P- ISSN 1991-8941 E-ISSN 2706-6703
2024,(18), (01):152 – 164

Journal of University of Anbar for Pure Science (JUAPS)

Open Access

Metal nanoparticles as a therapeutic antibacterial agents in the era of antibiotics resistance: A review

Layth L. Hamid*, Hanan Hamed

Department of Biology, College of science, University of Anbar, Ramadi 31001, Iraq

ARTICLE INFO

Received: 03/ 05 /2024
Accepted: 24 / 05 / 2024
Available online: 19 / 06 / 2024

DOI: 10.37652/juaps.2024.149400.1249

Keywords

metal nanoparticles, antibiotics, multi-drug resistant, antibacterial, nanoparticles synthesis.

ABSTRACT

The increasing resistance of microorganisms to commonly used antibiotics has become a significant public health problem. To address this issue, new approaches are urgently needed to combating these types of pathogenic microbes. Nanoscience has led to the development of novel antibacterial materials including metal nanoparticles like silver, zinc, copper, gold, nickel, magnesium, iron, titanium, palladium selenium and aluminum. These materials have shown significant bactericidal properties against wide range of multi-drug resistant bacterial strains. Metal nanoparticles physically disrupt and inactivate various cellular contents of microorganisms without effected by resistance mechanisms. Nanomaterials small size, prolonged antibacterial effectiveness, and low toxicity contribute to reduce environmental hazards. However, scientists need to address several challenges, including health and bioethical concerns, risks of toxicity, and physiological and medical considerations associated with the use of nanomaterials as antibacterial drugs. Due to the lack of bacterial resistance mechanisms against nanoparticles, we could see these molecules replacing antibiotics in the treatment of pathogenic bacteria.

.

Introduction

The discovery of penicillin revolutionized medicine and proved the beguines for synthesized and modified many antimicrobial drug which known as antibiotics [1].

Antibiotics are used to combat microbial infections that caused by pathogenic microorganisms such as bacteria and fungi. The mechanisms of antibiotics activity can be classified into five classes including the suppression of cell wall synthesis, DNA replication, protein biosynthesis, membrane functions and metabolic pathways [2] (figure 1).

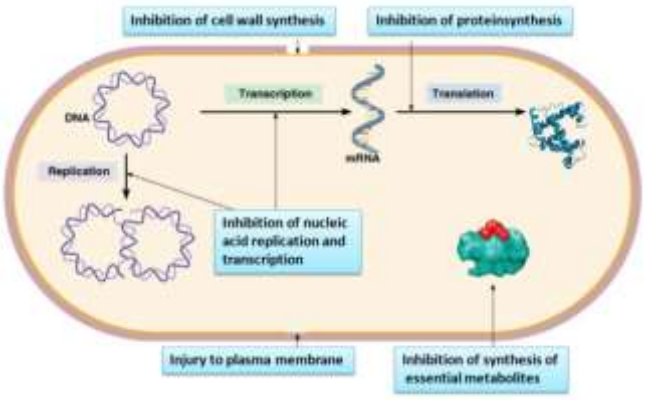

Figure 1. The action mechanisms of antibiotics [3].

Since microbial infections have a major concern in the medical field due to their significant threat to human health that lead to dangerous illness cases and even death. Recently, the abuse and overuse of antibiotics have led to the spread of multi-drug resistant (MDR) bacterial strains [4]. Antibiotic resistance can occur through two main forms: natural and acquired

*Corresponding author at : Biology department, College of science, University of Anbar, Ramadi 31001, Iraq
ORCID:https:// https://orcid.org/0000-0002-9705-9249 ,
Tel: +9647810963408
Email: layth94@uoanbar.edu.iq

resistance. Natural resistance is the result of resistance gene that either be often expressed (innate) or activated following antibiotic treatment (mediated) while acquired form result mutations or acquiring resistance genetic materials through processes such as translation, transposition or conjugation [5]–[7]. Mechanisms of antimicrobial resistance (AMR) include limitation of drug uptake, modification of drug targets, efflux of drugs and inactivation of drugs [8] (figure 2).

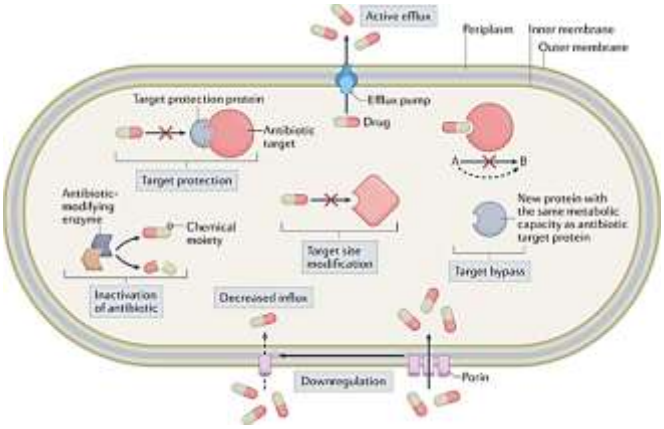

Figure 2. The mechanisms of antibiotics resistance [9].

The global spread of MDR bacteria has led to increased prolonged illnesses, healthcare costs and mortality rates. To overcome this issue, harnessing of therapeutic nanotechnology for drug production and combating MDR bacterial strains have been proposed [10], [11]. Nanotechnology has made significant advancement in the fabrication of nano inorganic and organic particles that have important medical applications such as therapeutics, diagnostics and drug delivery [12]. The unique physicochemical properties of nanoparticles (NPs) are considered innovative tools that can be utilizing for diagnostic, targeted drug delivery, noninvasive imaging and for treatment of various chronic diseases [13], [14]. NPs offer a promising antimicrobial compounds to tackle the challenges associated with antibiotic resistance through distinct mechanisms compared to traditional antibiotics [11].

Methods for synthesis of NPs

The synthesis of NPs can be achieved through three main approaches include physical, chemical and biological (figure 3). The chemical and biological approaches referred to as the bottom-up approach that involve assembly and formation of NPs from smaller compounds while the physical methods known as the top-down approach that involve the manipulation of bulk materials to obtains NPs [15].

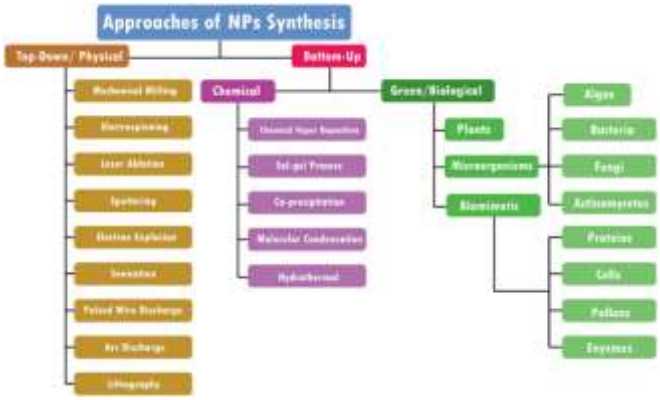

Figure 3. The methods of NPs synthesis [15].

Antibacterial mechanisms of metal nanoparticles (MNPs)

Metal nanoparticles MNPs possess advantages as active antibacterial agents that act through various mechanisms to kill microorganisms or prevent their growth. These mechanisms include the damage of molecules such as DNA, proteins, cellular membranes and mechanical disruption of cellular components) as well as the generation of new molecules (such as reactive oxygen species (ROS) and modification of signals transduction) (figure 4) [16]–[18]. Biofilms serves as environments for microorganisms to persist, multiply and interconnect by quorum sensing (QS). Traditional antibiotics resolves infections caused by planktonic bacterial form but fails to destroy the biofilm itself. In some cases, MDR arises from the failure of antibiotics to penetrate the biofilms and the alter the phenotype of bacteria inside this structure [19]. The large surface areas of MNPs relative to their sizes enabling them to enter biofilms effectively and act as active antimicrobial agents [20]–[27]. Gram-negative (G –ve) bacteria are inherently more protected against antibiotics compared to gram positive (G +ve) bacteria due to the presence of outer membranes. The outer membrane of G –ve bacteria consists of lipoproteins, phospholipid bilayer and endotoxin [28]. The synthesis of efflux pumps on the outer membranes that quickly

remove antibiotics from the bacterial cell as soon as the antibiotics enters. The accumulation of MNPs in the outer membranes resulting in destabilization, collapse potential and depletion of intracellular energy for these membranes [29]. Electrostatic interaction is a crucial antibacterial mechanism that enabling the adhesion of positively charged MNPs with bacterial cell walls [18], [30], [31]. MNPs can alter respiratory enzymes on bacterial membranes leading to the generation of ROS that react with proteins and lipids on the membrane. Also, ROS can also directly damage components within the bacterial cytoplasm [32]. The high absorption coefficient of MNPs can modulate signal transduction in bacteria by affecting protein phosphorylation that lead to inhibition of cell growth and cell cycle development. The other mechanism of antibacterial therapy of MNPs involves the inhibition of quorum sensing that lead to inactivation of signal molecules in the communication circuit system of biofilm bacteria and disrupting their structure [33]–[35].

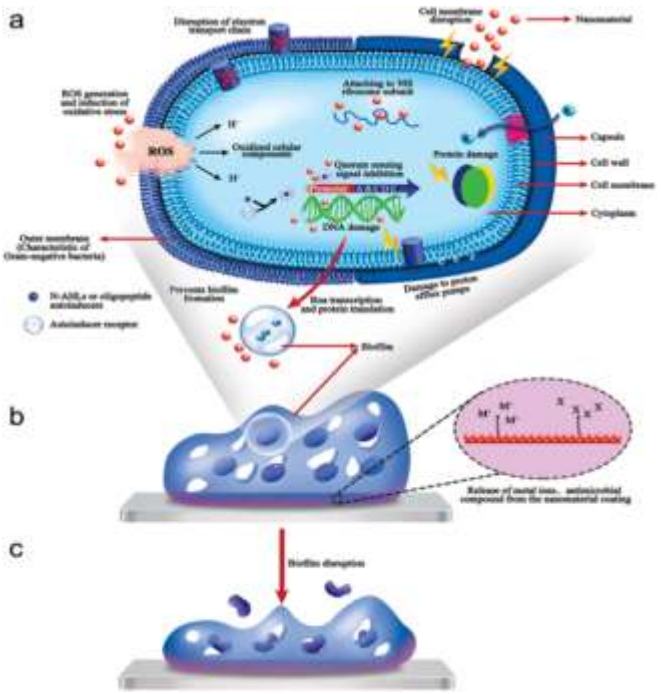

Figure 4. Antibacterial mechanisms of MNPs [18].

Silver nanoparticles (Ag NPs)

Silver-based nanocompounds are widely used in various industries due to their potent antibacterial, antifungal and antiviral activities [36]–[38]. The antibacterial mechanisms of Ag NPs have been extensively studied. Ag NPs physically cause cell death by binding with bacterial cell walls that resulting structural disruptions and increase membrane permeability [39]. Ag NPs also interact with bacterial proteins, and preventing DNA replication [40]. Previous studies have highlighted the ability of Ag NPs to inhibit the growth and multiplication of various bacteria including *S. aureus*, *C. koseri*, *S. typhii*, *B. cereus*, *E. coli*, *P. aeruginosa*, *K. pneumonia*, and *V. parhaemolyticus* [41]. Upon exposure of MDR bacteria to Ag NPs, notable changes were observed in the bacterial cells including the cell wall become thinner, the cell membrane shriveled and fractured, the cellular contents leaked out and accumulation of ROS [42]. Combination therapies involving Ag NPs and other antimicrobials agents have shown promise in tackling MDR bacteria and reducing toxicity thereby increasing the antibacterial effects against wide range of pathogenic bacterial strains. For example, a long-lasting microbicidal outcome lasting 5 weeks when treating *E. coli* with 250 µg/ml of Ag NPs in nanohybrid containing albumin-conjugated Ag [43].

Gold nanoparticles (Au NPs)

Au is generally considered non-toxic metallic element but this behavior can convert when it oxidized [44]. Various studies have highlighted the potential of Au NPs in various biomedical applications, particularly in antibacterial and anti-biofilm photothermal treatments. Furthermore, these nanomaterials have been extensively studied for applications such as bio-imaging, gene delivery, targeted drug delivery, diagnostics, bio-sensing, photo-induced therapy, anti-cancer and tissue engineering [45], [46]. For antibacterial properties, Au NPs have demonstrated activity against both G +ve and G -ve bacterial strains [47]. Their antibacterial mechanism depends on their nano-sizes. Smaller NPs create large irreversible pores during their translocation across the bacterial cell membrane leading to bacterial cell death [48]. Larger NPs in the size range of 80-100 nm while unable to freely cross the bacterial cell membrane have also been shown to eliminate bacterial cells [49]. Light activation is utilizing to enhance the antibacterial activity of Au NPs in two main strategies that are antibacterial photothermal therapy (APTT) and

antibacterial photodynamic therapy (APDT). These approaches have the advantage of being difficult for bacteria to develop resistance against. In APTT, Au NPs are used to convert light into thermal energy which generates localized hyperthermia upon laser irradiation and effectively eradicates bacteria and biofilm structures [50], [51]. APDT involves irradiating photosensitizers that generate ROS that leading to inhibit bacterial growth. APDT is generally less efficient against G -ve bacteria compared to G +ve bacteria, but combining APDT with other antibacterial methods can enhance its effectiveness [52].

Zinc nanoparticles (Zn NPs)

Zinc ions (Zn^{2+}) are essential trace metals for microbial metabolism and are present in the active site of many enzymes. Zn^{2+} plays a crucial role in various metabolic reactions including the anabolic and catabolic of carbohydrates, lipids and proteins [53]. The concentration of Zn^{2+} is a critical agent affecting bacterial growth. At low concentration, the Zn^{2+} promotes growth but excessive Zn^{2+} inhibits bacterial growth. Excess Zn^{2+} can compete with other metals leading to mismatches in metal-binding proteins, protein denaturation, enzyme inactivation, membrane rupture release of cytoplasmic contents and cell death [54]–[56]. Zn NPs compared to common Zn^{2+} possess unique properties that allow them to easily penetrate the bacterial cell walls due to their nano-sizes. Zn NPs exhibit antibacterial effects by disrupting the cell membrane, inducing oxidative stress and generating ROS [57]. They have shown inhibitory effects against various bacteria, such as *L. monocytogenes*, *E. coli*, *S. aureus*, and *K. pneumonia* [58], [59]. Zn NPs have also exhibited photocatalytic antibacterial efficacy when exposed to ultraviolet irradiation, where excited electrons and positively charged holes react with oxygen, hydroxyl groups, and water to produce ROS. These ROS then interact with biological macromolecules, leading to cell damage and inhibition of bacterial growth [60], [61]. Interestingly, Zn NPs exhibit higher activity against G +ve bacteria than G -ve bacteria, possibly due to variances in cell wall composition [62].

Copper nanoparticles (Cu NPs)

Copper (Cu) ions, an essential trace element plays a vital role in the organs biological functions and metabolism in organisms. However, both low and high concentrations of Cu ions can have harmful effects [63], [64]. Cu ions can act as an electron donor/acceptor, switching between the redox forms of Cu (I) and Cu (II) in certain enzymes thereby rising toxicity to bacterial cells [65], [66]. Another proposed mechanism of Cu ion-induced toxicity involves the displacement of Fe ion from Fe-S structure [67]. Cu NPs have shown effective ability to killing MDR bacterial strains. By combining Cu NPs with other antibacterial drugs, an effective strategy that target MDR bacteria can be developed. The use of a Cu-cotton nanocomposite has been shown to enhance the release of Cu ions and effectively kill MDR bacteria [66]. Capping Cu NPs with a cationic polymer like chitosan enhances their ability to bind with the negative charged cell envelope [68]. G +ve bacteria such as *S. aureus* are generally more sensitive to Cu NPs than G -ve bacteria like *E. coli* [66]. Based on their sizes, Cu NPs can be toxic to bacterial cells due to generation of ROS on their surfaces [69].

Nickel nanoparticles (Ni NPs)

Ni NPs exhibit antibacterial properties against MDR bacteria such as *K. pneumoniae* and *E. coli*. Furthermore, Ni NPs find applications in water disinfection, industry, medical field, and food packaging [70]. While the antibacterial properties of Ni NPs is not as potent as those made from Ag NPs and Si NPs but it is powerful than that of Au NPs [71]. Additionally, there has been a shift towards eco-friendly manufacturing approaches, moving away from physical and chemical methods to green synthesis routes utilizing plants and microorganisms extracts [72]. Surface interactions of Ni NPs with polymers is another method to enhance their antibacterial properties while improving cytocompatibility. For instance, the loading of Ni NPs (120-150 nm) into chitin nanogels has resulted in higher toxicity against microorganisms at lower concentrations than pure Ni NPs. In vitro cytocompatibility tests conducted on A549 and L929 cells indicate that Ni NPs -loaded chitin particles are entirely non-toxic [73]. Alteration in the morphology and size of Ni NPs can

lead to improvements in their antimicrobial activity and cytocompatibility. Morphology modulation is dependent on the synthesis rate in various crystallographic states which can be modulated by setting experimental conditions like the ratio of metal ions and reducing agents, pH, irradiation period and production energy. Ni nanoplates offer more differences in shape and dimension [74]. For instance, novel platinum-on-flower-like Ni NPs have been synthesized using ultraviolet irradiation to induce the accumulation of ROS thereby enhancing their antibacterial activity [75].

Magnesium nanoparticles (Mg NPs)

Mg NPs offer an attractive alternative to other heavy metal-based NPs such as Ag NPs, Fe NPs, and Zn NPs. This is because Mg NPs can be efficiently degraded and metabolized within the body and their degradation products include magnesium ions (Mg^{2+}) and hydroxide ions (OH^-) can be easily discarded. Mg NPs have gained significant attention in recent years due to their versatile applications in catalysis, biomedical materials, and absorbents. Extensive research has highlighted the antibacterial properties and ability to combat biofilm formation exhibited by Mg NPs against various bacteria. Therefore, Mg NPs have the potential to serve as an effective nano-carrier material for the delivery of therapeutic compounds [76]. The bactericidal mechanism of Mg NPs involves the physical destructions of cell wall after adsorption on it [11]. Studies have shown that Mg NPs exhibit effectiveness against various pathogenic bacteria including *E. coli, P. aeruginosa, S. epidermidis, S. aureus, C. albicans, C. albicans FR, C. glabrata,* and *C. glabrata ER*. Furthermore, Mg NPs have shown promise as antimicrobial agents against phytopathogens, indicating their potential in prevent bacterial infections of plants in the future [77].

Iron nanoparticles (Fe NPs)

In their bulk form, metal Fe is typically inert and lack inherent antibacterial activity while nano form of this metal represent an effective antibacterial agent. However, various studies have demonstrated that surface modification of Fe NPs can activate their antiadherent and antibacterial properties, leading to the eradication of biofilm structure for both G -ve and G +ve bacteria [78]. The antibacterial effect of Fe NPs has been investigated against various pathogenic bacteria such as *S. aureus, E. coli,* and *S. dysentery* [79]. By incorporating antimicrobial drugs like erythromycin onto Fe NPs, an enhanced antibacterial effect has been observed on the culture of *S. pneumoniae*. Similarly, when alginate-capped Fe NP-tobramycin conjugates were used to treat *P. aeruginosa* bacterium responsible for nosocomial infections, their bactericidal potential was significantly enhanced. Also, this incorporation has demonstrated an ability to inhibit biofilm structure for this bacteria. Fe NPs represent a promising and cost-effective alternative drug for prevent and treatment of bacterial [80], [81].

Titanium nanoparticles (Ti NPs)

The microbicidal and antibiofilm properties of Ti NPs making them effective against various microorganisms such as bacteria, fungi, viruses, and parasites. Ti NPs has found numerous applications in the food package, medicine, drug delivery vehicles, cosmetics, air/water purification, and as antimicrobial coatings on biomedical equipment. These nanomaterial have demonstrated antibacterial effects toward bacterial strains such as *E. coli*, *P. aeruginosa*, *S. aureus*, and *E. faecium* [82]. Furthermore, Ti NPs showed enhanced antibacterial efficacy against pandrug-resistant (PDR) *E. coli* bacterial species which are a major cause of bovine mastitis around the world. For non-toxic and biocompatible antimicrobial formulation, chitosan-coated Ti NPs (CS-coated Ti NPs) prepared using the ionic gelation method have exhibited improved antibacterial properties. These combination has shown more antibacterial properties against PDR *E. coli* opening up new possibilities for alternative treatment strategies against highly resistant bacterial species. The antimicrobial mechanism of Ti NPs involves their photocatalytic activities. Under light exposure, Ti NPs generates ROS or disrupts the integrity of the microbial cell membrane that lead to oxidation of cellular components, causing destruction and eliminate bacterial growth [83], [84].

Palladium nanoparticles (Pd NPs)

Pd NPs have significant importance in various fields due to their recyclability, and thermal and mechanical stability compared to other elements in Group 10 of the periodic table [85]. Chemical methods have been employed to synthesize Pd NPs with size-dependent antimicrobial activities against bacteria such as *E. coli* and *S. aureus* [86]. Biosynthesis methods have also been employed to prepare antibacterial Pd NPs that are relatively non-toxic and biocompatible, utilizing biological extracts from plants and microorganisms [87], [88]. Pd NPs exhibits a higher propensity for ligand exchange compared to other metals. Ligand dissociation generates active metal species that can readily interact with other compounds [89]. Consequently, Pd NPs possess high toxicity to bacteria due to their increased reactivity, especially the smaller nanosizes. However, the surface modification of Pd NPs with organic materials have garnered interest of researchers in the field of pharmaceutical nano-drugs. Pd NPs hybrid with halosubstituted benzylamine, oxime or thiosemicarbazone ligands have been prepared, demonstrating high microbicidal activity against both G -ve and G +ve bacterial strains [18].

Selenium nanoparticles (Se NPs)

Se NPs are extensively utilized for preventing the growth of medical or foodborne pathogens due to their antibiofilm activity [90]. Compared to other NPs which can be toxic to human cells due to the formation of ROS, Se NPs is considered non-toxic and biocompatible [91]. Smaller Se NPs have a more pronounced antibacterial effect against *S. aureus* infections compared to larger NPs [92]. Furthermore, Se NPs exhibit anti-fungal characteristics, as probiotics containing Se NPs have demonstrated a significant inhibition in the growth of *C. albicans* [93]. In the biomedical field, the green synthesis of Se NPs from nonpathogenic and eco-friendly actinobacteria was first reported in 2015. Furthermore, Se NPs exhibit effective antimicrobial properties toward *P. aeruginosa, S. aureus, E. coli,* and *S. pyogenes,* as well as antifungal properties against *A. clavatus*. Their antimicrobial activity is comparable to that of the antibiotic ampicillin [94]. Also, Se NPs were found to possess both antibiofilm and antioxidant activities and were successfully applied to expedite wound healing in rats with a high success rate [90]. In the food industry, Se NPs have been employed for inhibition of many foodborne bacteria such as *E. coli, S. aureus,* various Salmonella species, and *L. monocytogenes* [95].

Aluminum nanoparticles (Al NPs)

The growth inhibitory effect of Al NPs on *E. coli* extends across a broad concentration range (10-1000 μg mL−1) [96]. Similar to other metal oxide NPs, the increased generation of rea ROS is one of the key bactericidal mechanisms of Al NPs [18]. When loaded with other biopolymers, Al NPs exhibit significant microbicidal activities. For instance, the surface interaction of Al NPs with polymers, such as the combination of polylactic acid-Al_2O_3 or alginate-chitosan with Al_2O_3, significantly enhances the oxygen content, water retention, and aroma of these films. These antibacterial materials are extensively used in food packaging films. Al-doped Zn coatings on polylactic acid films exhibit high antimicrobial properties toward E. coli and are employed in food packaging [97]. Chitosan/silica nanocomposite films doped with Al NPs demonstrate favorable spectroscopic and antimicrobial properties, making them suitable for optical and medical applications [98]. In the case of inorganic Al_2O_3 materials, nano-Ag-TiO_2 hybrids are embedded in anodic Al_2O_3 templates, leveraging the high porosity of these templates to improve the contact-killing and release-killing actions of the nanoparticles against biofilms [99].

Limitations

The increasing require for efficient and innovative microbicidal therapeutics and diagnostics has arisen due to the emergence of MDR microbial strains that are developing resistance to traditional antibiotics, posing a significant health issues. MNPs have shown great potential as microbicidal agents toward MDR bacterial strains, but it is crucial to dominate their size, shape, and stability. Various factors, such as shape, size, surface charge and chemistry, composition, MNPs stability, administration dosage, and the integrity of the host's immune system, directly or indirectly influence the interaction between MNPs and living cells. The

effectiveness of MNPs as microbicidal agents or drug delivery vehicles depends on their ability to permeate cells and distribute throughout different organs in the body like nerve cells, blood vessels, and the lymphatic system. However, the accumulation of MNPs in living cells, cellular structures, and tissues may have negative health effects [100]. In some cases, the small size of MNPs has been associated with toxic or inflammatory responses. Their ultrafine nature and large surface area enable interactions with cellular organelles, leading to toxicity, inflammation, activation of signaling pathways, induction of ROS, and inception of apoptosis [101]. Engineered MNPs can also interact with components of the immune system, resulting in the release of proinflammatory and inflammatory cytokines. Consequently, these NPs have the potential to modulate the immune system, which can have undesirable effects on the human body [102]–[105]. In mice, the exposure to CNTs has been associated with the formation of granulomas. Moreover, the translocation of NPs to extrapulmonary regions such as the heart, liver, brain, and kidneys has been observed in humans and animals [106], [107]. Therefore, wariness must be exercised when study and applying these materials, and their applications should only occur after identifying and addressing their potential adverse events.

Conclusion

The emergence of drug-resistant microbes and the development of MDR among bacteria pose significant challenges in the medical field, despite the synthesis of numerous potential antibacterial therapeutics, whether through synthetic or biological means. There is an urgent need for innovative strategies to effectively address MDR bacterial strains. Nanomedicine has opened up new avenues for antibacterial therapeutics and diagnostics by utilizing innovative nanomaterials. These NPs present an alternative to antibiotics and show promising potential in addressing the issue of MDR. This review focuses primarily on the antimicrobial mechanisms of MNPs that contribute to the development of efficient antimicrobial agents and the prevention of bacterial infections. However, while these NPs have significant relevance as therapeutic agents in biomedicine, their limitations in terms of human health cannot be ignored. It is essential to exploit this technology in an efficient manner while carefully treatment their side effects and ensuring that they do not cause harm to individuals or the environment.

Acknowledgments

Not applicable.

Conflict of Interest

Not applicable.

References

[1] G. A. Durand, D. Raoult, and G. Dubourg, ‘Antibiotic discovery: history, methods and perspectives’, Int. J. Antimicrob. Agents, vol. 53, no. 4, pp. 371–382, 2019.

[2] T. M. Uddin et al., ‘Antibiotic resistance in microbes: History, mechanisms, therapeutic strategies and future prospects’, J. Infect. Public Health, vol. 14, no. 12, pp. 1750–1766, 2021.

[3] A. I. Barzic and S. Ioan, Antibacterial drugs—From basic concepts to complex therapeutic mechanisms of polymer systems, vol. 2015. IntechOpen London, UK, 2015.

[4] M. Gajdács and F. Albericio, ‘Antibiotic resistance: from the bench to patients’, Antibiotics, vol. 8, no. 3. MDPI, p. 129, 2019.

[5] M. J. Culyba, C. Y. Mo, and R. M. Kohli, ‘Targets for combating the evolution of acquired antibiotic resistance’, Biochemistry, vol. 54, no. 23, pp. 3573–3582, 2015.

[6] W. C. Reygaert, ‘An overview of the antimicrobial resistance mechanisms of bacteria’, AIMS Microbiol., vol. 4, no. 3, p. 482, 2018.

[7] N. A. Lerminiaux and A. D. S. Cameron, ‘Horizontal transfer of antibiotic resistance genes in clinical environments’, Can. J. Microbiol., vol. 65, no. 1, pp. 34–44, 2019.

[8] G. Kapoor, S. Saigal, and A. Elongavan, ‘Action and resistance mechanisms of antibiotics: A guide for clinicians’, J. Anaesthesiol. Clin. Pharmacol., vol. 33, no. 3, p. 300, 2017.

[9] E. M. Darby et al., 'Molecular mechanisms of antibiotic resistance revisited', Nat. Rev. Microbiol., vol. 21, no. 5, pp. 280–295, 2023.

[10] H. S. Tuli, 'Synergistic effect of copper nanoparticles and antibiotics to enhance antibacterial potential', 2019.

[11] F. Fatima, S. Siddiqui, and W. A. Khan, 'Nanoparticles as novel emerging therapeutic antibacterial agents in the antibiotics resistant era', Biol. Trace Elem. Res., vol. 199, pp. 2552–2564, 2021.

[12] A. K. Thabit, J. L. Crandon, and D. P. Nicolau, 'Antimicrobial resistance: impact on clinical and economic outcomes and the need for new antimicrobials', Expert Opin. Pharmacother., vol. 16, no. 2, pp. 159–177, 2015.

[13] I. Y. Wong, S. N. Bhatia, and M. Toner, 'Nanotechnology: emerging tools for biology and medicine', Genes Dev., vol. 27, no. 22, pp. 2397–2408, 2013.

[14] M. Akhtar, M. K. Swamy, A. Umar, and A. A. Al Sahli, 'Biosynthesis and characterization of silver nanoparticles from methanol leaf extract of Cassia didymobotyra and assessment of their antioxidant and antibacterial activities', J. Nanosci. Nanotechnol., vol. 15, no. 12, pp. 9818–9823, 2015.

[15] K. A. Altammar, 'A review on nanoparticles: characteristics, synthesis, applications, and challenges', Front. Microbiol., vol. 14, p. 1155622, 2023.

[16] K. B. A. Ahmed, T. Raman, and A. Veerappan, 'Future prospects of antibacterial metal nanoparticles as enzyme inhibitor', Mater. Sci. Eng. C, vol. 68, pp. 939–947, 2016.

[17] Y. N. Slavin, J. Asnis, U. O. Hńfeli, and H. Bach, 'Metal nanoparticles: understanding the mechanisms behind antibacterial activity', J. Nanobiotechnology, vol. 15, pp. 1–20, 2017.

[18] P. Makvandi, C. Wang, E. N. Zare, A. Borzacchiello, L. Niu, and F. R. Tay, 'Metal-based nanomaterials in biomedical applications: antimicrobial activity and cytotoxicity aspects', Adv. Funct. Mater., vol. 30, no. 22, p. 1910021, 2020.

[19] K. Ikuma, A. W. Decho, and B. L. T. Lau, 'When nanoparticles meet biofilms—interactions guiding the environmental fate and accumulation of nanoparticles', Front. Microbiol., vol. 6, p. 591, 2015.

[20] M. Zhang, K. Zhang, B. De Gusseme, W. Verstraete, and R. Field, 'The antibacterial and anti-biofouling performance of biogenic silver nanoparticles by Lactobacillus fermentum', Biofouling, vol. 30, no. 3, pp. 347–357, 2014.

[21] M. Y. Al-darwesh, S. S. Ibrahim, and L. L. Hamid, 'Ficus carica latex mediated biosynthesis of zinc oxide nanoparticles and assessment of their antibacterial activity and biological safety', Nano-Structures & Nano-Objects, vol. 38, p. 101163, 2024, doi: https://doi.org/10.1016/j.nanoso.2024.101163.

[22] M. F. Abdulrahman, A. S. Al-Rawi, L. L. Hamid, A. M. Aljumialy, W. M. Saod, and A. M. Al-Fahdawi, 'Preparation of polyvinyl alcohol (PVA) aerogel microsphere loaded with biogenic zinc oxide nanoparticles as potential antibacterial drug', J. Mol. Struct., p. 137901, 2024.

[23] W. M. Saod, L. L. Hamid, N. J. Alaallah, and A. Ramizy, 'Biosynthesis and antibacterial activity of manganese oxide nanoparticles prepared by green tea extract', Biotechnol. Reports, vol. 34, p. e00729, 2022.

[24] W. M. Saod, M. S. Al-Janaby, E. W. Gayadh, A. Ramizy, and L. L. Hamid, 'Biogenic synthesis of iron oxide nanoparticles using Hibiscus sabdariffa extract: Potential for antibiotic development and antibacterial activity against multidrug-resistant bacteria', Curr. Res. Green Sustain. Chem., p. 100397, 2024.

[25] M. El-Subeyhi, L. L. Hamid, E. W. Gayadh, W. M. Saod, and A. Ramizy, 'Biogenic Synthesis and Characterisation of Novel Potassium Nanoparticles by Capparis spinosa Flower Extract and Evaluation of Their Potential Antibacterial, Anti-biofilm and Antibiotic Development', Indian J. Microbiol., pp. 1–10, 2024.

[26] M. Y. Al-darwesh, S. S. Ibrahim, and M. A. Mohammed, 'A Review on Plant Extract Mediated Green Synthesis of Zinc oxide Nanoparticles and

Their biomedical Applications', Results Chem., p. 101368, 2024.

[27] L. L. Hamid, A. Y. Ali, M. M. Ohmayed, A. Ramizy, and T. Y. Mutter, 'Antimicrobial activity of silver nanoparticles and cold plasma in the treatment of hospital wastewater', Kuwait J. Sci., p. 100212, 2024.

[28] L. B. Capeletti et al., 'Tailored silica–antibiotic nanoparticles: overcoming bacterial resistance with low cytotoxicity', Langmuir, vol. 30, no. 25, pp. 7456–7464, 2014.

[29] C.-N. Lok et al., 'Proteomic analysis of the mode of antibacterial action of silver nanoparticles', J. Proteome Res., vol. 5, no. 4, pp. 916–924, 2006.

[30] M. Mishra, S. Kumar, R. K. Majhi, L. Goswami, C. Goswami, and H. Mohapatra, 'Antibacterial efficacy of polysaccharide capped silver nanoparticles is not compromised by AcrAB-TolC efflux pump', Front. Microbiol., vol. 9, p. 823, 2018.

[31] R. Thomas, S. Snigdha, K. B. Bhavitha, S. Babu, A. Ajith, and E. K. Radhakrishnan, 'Biofabricated silver nanoparticles incorporated polymethyl methacrylate as a dental adhesive material with antibacterial and antibiofilm activity against Streptococcus mutans', 3 Biotech, vol. 8, pp. 1–10, 2018.

[32] J. A. Lemire, J. J. Harrison, and R. J. Turner, 'Antimicrobial activity of metals: mechanisms, molecular targets and applications', Nat. Rev. Microbiol., vol. 11, no. 6, pp. 371–384, 2013.

[33] Y. Du, T. Li, Y. Wan, and P. Liao, 'Signal molecule-dependent quorum-sensing and quorum-quenching enzymes in bacteria', Crit. Rev. Eukaryot. Gene Expr., vol. 24, no. 2, 2014.

[34] S. Ahmed, M. Ahmad, B. L. Swami, and S. Ikram, 'A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: a green expertise', J. Adv. Res., vol. 7, no. 1, pp. 17–28, 2016.

[35] D. Paul, J. Gopal, M. Kumar, and M. Manikandan, 'Nature to the natural rescue: silencing microbial chats', Chem. Biol. Interact., vol. 280, pp. 86–98, 2018.

[36] P. Makvandi, G. W. Ali, F. Della Sala, W. I. Abdel-Fattah, and A. Borzacchiello, 'Hyaluronic acid/corn silk extract based injectable nanocomposite: A biomimetic antibacterial scaffold for bone tissue regeneration', Mater. Sci. Eng. C, vol. 107, p. 110195, 2020.

[37] P. Makvandi, G. W. Ali, F. Della Sala, W. I. Abdel-Fattah, and A. Borzacchiello, 'Biosynthesis and characterization of antibacterial thermosensitive hydrogels based on corn silk extract, hyaluronic acid and nanosilver for potential wound healing', Carbohydr. Polym., vol. 223, p. 115023, 2019.

[38] F. K. Alsammarraie, W. Wang, P. Zhou, A. Mustapha, and M. Lin, 'Green synthesis of silver nanoparticles using turmeric extracts and investigation of their antibacterial activities', Colloids Surfaces B Biointerfaces, vol. 171, pp. 398–405, 2018.

[39] G. Franci et al., 'Silver nanoparticles as potential antibacterial agents', Molecules, vol. 20, no. 5, pp. 8856–8874, 2015.

[40] D. Seth et al., 'Nature-inspired novel drug design paradigm using nanosilver: efficacy on multi-drug-resistant clinical isolates of tuberculosis', Curr. Microbiol., vol. 62, pp. 715–726, 2011.

[41] K. S. Siddiqi, A. Husen, and R. A. K. Rao, 'A review on biosynthesis of silver nanoparticles and their biocidal properties', J. Nanobiotechnology, vol. 16, no. 1, pp. 1–28, 2018.

[42] S. Liao et al., 'Antibacterial activity and mechanism of silver nanoparticles against multidrug-resistant Pseudomonas aeruginosa', Int. J. Nanomedicine, pp. 1469–1487, 2019.

[43] B.-M. Chang, L. Pan, H.-H. Lin, and H.-C. Chang, 'Nanodiamond-supported silver nanoparticles as potent and safe antibacterial agents', Sci. Rep., vol. 9, no. 1, p. 13164, 2019.

[44] M. Okkeh, N. Bloise, E. Restivo, L. De Vita, P. Pallavicini, and L. Visai, 'Gold nanoparticles: can they be the next magic bullet for multidrug-resistant bacteria?', Nanomaterials, vol. 11, no. 2, p. 312, 2021.

[45] A. Kukreja et al., 'Preparation of gold core-mesoporous iron-oxide shell nanoparticles and their application as dual MR/CT contrast agent in human

gastric cancer cells', J. Ind. Eng. Chem., vol. 48, pp. 56–65, 2017.

[46] S. Khanna et al., 'A Simple Colorimetric Method for Naked-Eye Detection of Circulating Cell-Free DNA Using Unlabelled Gold Nanoparticles', ChemistrySelect, vol. 3, no. 41, pp. 11541–11551, 2018.

[47] K. Zheng, M. I. Setyawati, D. T. Leong, and J. Xie, 'Antimicrobial gold nanoclusters', ACS Nano, vol. 11, no. 7, pp. 6904–6910, 2017.

[48] E. A. Ortiz-Benítez, N. Velázquez-Guadarrama, N. V. Durán Figueroa, H. Quezada, and J. de J. Olivares-Trejo, 'Antibacterial mechanism of gold nanoparticles on Streptococcus pneumoniae', Metallomics, vol. 11, no. 7, pp. 1265–1276, 2019.

[49] S. Shaikh et al., 'Mechanistic insights into the antimicrobial actions of metallic nanoparticles and their implications for multidrug resistance', Int. J. Mol. Sci., vol. 20, no. 10, p. 2468, 2019.

[50] W. Jo and M. J. Kim, 'Influence of the photothermal effect of a gold nanorod cluster on biofilm disinfection', Nanotechnology, vol. 24, no. 19, p. 195104, 2013.

[51] P. Pallavicini et al., 'Modular approach for bimodal antibacterial surfaces combining photo-switchable activity and sustained biocidal release', Sci. Rep., vol. 7, no. 1, p. 5259, 2017.

[52] I. Venditti, 'Engineered gold-based nanomaterials: Morphologies and functionalities in biomedical applications. a mini review', Bioengineering, vol. 6, no. 2, p. 53, 2019.

[53] K. Hantke, 'Bacterial zinc uptake and regulators', Curr. Opin. Microbiol., vol. 8, no. 2, pp. 196–202, 2005.

[54] D. K. Blencowe and A. P. Morby, 'Zn (II) metabolism in prokaryotes', FEMS Microbiol. Rev., vol. 27, no. 2–3, pp. 291–311, 2003.

[55] B. L. Nairn et al., 'The response of Acinetobacter baumannii to zinc starvation', Cell Host Microbe, vol. 19, no. 6, pp. 826–836, 2016.

[56] K. Blecher, A. Nasir, and A. Friedman, 'The growing role of nanotechnology in combating infectious disease', Virulence, vol. 2, no. 5, pp. 395–401, 2011.

[57] E. Taylor and T. J. Webster, 'Reducing infections through nanotechnology and nanoparticles', Int. J. Nanomedicine, pp. 1463–1473, 2011.

[58] L. S. Reddy, M. M. Nisha, M. Joice, and P. N. Shilpa, 'Antimicrobial activity of zinc oxide (ZnO) nanoparticle against Klebsiella pneumoniae', Pharm. Biol., vol. 52, no. 11, pp. 1388–1397, 2014.

[59] M. Mirhosseini and V. Arjmand, 'Reducing pathogens by using zinc oxide nanoparticles and acetic acid in sheep meat', J. Food Prot., vol. 77, no. 9, pp. 1559–1564, 2014.

[60] K. S. Siddiqi, A. ur Rahman, null Tajuddin, and A. Husen, 'Properties of zinc oxide nanoparticles and their activity against microbes', Nanoscale Res. Lett., vol. 13, pp. 1–13, 2018.

[61] P. V Pimpliskar, S. C. Motekar, G. G. Umarji, W. Lee, and S. S. Arbuj, 'Synthesis of silver-loaded ZnO nanorods and their enhanced photocatalytic activity and photoconductivity study', Photochem. Photobiol. Sci., vol. 18, pp. 1503–1511, 2019.

[62] S. Vijayakumar, B. Vaseeharan, B. Malaikozhundan, and M. Shobiya, 'Laurus nobilis leaf extract mediated green synthesis of ZnO nanoparticles: Characterization and biomedical applications', Biomed. Pharmacother., vol. 84, pp. 1213–1222, 2016.

[63] C. Rensing and G. Grass, 'Escherichia coli mechanisms of copper homeostasis in a changing environment', FEMS Microbiol. Rev., vol. 27, no. 2–3, pp. 197–213, 2003.

[64] C. Espírito Santo, P. V. Morais, and G. Grass, 'Isolation and characterization of bacteria resistant to metallic copper surfaces', Appl. Environ. Microbiol., vol. 76, no. 5, pp. 1341–1348, 2010.

[65] G. Grass, C. Rensing, and M. Solioz, 'Metallic copper as an antimicrobial surface', Appl. Environ. Microbiol., vol. 77, no. 5, pp. 1541–1547, 2011.

[66] C.-W. Chen, C.-Y. Hsu, S.-M. Lai, W.-J. Syu, T.-Y. Wang, and P.-S. Lai, 'Metal nanobullets for multidrug resistant bacteria and biofilms', Adv. Drug Deliv. Rev., vol. 78, pp. 88–104, 2014.

[67] L. Macomber and J. A. Imlay, 'The iron-sulfur clusters of dehydratases are primary intracellular targets of copper toxicity', Proc. Natl. Acad. Sci., vol. 106, no. 20, pp. 8344–8349, 2009.

[68] V. Ravishankar Rai and A. Jamuna Bai, 'Nanoparticles and their potential application as antimicrobials', A Méndez-Vilas A, Ed. Mysore Formatex, pp. 197–209, 2011.

[69] A. Pramanik, D. Laha, D. Bhattacharya, P. Pramanik, and P. Karmakar, 'A novel study of antibacterial activity of copper iodide nanoparticle mediated by DNA and membrane damage', Colloids Surfaces B Biointerfaces, vol. 96, pp. 50–55, 2012.

[70] B. K. Hafshejani, M. Mirhosseini, F. Dashtestani, F. Hakimian, and B. F. Haghirosadat, 'Antibacterial activity of nickel and nickel hydroxide nanoparticles against multidrug resistance K. pneumonia and E. coli isolated urinary tract.', Nanomedicine J., vol. 5, no. 1, 2018.

[71] W. Zhang, Y. Li, J. Niu, and Y. Chen, 'Photogeneration of reactive oxygen species on uncoated silver, gold, nickel, and silicon nanoparticles and their antibacterial effects', Langmuir, vol. 29, no. 15, pp. 4647–4651, 2013.

[72] R. M. Silva et al., 'Proteic sol-gel synthesis, structure and magnetic properties of Ni/NiO core-shell powders', Ceram. Int., vol. 44, no. 6, pp. 6152–6156, 2018.

[73] N. A. Kumar, N. S. Rejinold, P. Anjali, A. Balakrishnan, R. Biswas, and R. Jayakumar, 'Preparation of chitin nanogels containing nickel nanoparticles', Carbohydr. Polym., vol. 97, no. 2, pp. 469–474, 2013.

[74] M. Imran Din and A. Rani, 'Recent advances in the synthesis and stabilization of nickel and nickel oxide nanoparticles: a green adeptness', Int. J. Anal. Chem., vol. 2016, 2016.

[75] L. Zhu et al., 'Synthesis of novel platinum-on-flower-like nickel catalysts and their applications in hydrogenation reaction', Appl. Surf. Sci., vol. 423, pp. 836–844, 2017.

[76] S. Das, K. Vishakha, S. Banerjee, D. Nag, and A. Ganguli, 'Tetracycline-loaded magnesium oxide nanoparticles with a potential bactericidal action against multidrug-resistant bacteria: In vitro and in vivo evidence', Colloids Surfaces B Biointerfaces, vol. 217, p. 112688, 2022.

[77] L. Cai, J. Chen, Z. Liu, H. Wang, H. Yang, and W. Ding, 'Magnesium oxide nanoparticles: effective agricultural antibacterial agent against Ralstonia solanacearum', Front. Microbiol., vol. 9, p. 790, 2018.

[78] N. Beyth, Y. Houri-Haddad, A. Domb, W. Khan, and R. Hazan, 'Alternative antimicrobial approach: nano-antimicrobial materials', Evidence-based Complement. Altern. Med., vol. 2015, 2015.

[79] S. Saqib et al., 'Synthesis, characterization and use of iron oxide nano particles for antibacterial activity', Microsc. Res. Tech., vol. 82, no. 4, pp. 415–420, 2019.

[80] M. Aparicio-Caamaño, M. Carrillo-Morales, and J. J. Olivares-Trejo, 'Iron oxide nanoparticle improves the antibacterial activity of erythromycin', J Bacteriol Parasitol, vol. 7, no. 267, p. 2, 2016.

[81] L. M. Armijo et al., 'Antibacterial activity of iron oxide, iron nitride, and tobramycin conjugated nanoparticles against Pseudomonas aeruginosa biofilms', J. Nanobiotechnology, vol. 18, no. 1, pp. 1–27, 2020.

[82] T. Itabashi et al., 'Bactericidal and antimicrobial effects of pure titanium and titanium alloy treated with short-term, low-energy UV irradiation', Bone Joint Res., vol. 6, no. 2, pp. 108–112, 2017.

[83] Y. Li, W. Zhang, J. Niu, and Y. Chen, 'Mechanism of photogenerated reactive oxygen species and correlation with the antibacterial properties of engineered metal-oxide nanoparticles', ACS Nano, vol. 6, no. 6, pp. 5164–5173, 2012.

[84] P. V Baptista et al., 'Nano-strategies to fight multidrug resistant bacteria—"A Battle of the Titans"', Front. Microbiol., vol. 9, p. 1441, 2018.

[85] J. R. Anasdass, P. Kannaiyan, R. Raghavachary, S. C. B. Gopinath, and Y. Chen, 'Palladium nanoparticle-decorated reduced graphene oxide sheets synthesized using Ficus carica fruit extract: A catalyst for Suzuki cross-coupling reactions', PLoS One, vol. 13, no. 2, p. e0193281, 2018.

[86] C. P. Adams, K. A. Walker, S. O. Obare, and K. M. Docherty, 'Size-dependent antimicrobial effects of novel palladium nanoparticles', PLoS One, vol. 9, no. 1, p. e85981, 2014.

[87] S. Gnanasekar et al., 'Antibacterial and cytotoxicity effects of biogenic palladium nanoparticles synthesized using fruit extract of Couroupita guianensis Aubl.', J. Appl. Biomed., vol. 16, no. 1, pp. 59–65, 2018.

[88] S. Ghosh, 'Copper and palladium nanostructures: a bacteriogenic approach', Appl. Microbiol. Biotechnol., vol. 102, no. 18, pp. 7693–7701, 2018.

[89] M. Y. Vaidya, A. J. McBain, J. A. Butler, C. E. Banks, and K. A. Whitehead, 'Antimicrobial efficacy and synergy of metal ions against Enterococcus faecium, Klebsiella pneumoniae and Acinetobacter baumannii in planktonic and biofilm phenotypes', Sci. Rep., vol. 7, no. 1, p. 5911, 2017.

[90] G. M. Khiralla and B. A. El-Deeb, 'Antimicrobial and antibiofilm effects of selenium nanoparticles on some foodborne pathogens', LWT-Food Sci. Technol., vol. 63, no. 2, pp. 1001–1007, 2015.

[91] Q. Wang, P. Larese-Casanova, and T. J. Webster, 'Inhibition of various gram-positive and gram-negative bacteria growth on selenium nanoparticle coated paper towels', Int. J. Nanomedicine, pp. 2885–2894, 2015.

[92] D. Chudobova et al., 'Comparison of the effects of silver phosphate and selenium nanoparticles on Staphylococcus aureus growth reveals potential for selenium particles to prevent infection', FEMS Microbiol. Lett., vol. 351, no. 2, pp. 195–201, 2014.

[93] E. Kheradmand, F. Rafii, M. H. Yazdi, A. A. Sepahi, A. R. Shahverdi, and M. R. Oveisi, 'The antimicrobial effects of selenium nanoparticle-enriched probiotics and their fermented broth against Candida albicans', DARU J. Pharm. Sci., vol. 22, pp. 1–6, 2014.

[94] N. Srivastava and M. Mukhopadhyay, 'Green synthesis and structural characterization of selenium nanoparticles and assessment of their antimicrobial property', Bioprocess Biosyst. Eng., vol. 38, pp. 1723–1730, 2015.

[95] T. H. D. Nguyen, B. Vardhanabhuti, M. Lin, and A. Mustapha, 'Antibacterial properties of selenium nanoparticles and their toxicity to Caco-2 cells', Food Control, vol. 77, pp. 17–24, 2017.

[96] M. A. Ansari, H. M. Khan, A. A. Khan, S. S. Cameotra, Q. Saquib, and J. Musarrat, 'Interaction of Al2O3 nanoparticles with Escherichia coli and their cell envelope biomolecules', J. Appl. Microbiol., vol. 116, no. 4, pp. 772–783, 2014.

[97] D. Valerini et al., 'Aluminum-doped zinc oxide coatings on polylactic acid films for antimicrobial food packaging', Thin Solid Films, vol. 645, pp. 187–192, 2018.

[98] A. M. El Nahrawy, A. B. Abou Hammad, M. S. Abdel-Aziz, and A. R. Wassel, 'Spectroscopic and antimicrobial activity of hybrid chitosan/silica membranes doped with Al 2 O 3 nanoparticles', Silicon, vol. 11, pp. 1677–1685, 2019.

[99] R. S. Sabry, A. H. Ali Al-fouadi, and H. K. Habool, 'Enhanced antibacterial activity of anodic aluminum oxide membranes embedded with nano-silver-titanium dioxide', J. Adhes. Sci. Technol., vol. 32, no. 8, pp. 874–888, 2018.

[100] P. D. Dwivedi, A. Misra, R. Shanker, and M. Das, 'Are nanomaterials a threat to the immune system?', Nanotoxicology, vol. 3, no. 1, pp. 19–26, 2009.

[101] L. Gonzalez, D. Lison, and M. Kirsch-Volders, 'Genotoxicity of engineered nanomaterials: a critical review', Nanotoxicology, vol. 2, no. 4, pp. 252–273, 2008.

[102] M. Korani, E. Ghazizadeh, S. Korani, Z. Hami, and A. Mohammadi-Bardbori, 'Effects of silver nanoparticles on human health', Eur. J. Nanomedicine, vol. 7, no. 1, pp. 51–62, 2015.

[103] V. Kumar, N. Sharma, and S. S. Maitra, 'In vitro and in vivo toxicity assessment of nanoparticles', Int. Nano Lett., vol. 7, no. 4, pp. 243–256, 2017.

[104] J. Indrakumar and P. S. Korrapati, 'Steering efficacy of nano molybdenum towards cancer: mechanism of action', Biol. Trace Elem. Res., vol. 194, pp. 121–134, 2020.

[105] A. Marzban, B. Seyedalipour, M. Mianabady, A. Taravati, and S. M. Hoseini, 'Biochemical, toxicological, and histopathological outcome in rat brain following treatment with NiO and NiO nanoparticles', Biol. Trace Elem. Res., vol. 196, pp. 528–536, 2020.

[106] T. Y. Poh et al., 'Inhaled nanomaterials and the respiratory microbiome: clinical, immunological

and toxicological perspectives', Part. Fibre Toxicol., vol. 15, pp. 1–16, 2018.

[107] F. Fatima, N. Pathak, S. R. Verma, and P. Bajpai, 'Toxicity and immunomodulatory efficacy of biosynthesized silver myconanosomes on pathogenic microbes and macrophage cells', Artif. Cells, Nanomedicine, Biotechnol., vol. 46, no. 8, pp. 1637–1645, 2018.

الجسيمات النانوية المعدنية كعوامل علاجية مضادة للبكتريا في حقل مقاومة المضادات الحياتية : مراجعة

ليث لطيف حامد، حنان حامد محمد

قسم علوم الحياة ، كلية العلوم ، جامعة الأنبار ، الأنبار ، العراق

layth94@uoanbar.edu.iq

الخلاصة:

أصبحت المقاومة المتزايدة للمضادات الحياتية مشكلة صحية عامة تنذر لخطر كبير. ولمعالجة هذه المشكلة، وجب استخدام أساليب جديدة لمكافحة هذه الأنواع من الميكروبات المسببة للامراض. أدى ظهور علم النانو الى تطوير مواد جديدة مضادة للبكتريا بما في ذلك الجسيمات النانوية المعدنية مثل الفضة والزنك والنحاس والذهب والنيكل والمغنيسيوم والحديد والتيتانيوم والسيلينيوم والبلاديوم والالمنيوم. وقد اظهرت هذه المواد خواص مميزة في مكافحة مجموعة واسعة من السلالات المقاومة للمضادات الحياتية. تقوم الجسيمات النانوية المعدنية بتدمير او تثبيط المحتويات الخلوية المختلفة للكائنات الدقيقة دون ان تتأثر بآليات المقاومة في هذه الأنواع. تساهم المواد النانوية ذات الاحجام الصغيرة والفعالية العالية المضادة للميكروبات والسمية المنخفضة في تقليل المخاطر البيئية لمثل هذه العوامل. ومع ذلك يحتاج العلماء الى مواجهة العديد من التحديات، بما في ذلك المخاوف الصحية والأخلاقية الحيوية، ومخاطر السمية، والاعتبارات الفسيولوجية والطبية المرتبطة باستخدام المواد النانوية كعلاجات مضادة للبكتريا. ونظرا لعدم وجود آليات مقاومة بكتيرية ضد الجسيمات النانوية المعدنية، يمكن ان تكون هذه الجسيمات واعدة في مكافحة السلالات البكتيرية المقاومة للمضادات الحياتية.

الكلمات المفتاحية: *جسيمات نانوية معدنية، مضادات حياتية ، مقاومة مضادات حياتية متعددة ،مضادات بكتيرية ،تصنيع الجسيمات النانوية.*