhancement in antimicrobial efficacy. Notably, even at relatively low silver concentrations, these nanocomposites exhibit significant bactericidal activity, making them a cost-effective and efficient option for diverse antibacterial applications.

Fantozzy et al. [69] investigated the effect of silver doping on the antibacterial performance of $MgFe_2O_4$ nanoparticles. The results (Figure 2) demonstrated that the incorporation of silver ions into the structure led to a significant enhancement in the antibacterial properties. Also, with increasing silver dopant levels, an increase in antibacterial properties was observed.

Rabbi and colleagues [70] synthesized the magnetic iron oxide/silver (IO/Ag) nanocomposites via a co-precipitation method, where bare iron oxide nanoparticles were stabilized using green-synthesized silver nanoparticles.

The catalytic reduction performance of the IO/Ag nanocomposite was evaluated using $NaBH_4$ as a reducing agent, demonstrating effective degradation of the anionic azo dye Congo Red (CR). Complete degradation of 20 mL of 0.1 mM CR solution was achieved within 2 minutes when 40 μg/mL of IO/Ag particles were applied. The nanocomposite also exhibited moderate antibacterial activity against four pathogenic bacterial strains, including both Gram-positive (*Staphylococcus aureus*) and Gram-negative bacteria (*Escherichia coli*, *Shigella dysenteriae*, and *Shigella boydii*). Antibacterial activity was found to increase with particle concentration, with inhibition zones ranging from 7 to 12.5 mm, reaching a maximum inhibition zone of 12.5 mm against *S. aureus* at a concentration of 105 μg/disc. Notably, the bare IO nanoparticles did not exhibit any antibacterial effect, indicating that the observed antimicrobial performance is attributable to the presence of silver nanoparticles in the composite.

Regarding the mechanisms of antibacterial action, two primary pathways are suggested, which are the release of silver ions (Ag^+) from the nanoparticles, which penetrate bacterial membranes and disrupt vital cellular processes such as respiration and osmotic balance, and direct contact-based bacterial membrane disruption via anchored AgNPs on the nanocomposite surface. In addition to their antibacterial capabilities, the IO/Ag nanocomposite particles demonstrated significant antioxidant activity, with 94% DPPH free radical scavenging observed at a particle concentration of 100 μg/mL.

Overall, these biocompatible and relatively low-toxicity IO/Ag nanocomposites show promise as bioactive materials for a wide range of applications in biomedicine and health-related consumer products, particularly due to their recoverability from application media, which minimizes potential environmental and health risks.

In a related study, Güneş et al. [71] successfully synthesized magnetic iron oxide nanoparticles (MIONPs) via a chemical co-precipitation method. To improve their surface functionality, activated carbon (AC) derived from Hibiscus esculentus (HE) fruit was utilized to coat the nanoparticles, yielding MIONPs/HEAC nanocomposites. Subsequently, to enhance the antimicrobial performance of the system, silver ions were chemically reduced and deposited onto the MIONPs/HEAC surfaces, forming MIONPs/HEAC@Ag nanocomposites. Antibacterial evaluations revealed that both MIONPs/HEAC and MIONPs/HEAC@Ag exhibited inhibitory effects against *Staphylococcus aureus* and *Escherichia coli*. Notably, the MIONPs/HEAC@Ag nanocomposite demonstrated superior antimicrobial efficacy, which is attributed to the synergistic interplay between the intrinsic magnetic properties of iron oxide and the potent bactericidal activity of silver nanoparticles (Figure 3).

4.2. Zinc (Zn^{2+})

Zinc ions (Zn^{2+}), as a biocompatible antibacterial dopant in magnetic nanoparticles, possess moderate but effective antibacterial activity, making them particularly attractive for biomedical applications where antimicrobial efficacy must be balanced with biocompatibility [72]. As an essential trace element in human physiology, zinc participates in numerous enzymatic and regulatory pathways, and its incorporation into antibacterial materials is generally well tolerated by biological systems. The antibacterial mechanism of Zn^{2+} primarily involves the inhibition of critical bacterial enzymes, disruption of membrane integrity, and induction of oxidative stress through the generation of reactive oxygen species [73]. Zn^{2+} is typically doped with iron oxide matrices such as Fe_3O_4 or γ-Fe_2O_3. This doping not only imparts antimicrobial functionality but also enhances the overall biological safety and colloidal stability of the nanomaterial. Zinc-doped MNPs have demonstrated particular effectiveness against Gram-positive bacterial strains, which are often

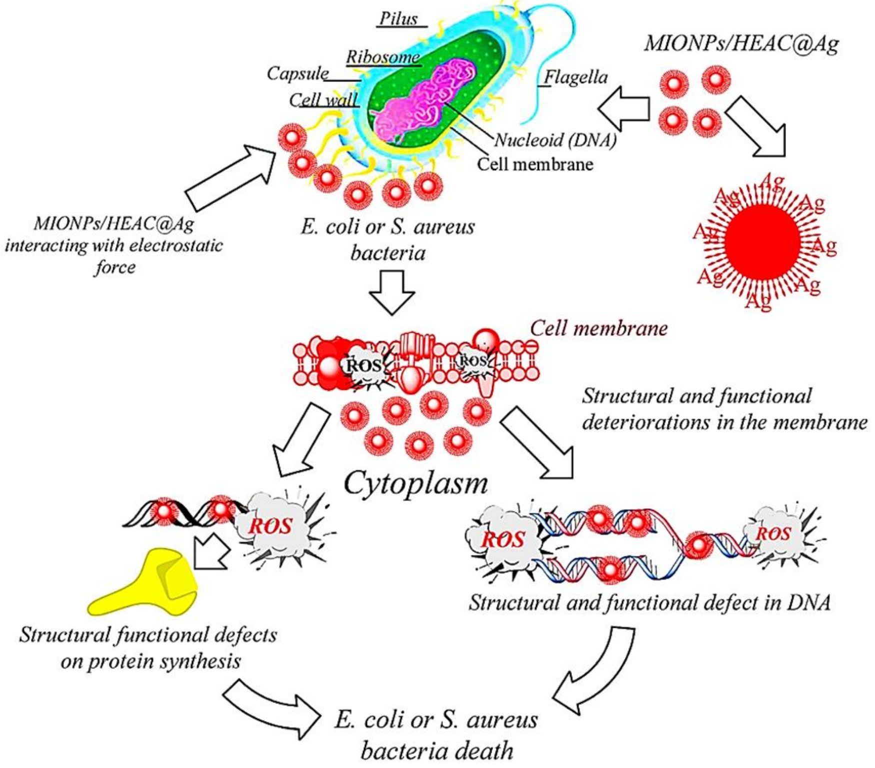

Figure 3. The scheme of antimicrobial mechanisms of MIONPs/HEAC@Ag nanocomposites. Reprinted/adapted with permission from Ref. [71]. 2025, MDPI.

more resilient to conventional treatments due to their thick peptidoglycan layers. Additionally, Zn-doping has been shown to improve the chemical stability and reduce the cytotoxicity of the nanoparticles, making them especially suitable for applications requiring prolonged or repeated exposure [74-76].

In the medical field, zinc-functionalized MNPs are widely explored as components of bone cements, scaffold materials, and other bioactive platforms intended for orthopedic applications. Their antimicrobial properties help prevent post-surgical infections, while their biocompatibility supports tissue integration and healing [77, 78]. Zinc's application also extends to the food industry, where it serves as a safe and effective antimicrobial active material and additive in various food packaging systems. Zn-doped MNPs are incorporated into edible coatings and biodegradable films used to preserve perishable goods such as fresh fruits, vegetables, and meats. These films not only inhibit microbial growth but also contribute greatly to the extended shelf life of products and reduced spoilage under storage conditions [79-81].

Hosseinzadeh et al. [82] investigated the effects of zinc doping and surface coating with various morphologies of zinc oxide on the Zn^{2+} ion release rate, antibacterial activity, and biological properties of Fe_3O_4 nanoparticles. Their findings revealed that the lowest zinc ion release rate was observed in structures incorporating zinc as a dopant, while the highest release rate corresponded to nanoparticles coated with mesoporous zinc oxide. This increased release rate was directly correlated with the surface area exposed to the reaction medium. Moreover, as the zinc ion release rate increased, there was a marked enhancement in both the inhibition of bacterial growth and bactericidal activities of the compounds. These results suggest a direct relationship between the release of zinc ions and the antibacterial efficacy of the nanoparticles.

Yusof et al. [83] investigated the antibacterial activity of biologically synthesized ZnO NPs against poultry-associated foodborne pathogens, *Salmonella spp.*, *E. coli*, and *S. aureus* (Figure 4). The Zn^{2+} dissolution study revealed that ZnO NPs dissolved more ions than their bulkier counterparts, implying that the release of high Zn^{2+} was responsible for the antibacterial activity. Based on the agar well diffusion assay, MIC and MBC, time-kill assay, and antibiofilm activity tests, the ZnO NPs exhibited effective antibacterial actions against poultry-associated foodborne pathogens, with *S. aureus* as the most susceptible to ZnO NPs. The ROS formation, cellular leakage, and SEM study revealed that the underlying antibacterial mechanisms of ZnO NPs include the generation of ROS, oxidative stress on the bacterial cell membrane leading to membrane damage, and cellular material leakage, which ultimately leads to cell death.

Overall, the incorporation of zinc into magnetic nanoparticles enhances their antimicrobial spectrum while maintaining a favorable safety profile. Its multi-functionality and compatibility with both biomedical and food-grade applications make Zn^{2+} a valuable dopant for the development of next-generation antimicrobial nanomaterials.

4.3. Copper (Cu^{2+})

Copper ions (Cu^{2+}), as a potent antibacterial dopant in magnetic nanoparticles, are well recognized for their strong antibacterial activity, particularly against gram-negative bacteria, which are often more challenging to treat due to their complex outer membrane structures. The antimicrobial efficacy of Cu^{2+} arises from its ability to generate ROS, leading to oxidative damage of vital microbial components such as proteins and nucleic acids. This oxidative stress results in compromised cellular functions and eventual bacterial death [84].

When incorporated into magnetic nanoparticles, copper ions enhance the oxidative stress-inducing capacity of the nanomaterial, amplifying its bactericidal potential. Additionally, copper doping may synergize with other metal ions like silver and iron, resulting in multi-modal antibacterial activity that targets bacteria through complementary mechanisms. In medical applications, Cu^{2+}-doped MNPs have been utilized as topical antimicrobial agents for treating skin infections, leveraging their potent bactericidal effects while minimizing systemic toxicity [85]. Furthermore, copper-functionalized nanoparticles are increasingly investigated as coatings for orthopedic implants and surgical devices to prevent post-operative infections, a major concern in clinical settings [86].

By inhibiting bacterial colonization and biofilm formation, these coatings contribute to improved patient outcomes and implant longevity. In the food industry,

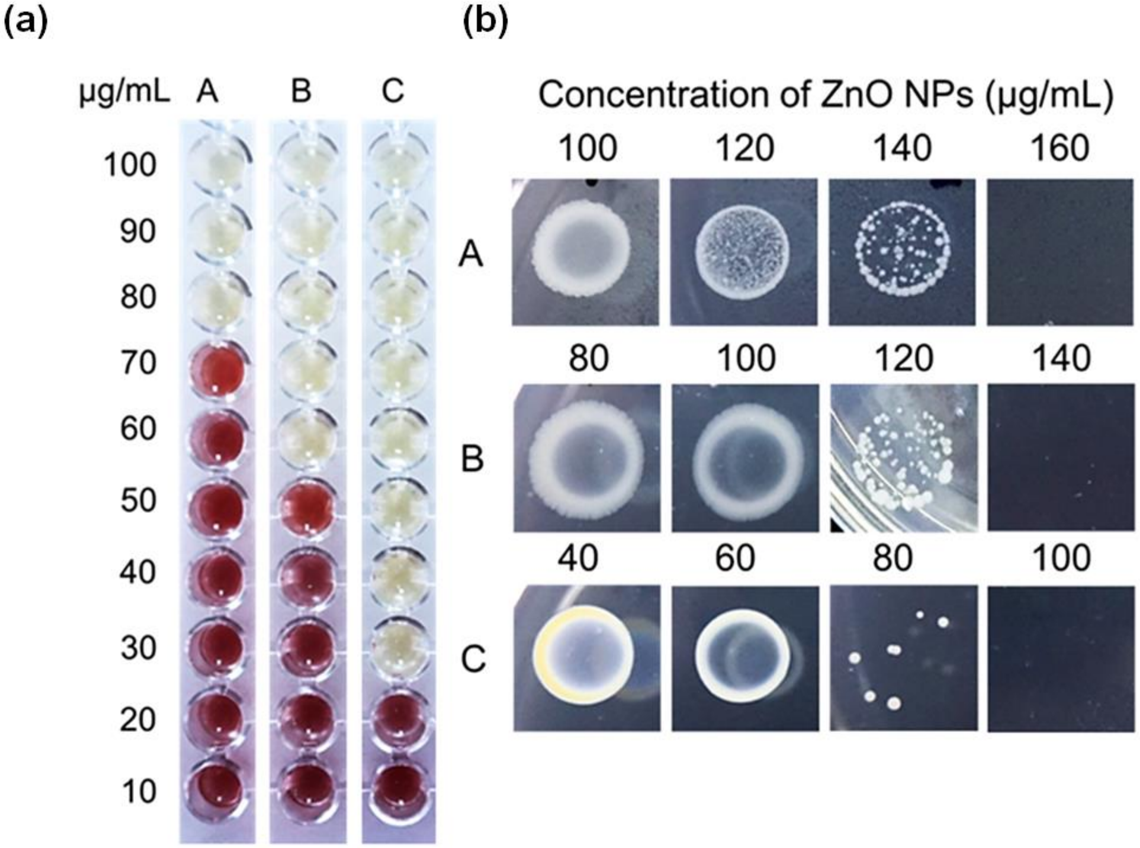

Figure 4. Minimum inhibitory concentration (MIC) (a) and minimum bactericidal concentration (MBC) (b) of biosynthesized ZnO NPs against *Salmonella* spp. (A), *E. coli* (B), and *S. aureus* (C). Reprinted/adapted with permission from Ref. [83]. 2016, MDPI.

copper-based MNPs are incorporated into nano-sanitizers and disinfectants designed for the effective decontamination of processing tools and surfaces, thereby reducing the risk of foodborne pathogens. Additionally, copper-doped nanomaterials are integrated into recyclable antimicrobial films, which serve as active packaging to inhibit microbial growth and prolong the shelf life of food products [87].

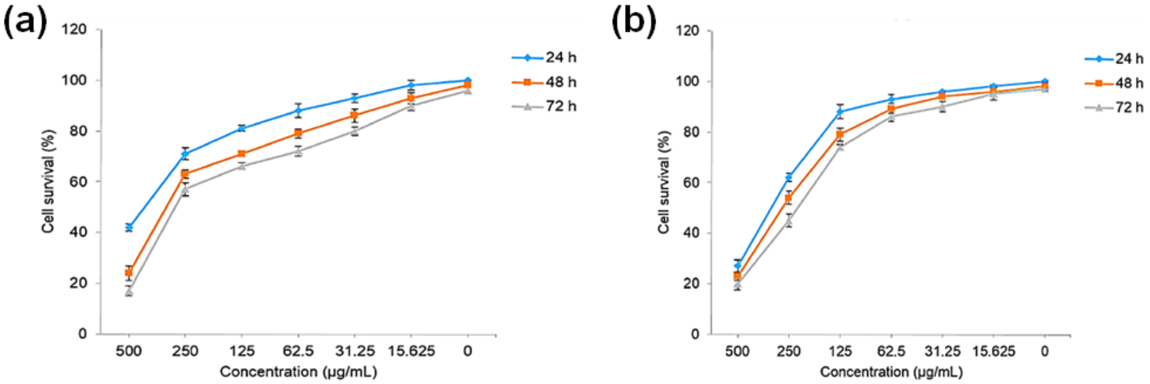

Figure 5. The cytotoxic effect of $CuFe_2O_4$ (a) and $ZnFe_2O_4$ (b) nanoparticles on MCF-7 cell-lines. Reprinted/adapted with permission from Ref. [89]. 2016, MDPI.

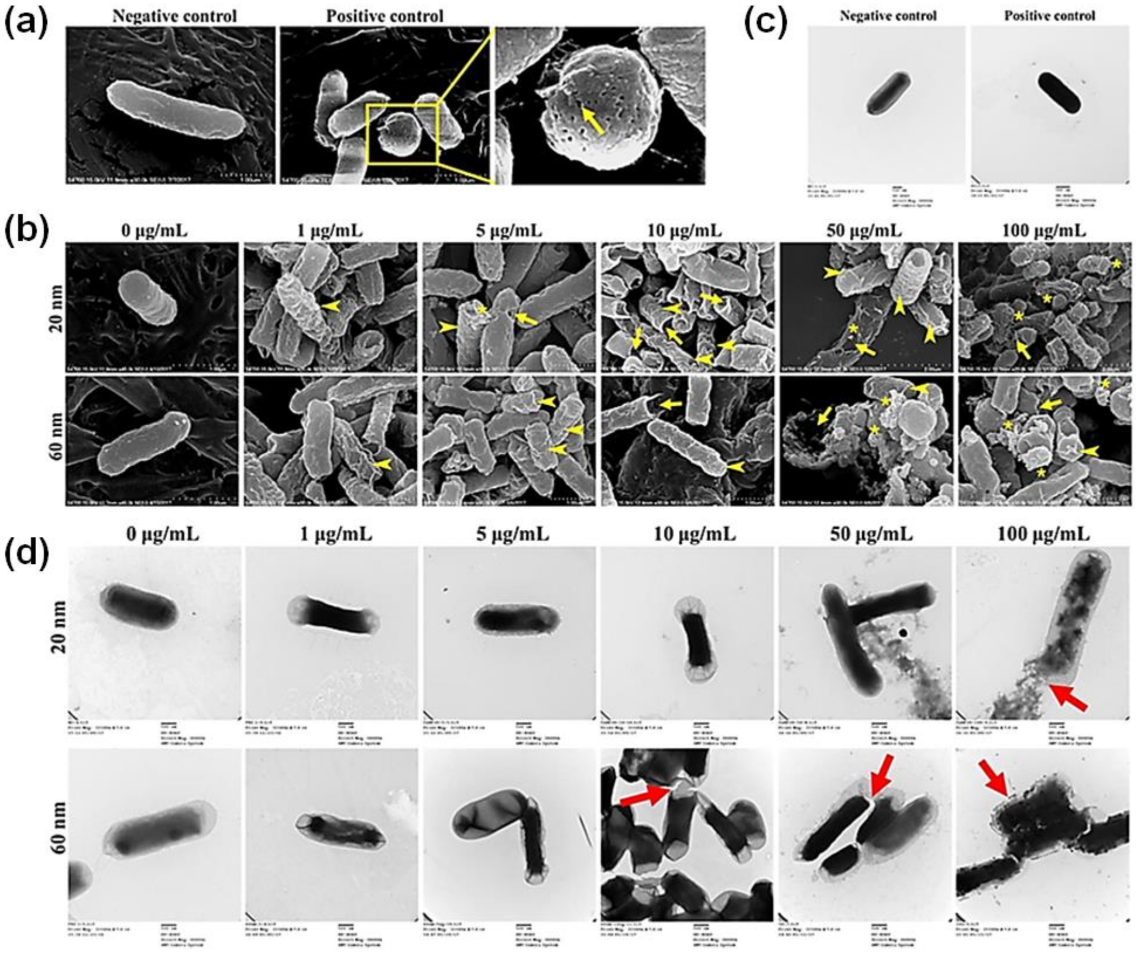

Figure 6. Electron microscopy images of *E. coli* treated with two sizes of CuNPs in different concentrations. Live or dead cells observed via SEM (a,b) and Live or dead cells observed via TEM (c,d). Reprinted/adapted with permission from Ref. [90]. 2022, MDPI.

Despite its potent antimicrobial properties, the high ROS generation associated with copper ions necessitates careful surface modification of MNPs to control potential cytotoxicity and ensure biocompatibility, especially for applications involving direct human contact [88]. These modifications can optimize the balance between efficacy and safety, broadening the practical utility of copper-doped MNPs in diverse antibacterial applications. In a study, Kanagesan et al. [89] investigated the cytotoxicity induced by copper and zinc doping in magnetite nanoparticles. The results (Figure 5) showed that the cytotoxic effect of copper ions on MCF-7 cells was greater than that of zinc ions.

Lai et al. [90] investigated the effects of copper oxide nanoparticles' size and concentration on their antibacterial properties through multiple mechanisms. The obtained results (Figure 6) demonstrated that both 20 nm and 60 nm CuNPs exhibited effective antimicrobial activity with minimal cytotoxicity toward normal human skin cells. ROS assays showed that both particle sizes increased intracellular ROS levels in *E. coli*, but only at low concentrations (1 and 5 μg/mL) did the 20 nm CuNPs generate significantly higher ROS compared to the 60 nm particles. Notably, no clear dose-dependent trend was observed in ROS production across increasing concentrations, consistent with the bactericidal analysis. Further evaluations, including DNA gel electrophoresis, annexin V-PI staining, and modulator rescue experiments, confirmed that the bactericidal effects of CuNPs were size and concentration-dependent, acting through multiple mechanisms.

Figure 7 provides a comprehensive schematic of the main toxicity pathways associated with copper oxide-based nanoparticles, as well as the surface contact-mediated antibacterial mechanisms operating under both wet and dry conditions. In wet environments, CuO NPs can release Cu^{2+} ions and induce oxidative stress through the generation of reactive oxygen species (ROS), leading to damage to bacterial membranes, proteins, and nucleic acids. Additionally, direct interaction with the bacterial cell surface can disrupt membrane integrity, resulting in leakage of intracellular contents.

Under dry conditions, the antibacterial effect is predominantly governed by physical contact between nanoparticles and bacterial surfaces, which may cause mechanical disruption and localized oxidative stress. Together, these mechanisms highlight the multifaceted nature of CuO NP-induced antimicrobial activity, influenced by both environmental conditions and nanoparticle properties.

4.4. Cobalt (Co^{2+})

Cobalt ions (Co^{2+}), as a multifunctional dopant in magnetic nanoparticles, are widely employed as dopants in magnetic nanoparticles primarily to modulate their magnetic and catalytic properties rather than to provide direct, strong antibacterial effects. While cobalt exhibits mild to moderate antibacterial activity, its main contribution lies in enhancing the physicochemical characteristics of MNPs, including improved thermal stability, increased coercivity, and elevated surface energy. These modifications are critical for optimizing nanoparticle performance in applications such as magnetic hyperthermia and magnetically controlled drug delivery [92-94].

When combined with more potent antibacterial ions like silver or copper, cobalt contributes to the development of multifunctional nanoplatforms that simultaneously offer enhanced magnetic responsiveness and broad-spectrum antimicrobial activity [95, 96]. In biomedical contexts, cobalt-doped MNPs are particularly valued for their role in specialized imaging techniques and magnetic hyperthermia therapies, where their enhanced magnetic anisotropy improves diagnostic resolution and therapeutic efficacy [97, 98]. Furthermore, cobalt's influence on nanoparticle stability and magnetic behavior facilitates precise magnetically guided drug release, offering controlled and targeted treatment options with added antibacterial protection.

Although cobalt's use in food-related applications remains limited due to concerns about potential toxicity, it is being explored in sensor technologies aimed at detecting microbial contamination, leveraging its magnetic properties for sensitive and rapid diagnostics [99, 100]. Overall, cobalt doping enhances the functional versatility of magnetic nanoparticles, making them

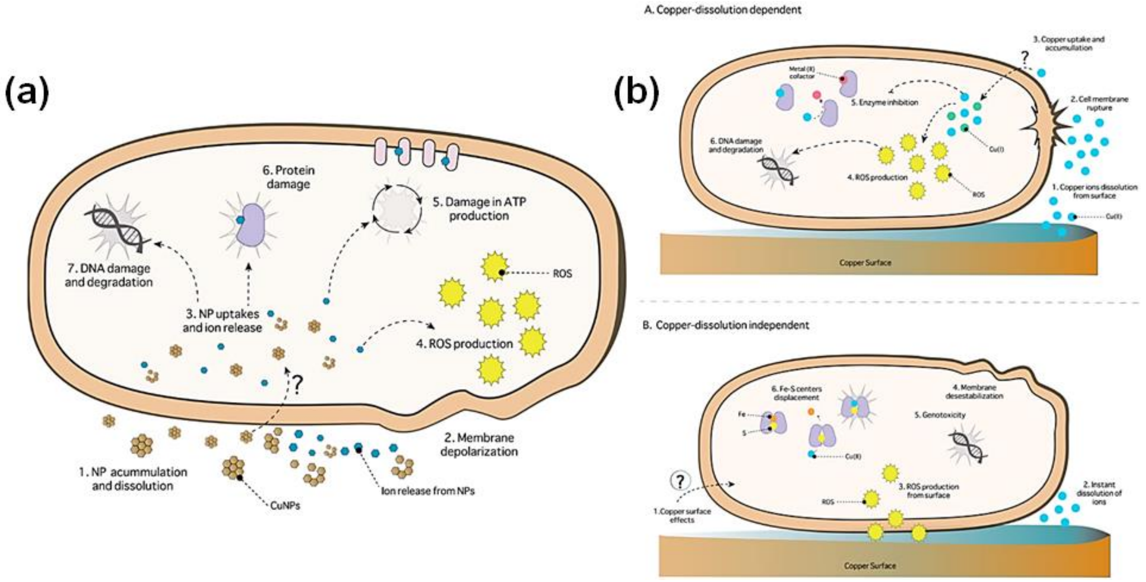

Figure 7. Schematic representation of the general toxicity mechanisms of copper oxide-based nanoparticles (a) and the surface contact-mediated antibacterial mechanisms under both wet and dry conditions (b). Reprinted/adapted with permission from Ref. [91]. 2023, MDPI.

valuable components in advanced biomedical devices and diagnostic tools, albeit with careful consideration of biocompatibility and safety profiles.

Kajani and coworkers [101] synthesized chitosan-coated mesoporous cobalt–iron nanoparticles (CoFeCH NPs) using a facile one-step hydrothermal method. The incorporation of chitosan (CH) significantly improved the biocompatibility of the nanoparticles on human cells in vitro, while simultaneously enhancing their antibacterial activity against both *Staphylococcus aureus* and *Escherichia coli*. Notably, CoFeCH NPs exhibited antibacterial efficacy comparable to, and in some cases exceeding, that of standard antibiotics. After 18 hours of incubation with 25 µg of the nanoparticles, inhibition zone diameters of 25.8 ± 1.4 mm (CoFe NPs) and 30.1 ± 1.9 mm (CoFeCH NPs) were recorded against *S. aureus*, whereas amoxicillin produced only a 13.1 ± 1.2 mm zone under the same conditions.

For *E. coli*, CoFeCH NPs also showed a significant increase in inhibition zone size (22.7 ± 2.9 mm) compared to uncoated CoFe NPs (17.6 ± 1.3 mm) and gentamicin (27.1 ± 1.6 mm). Control experiments using chitosan alone demonstrated only mild activity against *S. aureus* and no inhibition of *E. coli*, further emphasizing the synergistic antibacterial enhancement from CH coating. In addition to their antibacterial effects, both CoFe and CoFeCH NPs were evaluated as MRI contrast agents. CoFeCH NPs exhibited a transverse relaxivity (R_2) value of 91.3 $mM^{-1}\ s^{-1}$, slightly lower than that of bare CoFe NPs (97.4 $mM^{-1}\ s^{-1}$), due to the polymer coating. These

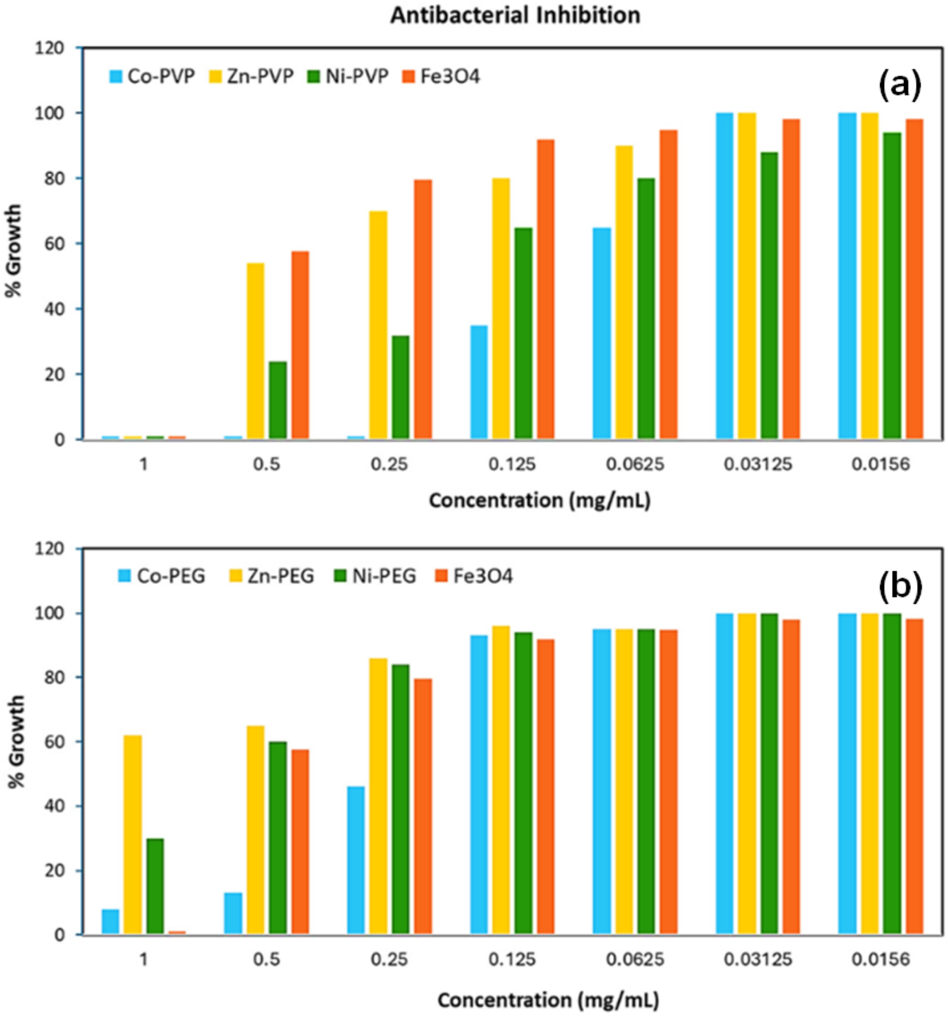

Figure 8. The evaluation of the inhibitory effects of the divalent metal-doped ferrite nanoparticles on the antibacterial properties of PVP (a) and PEG (b) ferrite nanoparticles against the Gram-negative *E. coli* bacteria. Reprinted/adapted with permission from Ref. [102]. 2025, MDPI.

findings suggest that CoFeCH NPs offer a promising multifunctional platform, combining enhanced antibacterial performance, improved biocompatibility, and effective MRI imaging capability.

AlMatri et al. [102] investigated the antibacterial properties of polymerized divalent metal-doped ferrite nanoparticles (PMFe_2O_4 NPs), where the divalent metal ions (M) included Ni, Zn, and Co (Figure 8). The study focused on evaluating their inhibitory effects against the Gram-negative bacterium *Escherichia coli*. Among the tested dopants, cobalt- and nickel-substituted ferrites exhibited the most pronounced antibacterial activity, resulting in significant inactivation of bacterial cells. These findings underscore the unique antimicrobial potential of biocompatible, metal-doped ferrites and highlight their applicability as effective antibacterial agents. Potential applications include water purification, biomedical device coatings, and other antimicrobial surface treatments.

4.5. Manganese (Mn^{2+})

Manganese ions (Mn^{2+}), as a functional dopant in magnetic nanoparticles, play a significant role in redox reactions and are known to enhance the production of ROS, thereby contributing to antimicrobial activity through oxidative stress mechanisms [58]. In magnetic nanoparticles, manganese is commonly incorporated within spinel ferrite structures such as $MnFe_2O_4$, where it imparts tunable magnetic properties alongside enhanced bactericidal effects.

The antimicrobial efficacy of manganese-doped nanoparticles can be further improved through surface engineering techniques that optimize nanoparticle interactions with bacterial cells. In medical applications, manganese-doped nanoparticles are utilized as dual-modality imaging agents, combining magnetic resonance imaging (MRI) capabilities with fluorescence properties for improved diagnostic precision [103]. Additionally, Mn^{2+}-functionalized MNPs serve as components of biodegradable drug delivery systems, where their antimicrobial surfaces help prevent infection while delivering therapeutic payloads. These features make manganese-doped nanomaterials highly attractive for integrated theranostic platforms [104, 105].

Though still in experimental stages, manganese-based MNPs are also being explored within the food industry for smart packaging applications and nanosensors designed to monitor food spoilage, leveraging their magnetic responsiveness and catalytic activity for real-time quality control [80, 106]. Furthermore, manganese doping enhances the control over nanoparticle magnetization and improves the biodegradability of the nanoparticle matrix, contributing to the development of environmentally friendly antimicrobial materials.

Dou et al. [107] investigated the antibacterial properties of manganese dioxide (MnO_2) nanosheets through mechanisms mediated by ROS generation and disruption of bacterial membrane integrity. The results showed that MnO_2 nanosheets possess potent antibacterial activity against *Salmonella* (Figure 9).

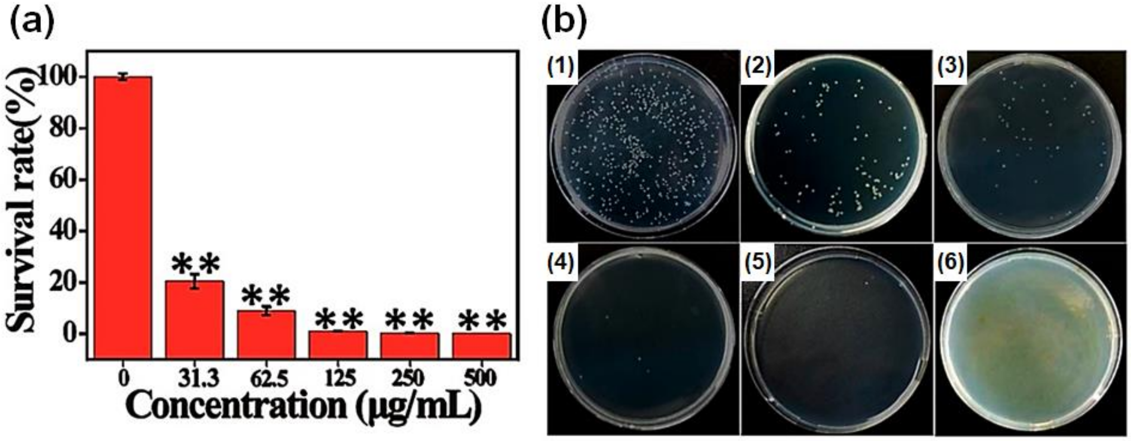

Figure 9. In vitro antibacterial activity of MnO_2 nanosheets against *Salmonella* pathogen: (a) Cell survival rates and (b) agar plates at different concentrations (0–500 μg/mL) with $p < 0.01$. Reprinted/adapted with permission from Ref. [107]. 2020, MDPI.

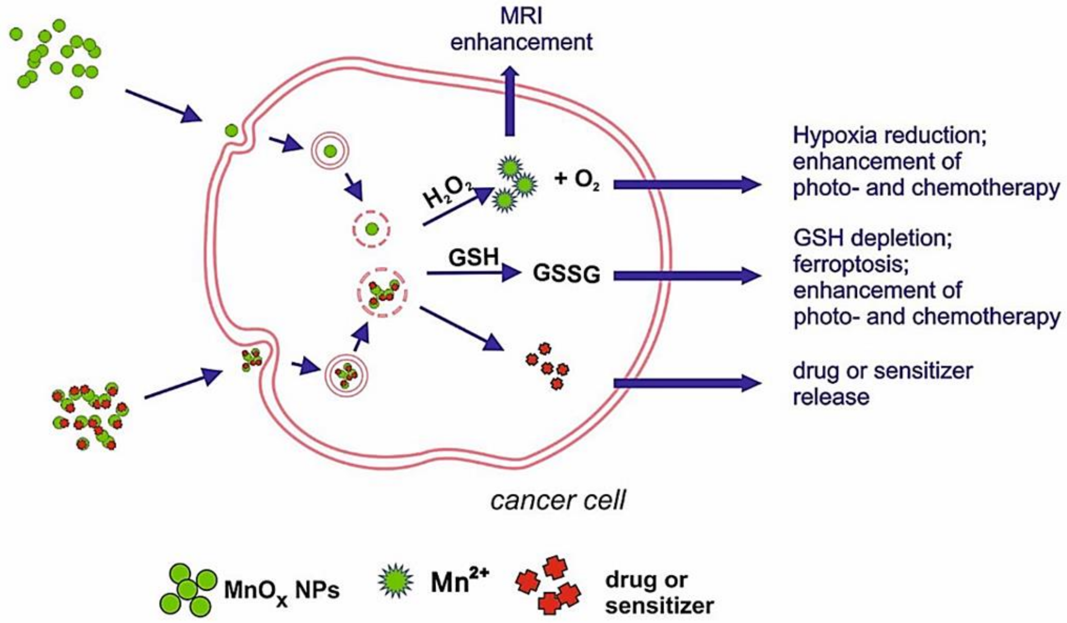

Figure 10. Schematic illustration of the main mechanisms involved in manganese oxide medical applications. Reprinted/adapted with permission from Ref. [108]. 2021, MDPI.

Growth curve analysis and colony-forming unit (CFU) assays revealed that a concentration of 125 µg/mL MnO_2 nanosheets could eliminate 99.2% of Salmonella cells.

These results were further confirmed by fluorescence-based live/dead staining. Furthermore, mechanistic studies showed that treatment with MnO_2 nanosheets significantly induced ROS production, enhanced ATPase activity, and led to leakage of intracellular electrolytes and protein content, ultimately resulting in bacterial cell death. Figure 10 schematically illustrates the key functional mechanisms of manganese oxide in medical applications. A summary of different dopants and their characteristics is presented in Table 2.

5. Applications of antibacterial magnetic nanoparticles in medical and food sectors

Magnetic nanoparticles with antibacterial properties have garnered significant attention as next-generation multifunctional nanomaterials, offering innovative solutions to persistent challenges in healthcare and food safety. Their distinctive physicochemical characteristics, including superparamagnetism, high specific surface area, customizable surface functionalities, and intrinsic or dopant-enhanced antimicrobial activity, render them highly versatile for a broad spectrum of biomedical and industrial applications.

Table 2. Dopants and their characteristics

Dopant	Antibacterial strength	Magnetic effect	Key applications	Toxicity/Biocompatibility
Ag^+	Very high	Slightly reduces magnetism	Medical coatings, packaging, wound care	Moderate (dose-dependent)
Zn^{2+}	Moderate	Slightly reduces magnetism	Bone scaffolds, food films, oral hygiene	High biocompatibility
Cu^{2+}	High	Slightly reduces magnetism	Disinfectants, orthopedic coatings, packaging	Moderate (requires surface control)
Co^{2+}	Mild to moderate	Enhances coercivity	Theranostics, drug delivery, sensors	Lower biocompatibility (caution needed)
Mn^{2+}	Moderate	Enhances magnetization	Imaging agents, smart food materials	Generally biocompatible at low doses

In the medical domain, these nanoparticles can be engineered for targeted antimicrobial therapy, biofilm disruption, controlled drug delivery, and theranostic systems, integrating both diagnostic and therapeutic functions. Their magnetic responsiveness enables remote manipulation using external magnetic fields, allowing for site-specific accumulation and minimally invasive treatments, particularly in localized infections or implant-associated complications.

Within the food industry, MNPs offer promising strategies for pathogen detection, active food packaging, and antibacterial surface coatings, contributing to extended shelf-life, reduced spoilage, and enhanced microbial safety [9, 109]. Additionally, their potential for magnetic separation and recycling makes them attractive candidates for sustainable and scalable antimicrobial interventions [110].

The following sections present a comprehensive overview of the principal applications of antibacterial MNPs across medical and food-related sectors, with an emphasis on their mechanistic roles, formulation strategies, and translational potential in real-world environments. Figure 11 highlights the potential and functional capabilities of magnetic/antibacterial nanoparticles for applications in the medical field.

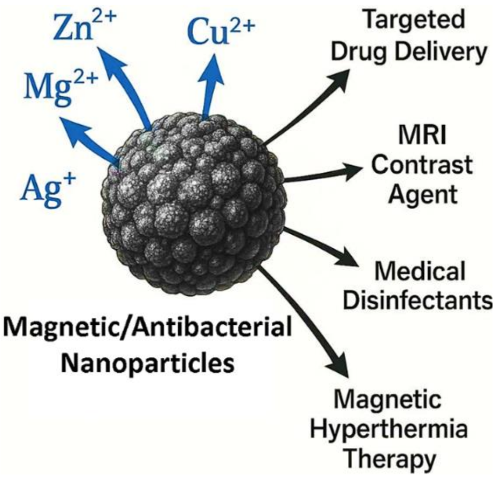

Figure 11. The potential and functional capabilities of magnetic/antibacterial nanoparticles for medical applications.

5.1. Medical applications

5.1.1. Targeted drug delivery: Antibacterial/magnetic nanoparticles have emerged as a promising platform for targeted antimicrobial drug delivery, offering precise spatial control over therapeutic agent localization through the application of external magnetic fields. This capability allows for the concentration of drug-loaded MNPs at specific infection sites, significantly enhancing therapeutic efficacy while reducing systemic drug exposure and associated toxicity, especially important in treating infections near vital or sensitive tissues.

The magnetic core, typically composed of biocompatible iron oxide nanoparticles (such as Fe_3O_4 or γ-Fe_2O_3), enables magnetic field-guided navigation and retention at the target site. Beyond their magnetic responsiveness, these nanoparticles can be surface-functionalized with a variety of antimicrobial agents, including broad-spectrum antibiotics, antimicrobial peptides (AMPs), or plant-derived bioactives, offering a flexible delivery vehicle adaptable to diverse clinical contexts [111, 112].

Surface modification plays a critical role in optimizing their biological performance. Coatings such as polyethylene glycol (PEG), chitosan, polylactic-co-glycolic acid (PLGA), or dextran serve multiple functions such as improving colloidal stability, preventing rapid clearance by the mononuclear phagocyte system (MPS), enhancing biocompatibility, and providing functional groups for further conjugation with targeting ligands or stimuli-responsive linkers [113, 114]. In addition, MNP-based systems can be engineered for controlled or stimuli-responsive drug release, enabling site-specific activation in response to local environmental cues such as acidic pH, bacterial enzymes, or oxidative stress, which are often present at infection or inflammation sites.

This precise delivery not only ensures high local drug concentration, improving bacterial eradication, but also helps in limiting the development of antimicrobial resistance, a growing concern in conventional systemic antibiotic therapies. Furthermore, the magnetic properties of the core can be exploited for real-time imaging via magnetic resonance imaging (MRI), facilitating simultaneous diagnosis and therapy (theranostics). This dual functionality is especially useful for monitoring treatment response in deep tissue infections or chronic biofilm-related diseases.

In summary, magnetic nanoparticle-based targeted drug delivery systems represent a cutting-edge approach in modern antimicrobial therapy, combining precision targeting, controlled release, reduced systemic toxicity, and enhanced therapeutic outcomes, making them candidates for translation into clinical applications in infectious disease management [26, 115, 116].

5.1.2. Magnetic hyperthermia for infection control: Magnetic hyperthermia therapy (MHT) represents an innovative, non-invasive strategy for infection control, particularly suited to addressing chronic infections, biofilm-associated microbial colonization, and antibiotic-resistant bacterial strains. In this approach, MNPs are delivered to the site of infection, either through systemic administration or localized injection, and then exposed to an alternating magnetic field (AMF).

Upon stimulation, the MNPs convert magnetic energy into localized thermal energy, typically raising the temperature of the surrounding microenvironment to 42–50 °C. This localized hyperthermia exerts a dual therapeutic effect. Firstly, the elevated temperature induces thermal stress in bacterial cells, leading to membrane destabilization, protein denaturation, and ultimately cell death, without causing damage to adjacent healthy tissues when precisely controlled.

Secondly, the generated heat has been shown to disrupt extracellular polymeric substances (EPS) in bacterial biofilms, facilitating biofilm dispersion and improving the penetration of antimicrobial agents into previously protected microbial communities.

The efficacy of magnetic hyperthermia is significantly enhanced when used in combination with antibiotics, as hyperthermic conditions increase membrane permeability, reduce efflux pump activity, and promote passive diffusion of drugs into bacterial cells. This synergistic effect allows for lower antibiotic doses, which can reduce toxicity and the risk of resistance development [117, 118]. Moreover, hyperthermia has been observed to sensitize multidrug-resistant (MDR) pathogens, including methicillin-resistant *Staphylococcus aureus* (MRSA), by impairing their stress-response pathways and virulence mechanisms.

Another advantage of this method lies in its spatial precision [117]. By using externally controlled magnetic fields, clinicians can achieve site-specific heating, allowing treatment of localized infections, such as orthopedic implants, catheters, and chronic wounds, while minimizing collateral damage to surrounding healthy cells and tissues. Furthermore, the integration of theranostic capabilities, via MRI-visible magnetic cores, allows for simultaneous imaging, tracking, and treatment of infected areas [119, 120].

Advanced designs also incorporate temperature-sensitive polymers or drug-loaded coatings, enabling thermo-responsive drug release synchronized with the hyperthermic stimulus, thus providing dual-mode antimicrobial activity [121]. In conclusion, magnetic hyperthermia represents a powerful adjunct or alternative to traditional antimicrobial strategies. Its ability to bypass conventional resistance mechanisms, penetrate biofilms, and synergize with antimicrobial agents positions it as a highly promising modality for managing persistent or device-related infections in clinical settings.

5.1.3. Wound healing and antibacterial coatings: Magnetic/antibacterial nanoparticles have demonstrated considerable potential in the field of wound management, particularly when incorporated into advanced wound dressings, hydrogels, or nanocomposite scaffolds. Their dual functionality, combining antibacterial activity with magnetic responsiveness, positions them as powerful tools for enhancing wound healing outcomes, especially in cases complicated by microbial contamination or chronic infection.

In wound care applications, MNPs are typically embedded within biocompatible matrices such as alginate, gelatin, chitosan, or polyethylene glycol-based hydrogels. These materials serve as controlled-release platforms, allowing for sustained and localized antimicrobial action at the wound site [122].

The antibacterial properties of MNPs help prevent the colonization and proliferation of pathogenic microorganisms, thereby reducing the risk of infection, a major impediment to effective tissue regeneration. Additionally, the magnetic properties of these nanoparticles open avenues for external control or real-time monitoring. For instance, the application of an external magnetic field can be used to manipulate the distribution of MNPs, enhance their retention in the wound area, or trigger the release of co-loaded therapeutic agents such as antibiotics or growth factors. This magnetically assisted therapy modulation adds a layer of precision to traditional wound treatments [43, 123].

Doping MNPs with antimicrobial metal ions such as silver (Ag^+) or zinc (Zn^{2+}) has been shown to significantly enhance their antibacterial efficacy. Silver-doped MNPs exert strong bactericidal effects by inducing oxidative stress, disrupting cell membranes, and interfering with DNA replication [124]. Similarly, zinc-doped MNPs contribute both antimicrobial activity and tissue repair modulation, as zinc plays a critical role in enzyme function, cellular proliferation, and immune regulation during wound healing [125].

Preclinical studies have demonstrated that wound dressings incorporating Ag or Zn-doped MNPs can accelerate wound closure, promote angiogenesis, reduce microbial burden, and minimize inflammatory responses [126]. Furthermore, their nanoscale dimensions facilitate intimate interaction with cellular structures, enhancing cellular uptake and integration within the wound bed. In summary, MNP-based wound healing systems offer a multifunctional platform for infection control and tissue regeneration. Their tunable surface chemistry, biocompatibility, and ability to synergize with magnetic guidance and bioactive dopants make them promising candidates for next-generation wound care technologies, particularly in the management of chronic wounds, burns, and diabetic ulcers.

5.1.4. Imaging and theranostics: Iron oxide magnetic nanoparticles, owing to their superparamagnetic properties, have been extensively utilized as contrast agents in magnetic resonance imaging (MRI). Their superparamagnetism significantly enhances MRI sensitivity and spatial resolution, enabling more accurate visualization of biological tissues and pathological abnormalities [127]. When combined with antimicrobial agents, these nanoparticles offer a multifunctional platform that integrates both diagnostic and therapeutic capabilities, a strategy commonly referred to as theranostics.

Theranostic systems based on iron oxide MNPs facilitate simultaneous infection detection and treatment, which is particularly advantageous for managing infections in challenging sites such as deep tissues or implanted medical devices, where conventional diagnostic and therapeutic methods often fail [128]. In these systems, iron oxide MNPs serve as drug carriers that enable targeted delivery of antimicrobial compounds directly to the infection site, thereby improving therapeutic efficacy and minimizing systemic side effects. Moreover, the magnetic properties of these nanoparticles allow for external magnetic guidance and localization, further enhancing the concentration of therapeutic agents at the target site.

Concurrently, the intrinsic MRI contrast ability of iron oxide MNPs enables real-time monitoring of the treatment progress, offering valuable feedback for personalized medical interventions. Consequently, iron oxide-based theranostic platforms represent a promising and innovative approach to overcoming the limitations of traditional infection management strategies and have become a significant focus of ongoing research in nanomedicine and drug delivery technologies. The following table summarizes recent developments in the use of antibacterial metal dopants in magnetic nanoparticles across medical applications, highlighting the materials used, mechanisms of action, and key research findings. Table 3 summarizes recent developments in antibacterial metal-doped magnetic nanoparticles in medical applications.

5.2. *Food industry applications*

Nowadays, due to the high volume of food production and consumption, as well as the diversity of products and the need to implement measures related to storage, increasing shelf life, quality control, and preventing spoilage, the feasibility and use of magnetic/antibacterial nanoparticles is increasing [139]. Figure 12 represented the potential and functional capabilities of magnetic/antibacterial nanoparticles for applications in the food industry.

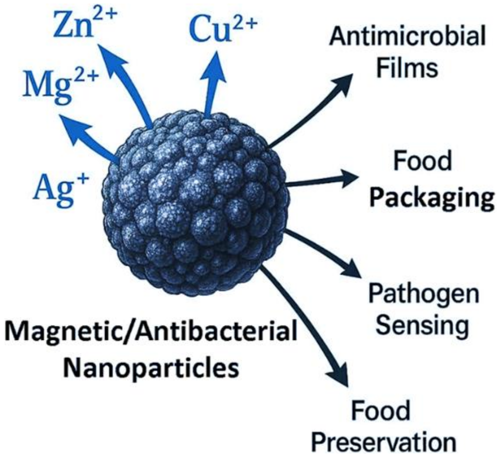

Figure 12. The potential and functional capabilities of magnetic/antibacterial nanoparticles in food industry.

Table 3. Recent developments in antibacterial metal-doped magnetic nanoparticles in medicine

Dopant/Coating	Magnetic NP system	Antibacterial application	Mechanism & key findings	Reference
Ag (Silver)	Superparamagnetic iron oxide-AgO core-shell; $AgFe_2O_4$	Wound dressings, infection therapy, biofilm prevention	Released Ag^+ + ROS; magnetic hyperthermia synergy; effective vs antibiotic-resistant strains	[129, 130]
Zn (Zinc)	ZnO-coated Fe_3O_4 nanocomposite; $ZnFe_2O_4$	Drug delivery + antimicrobial + anticancer	ZnO-SPION improved antibacterial, ROS generation, and membrane disruption	[131, 132]
Co (Cobalt)	$CoFe_2O_4$, Co@ferrite nanocrystals	Implant coatings, antibacterial surfaces	Co-doped ferrite showed zones of inhibition against E. coli, S. aureus, and ROS-mediated	[133]
Cu (Copper)	CuO@Fe_3O_4; $CuFe_2O_4$	Surface sterilization, antibacterial materials	Strong inhibition vs Gram (–/+) (e.g., *B. cereus*); Cu ions + ferrite matrix effect	[134-136]
Mg (Magnesium)	$MgFe_2O_4$; MgO-Fe_3O_4 nanocomposite	Broad-spectrum antibacterial coatings	$MgFe_2O_4$ showed enhanced activity vs. pure ferrite	[137, 138]

5.2.1. Antimicrobial food packaging: Incorporating antibacterial/magnetic nanoparticles into biodegradable films or coatings has emerged as a promising strategy to enhance the shelf life and safety of food products by inhibiting microbial growth. These nanocomposite materials function as active packaging systems, capable of releasing antimicrobial agents in a controlled manner in response to specific environmental stimuli such as changes in moisture levels or temperature. This responsive release mechanism helps to maintain an antimicrobial environment within the packaging, effectively reducing the risk of spoilage and contamination [139, 140].

Among the various types of MNPs, those doped with silver and zinc have gained particular attention due to their broad-spectrum antimicrobial properties against a wide range of bacteria, fungi, and other pathogens. The incorporation of silver and zinc ions enhances the antimicrobial efficacy of the nanocomposites through mechanisms such as disruption of microbial cell membranes, generation of reactive oxygen species, and interference with cellular metabolism. Furthermore, the use of biodegradable polymer matrices as carriers for MNPs aligns with the increasing demand for sustainable packaging solutions, addressing environmental concerns related to plastic waste.

The integration of MNPs within these eco-friendly materials not only improves food preservation but also contributes to reducing the ecological footprint of packaging materials [141, 142]. Overall, the development of antimicrobial food packaging incorporating MNPs represents an innovative and effective approach to ensuring food quality and safety, with significant potential for application in the food industry.

5.2.2. Food preservation and storage: Antibacterial/magnetic nanoparticles have shown significant potential as preservatives when dispersed directly into liquid or semi-solid food matrices at safe and controlled concentrations. These nanoparticles exhibit effective antimicrobial activity against common spoilage and pathogenic microorganisms, including *Escherichia coli*, *Listeria monocytogenes*, and *Salmonella* species, which are major contributors to foodborne illnesses and spoilage [143].

By inhibiting the growth and proliferation of these microorganisms, MNPs help to extend the shelf life of food products and maintain their sensory and nutritional quality during storage. An important advantage of using MNPs in food preservation lies in their intrinsic magnetic properties, which enable facile separation and removal of the nanoparticles from the food matrix after the preservation process, if necessary [139]. This magnetic recoverability not only facilitates recycling and reuse of the nanoparticles but also ensures that residual nanoparticle concentrations in the final food product remain within safe limits, thereby preserving food safety and regulatory compliance. Furthermore, the ability to control the dispersion and dosage of MNPs within different food systems allows for customizable preservation strategies tailored to specific food types and storage conditions [144].

This approach offers a promising alternative to traditional chemical preservatives, which often face consumer resistance due to concerns about toxicity and synthetic additives. Overall, the application of antibacterial/magnetic nanoparticles in food preservation and storage represents an innovative and versatile technology with the potential to improve food safety, reduce spoilage, and meet growing consumer demand for safer and more sustainable food preservation methods.

5.2.3. Biosensing and contaminant detection: Functionalized magnetic nanoparticles have emerged as highly effective tools for the selective detection of bacterial cells and toxins in food products. By doping the antibacterial ions or attaching specific recognition molecules, such as antibodies or peptides, to the surface of MNPs, these nanomaterials can selectively bind to target microbial contaminants with high affinity and specificity. This functionalization enables the precise identification and isolation of pathogens or harmful substances from complex food matrices.

The magnetic properties of these nanoparticles facilitate rapid and efficient separation of bound contaminants from the sample through magnetic separation techniques, significantly reducing detection time compared to conventional methods [145, 146]. Additionally, MNPs can be integrated with optical or electrochemical sensors, thereby enhancing sensitivity and enabling real-time monitoring of microbial contamination. Such biosensing platforms enable early detection of foodborne pathogens, improving food safety by allowing timely interventions within the supply chain [147]. This capability to rapidly and accurately identify contaminants at low concentrations contributes to minimizing the risk of foodborne illnesses, reducing economic losses due to spoilage, and ensuring compliance with regulatory standards.

Consequently, MNP-based biosensing technologies represent a promising advancement in food safety monitoring, combining the advantages of nanotechnology with efficient diagnostic approaches.

5.2.4. Water disinfection: Antibacterial/magnetic nanoparticles have been increasingly utilized in water treatment applications due to their ability to effectively remove or inactivate bacterial pathogens. Their high surface reactivity enables strong antimicrobial effects through mechanisms such as the disruption of microbial cell walls, the generation of reactive oxygen species, and the catalytic degradation of contaminants. This makes MNPs particularly suitable for the disinfection of water used in food processing environments, ensuring microbiological safety. Moreover, the magnetic properties of MNPs allow for their facile recovery and reuse through magnetic separation techniques, which enhances the sustainability and cost-effectiveness of disinfection processes.

This recoverability reduces the environmental impact typically associated with chemical disinfectants and supports the development of eco-friendly sanitation protocols [148, 149]. By integrating MNP-based disinfection strategies, food production facilities can achieve higher standards of hygiene and safety, contributing to improved product quality and consumer health. Overall, the use of antibacterial/magnetic nanoparticles in water and surface disinfection represents a promising approach that combines high antimicrobial efficacy with environmental sustainability, addressing critical challenges in food safety management.

Table 4 provides an overview of recent progress in utilizing antibacterial metal dopants in magnetic nanoparticles for food packaging, emphasizing the employed materials, antibacterial mechanisms, and significant experimental findings.

6. Conclusions, challenges, and prospects

The unique multifunctional properties of antibacterial/ magnetic nanoparticles have enabled their versatile application across diverse fields, particularly in the medical and food industries. Their ability to serve simultaneously as diagnostic and therapeutic agents has advanced precision medicine and non-invasive imaging techniques, improving the detection and treatment of infections.

In parallel, the integration of MNPs into food systems has introduced innovative solutions such as antimicrobial

Table 4. Metal-doped magnetic nanostructures in antimicrobial food packaging

Dopant/Coating	Magnetic NP system	Food packaging application	Mechanism & key findings	Reference
Ag (Silver)	AgO@Fe_3O_4 core–shell; $AgFe_2O_4$	Coating on paper packaging, PE film, NR/PE blends	Sustained Ag^+ release + ROS; improved mechanical/barrier properties; MIC ~3–5 µg/mL; extended shelf life of fruits and sausages; inhibited *E. coli*, *S. aureus*, *Salmonella*	[150]
Zn (Zinc)	ZnO embedded/magnetic composite; $ZnFe_2O_4$	Bio-starch/chitosan/ZnO films & coatings on PLA, gelatin, cellulose	Zn^{2+} release + ROS under light; good barrier, UV resistance; extended shelf life of poultry/meat; full inactivation of *E. coli*, *S. enterica*, *S. aureus*	[151]
Cu (Copper)	Cu-doped -magnetic nanoparticles ($CuFe_2O_4$)	Antibacterial films/paper/cardboard	Cu^+ ions + ROS; strong inhibition but toxic concerns; used by coating or pulp mixing	[152]
Co (Cobalt)	$CoFe_2O_4$NPs	Rarely in food-related applications; composite film with $CoFe_2O_4$/MXene/chitosan	Similar antibacterial properties to Cu and Zn, but toxicity concerns; further investigation needed	[153]

packaging, enhanced preservation, rapid contaminant detection, and effective disinfection methods, all of which contribute to improving food safety and extending shelf life.

Despite these promising developments, the successful translation of MNP-based technologies from research settings to practical, real-world use depends heavily on continued investigation into their biocompatibility, long-term biosafety, and functional optimization. Furthermore, addressing regulatory challenges and ensuring compliance with safety standards are essential to gain public trust and facilitate widespread adoption.

Overall, antibacterial/ magnetic nanoparticles offer a powerful and flexible platform with significant potential to enhance both human health and food security, paving the way for next-generation applications in nanomedicine and food technology.

Challenges and future perspectives of antibacterial/ magnetic nanoparticles in biomedical and food applications: Antibacterial magnetic nanoparticles hold considerable promise across biomedical and food sectors due to their unique physical properties and versatile antibacterial mechanisms. However, addressing the existence challenges, particularly those related to biosafety, regulatory compliance, and functional stability, will be crucial for their successful integration into real-world applications. Future efforts should prioritize the development of environmentally friendly, biocompatible, and multifunctional antibacterial/magnetic composites and nanocomposites with tailored performance to meet the specific demands of clinical and industrial settings.

Key challenges:

Biocompatibility and cytotoxicity: The release of metal ions (e.g., Ag^+, Cu^{2+}, Co^{2+}) from doped magnetic nanoparticles can lead to unintended cytotoxic effects, inflammation, or tissue damage. Long-term safety data and a comprehensive understanding of nanoparticle–cell interactions are still lacking.

Controlled ion and drug release: Achieving site-specific, controlled, and sustained release of therapeutic agents or metal ions remains a technical barrier, particularly in dynamic physiological or food-related environments.

Stability in biological and food matrices: Magnetic nanoparticles may undergo aggregation, surface modification, or loss of function when exposed to complex biological fluids or food components, compromising their antibacterial efficacy.

Regulatory and safety barriers: The lack of well-defined regulatory frameworks and standardized safety evaluations limits the approval and commercialization of antibacterial/magnetic nanocomposites-based products, especially in the food and healthcare sectors.

Future perspectives:

Design of multifunctional smart nanoparticles: Future research should focus on the development of AMNPs capable of integrating diagnostic, therapeutic, and targeting functions within a single platform, enabling more effective and personalized treatment strategies.

Stimuli-responsive systems: Stimuli-sensitive nanoparticles that respond to pH, temperature, magnetic fields, or enzymatic activity could offer controlled activation of antibacterial mechanisms only in infected tissues, minimizing off-target effects.

Surface engineering for enhanced selectivity: Advanced surface functionalization with biocompatible polymers, ligands, or targeting moieties can improve cellular uptake, reduce toxicity, and enhance specificity toward bacterial cells over host tissues.

Conflict of Interest

The authors declare no conflict of interest.

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