Hilla University College Journal For Medical Science

Volume 2 | Issue 4 Article 3

2024

Exploring the Role of Nanoparticles in Combating Microbial Infections: A Mini Review

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How to Cite This Article
Mohammed, Khaldoon Jasim; Hussein, Abdulhakeem Dahham; and Muhammad, Sundus Jassim (2024) "Exploring the Role of Nanoparticles in Combating Microbial Infections: A Mini Review," *Hilla University College Journal For Medical Science*: Vol. 2: Iss. 4, Article 3.
DOI: https://doi.org/10.62445/2958-4515.1035

REVIEW

Hilla Univ Coll J Med Sci

Exploring the Role of Nanoparticles in Combating Microbial Infections: A Mini Review

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Abstract

Background: Drug-resistant organisms are on the rise globally, and therefore studies for new forms of antimicrobial agents. Among them, nanoparticles find much utility in drug delivery and possess effectiveness against antibiotic-resistant strains. Such an approach is a successful one for public health since it has relative advantages in eradicating microbial infections.

Objective: The aim of this mini-review is to discuss the role of nanoparticles and their functions on microbial infections, especially regarding their antimicrobial activity. Method: This review involves the conduct of a systematic review of the literature through publications in different databases like PubMed, Scopus, and Web of Sciences, and only the peer-reviewed articles that are published are used. This comprises published articles that provide information on the occurrence of the role of nanoparticles, including metallic nanoparticles like iron oxide, gold, zinc oxide, and silver, in antimicrobial activity.

Results: There are various reports that nanoparticles possess antimicrobial properties through direct action on microbial cell membranes, oxidative stress induction, and inhibitory effects on biofilm formation. They demonstrate effectiveness against numerous types of pathogens, MDR bacteria. Due to their ability to target microbial infections, bypass resistance mechanisms, and act as drug delivery systems, nanoparticles have potential in the fight against deadly microbial infections.

Conclusions: Nanoparticles present an effective strategy in controlling microbial infection, especially that which is associated with drug-resistant pathogens. Due to the specific characteristics of some of them related to the diverse ways in which they exert their effect, they are useful in the combat against infection. However, more research is needed to address concerns about potential toxicity and improve its clinical applications.

Keywords: Nanoparticles, Antimicrobial resistance, Antibiotic, Microbial infections

1. Introduction

Microbial infections are major global health issues since they are responsible for causing varied diseases, from a simple infection to fatal ones. This is because the discovery of the antimicrobials has really been a breakthrough in dealing with such infections. However, there are problems that threaten the efficiency of these treatments; one of them is antimicrobial resistance (AMR). AMR takes place when microbes develop ways of counteracting the impact of antimicrobial drugs, thus making the drugs of no use [1]. Such situations result in protracted diseases, high costs of relapse, high mortality, and limited therapeutic interventions. AMR is a complex phenomenon that is informed by the utilization of antibiotics, more

Received 15 September 2024; accepted 23 November 2024.
Available online 25 December 2024

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https://doi.org/10.62445/2958-4515.1035

than recommended doses, massive consumption of antibiotics, weak access to clean water and sanitation facilities, inadequate infection control measures, and weak surveillance system mechanisms [2]. The global consequence of AMR is believed to have an impact on both human and animal health, as well as the environment [3]. Combating AMR is achievable, but this is only possible if it is a multi-sector and multi-country effort. Antimicrobial stewardship, infection prevention and control practices, research and development for new antimicrobials, and promotion of public awareness comprehensively address strategies in the prevention and control of AMR. In order to achieve reasonable solutions for possible prevention of AMR and to improve the overall results towards protecting the health of the global population's health, one has to dedicate a certain amount of time towards studying the role of microbial infections in the overall spectrum of world diseases [4, 5]. Nanoparticles have immense potential to provide novel solutions for the prevention of drug-resistant organisms. These particles have unique characteristics that enable them to combat various animal diseases. With the help of nanoparticles, antimicrobial treatments can be made more effective by targeting specific microbes [6]. Research has shown that nanoparticles possess significant potential to eradicate infections caused by bacteria, viruses, and fungi. Nanoparticles can be used in drug delivery systems to target the site of infection, enabling more effective handling of microbial infections [7]. They may also be useful in addressing the challenges associated with the current classes of antimicrobials, which include antibiotic resistance [8]. Furthermore, it has been established that particles of this size may augment the bioactivity of the therapeutic agents used in the fight against infections [9]. In addition, nanoparticles are useful to prevent the formation of biofilm; it is one of the main defense strategies of microbes leading to chronic inflammation and worsening of diseases. Nanotechnology is posing new ways to develop preventions as well as control of microbial infections for future development in the medical field [10]. This review aims to elaborate on the applicability of nanoparticles in microbial infections, their profiles of antimicrobial activity, mechanisms of action, and advantages. It outlines recent progress in the preparation of nanoparticles, surface modifications, and relationships between nanoparticles and conventional antibiotics. The review serves as a source of information for future researchers and clinical practitioners in need of nanotechnology for second-generation antimicrobial agents.

2. Antimicrobial potential of nanoparticles

2.1. Antibacterial, antifungal, and antiviral properties of nanoparticles

The use of nanoparticles has been proven to possess strong antimicrobial activity against bacteria, fungi, and viruses, thus becoming potential tools for new strategies in fighting microbial infections and resistance. Nanoparticles with sizes less than 1–100 nm have some special characteristics of physicochemistry, which make them effective against microorganisms [11]. Nanoparticles of silver (Ag), copper (Cu), and zinc oxide (ZnO)-based metal nanoparticles explored in this review have been found to exhibit promising antibacterial characteristics against several pathogenic bacteria [12]. The antibacterial mechanism primarily involves the following effects have been postulated: formation of reactive oxygen species (ROS), manipulation of bacterial cell membranes, and alteration of cellular functions. For example, CTAB-stabilized AgNPs had minimum inhibitory concentrations (MICs) ranging from as low as 0. As noted earlier, it is effective at 0.003 μM against *Escherichia coli* and *Staphylococcus aureus* [13]. Based on the current literature, the antibacterial properties of nanoparticles are known to be influenced by parameters such as size, shape, surface charge, and concentration [14].

2.1.1. Antifungal properties

The nanoparticles also possess significant antifungal activity against different pathogenic fungi, such as *Candida* species, *Aspergillus fumigatus*, and dermatophytes [15]. Metal nanoparticles have been found to possess good antifungal properties, with AgNPs showing a better candidacidal effect than the standard drugs in some instances. For example, the minimum inhibitory concentrations of AgNPs were in the range of 3. 0.1–2.5 $\Sigma\mu$/ml against numerous fungal species. The antifungal mechanisms include affecting the integrity of the cell wall and membrane, inhibiting general functional organelles such as mitochondria and ribosomes, and inhibiting cell division and reproduction [16]. In summary, Fig. 1 illustrates that it can be seen that nanoparticles (a) eliminate bacterial and fungal resistance (b) change the cell membrane potential (c) inhibit the formation of biofilms (d) stimulate immune responses (e) activate intracellular reactive oxygen species.

2.1.2. Antiviral properties

Nanoparticles, particularly those of metallic origin, have been found to possess antiviral properties

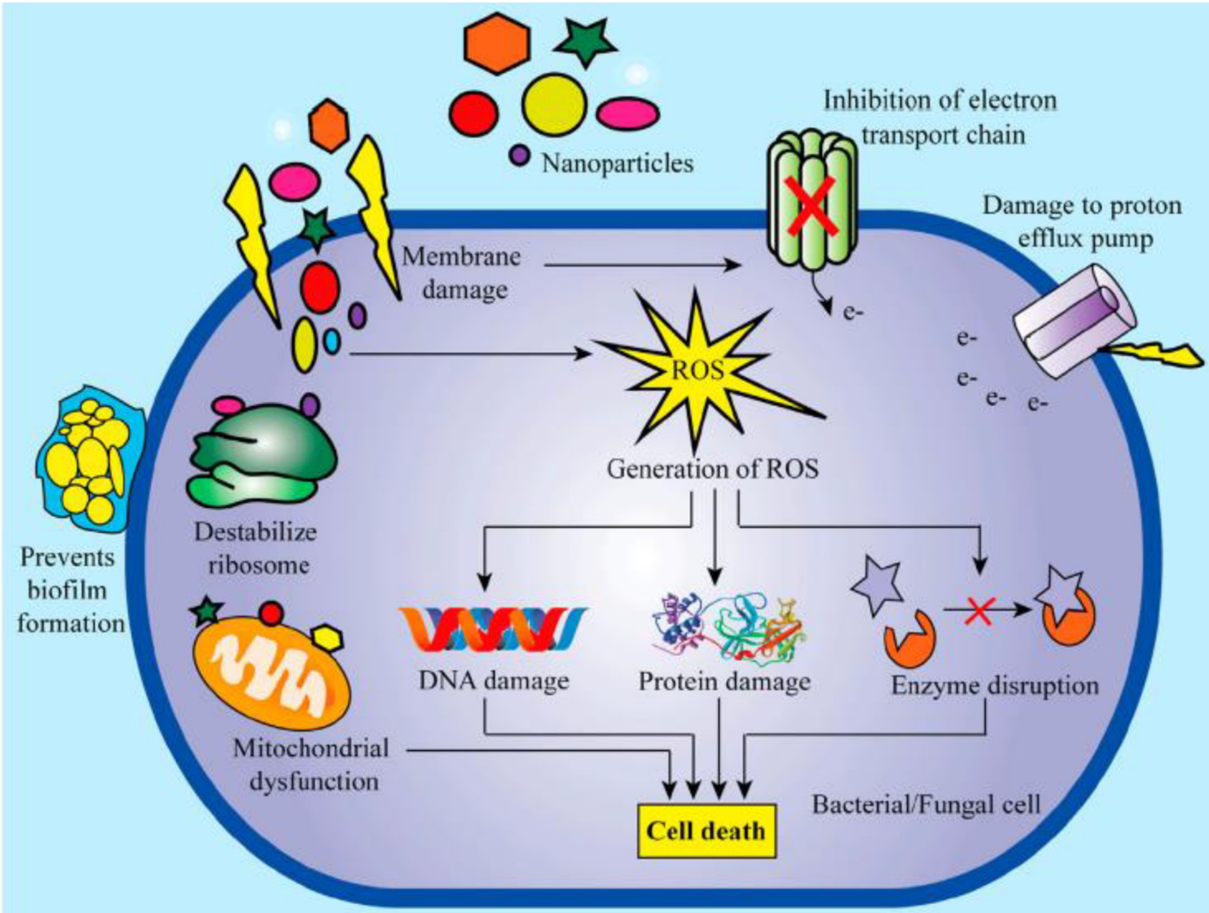

Fig. 1. Diagram shows that nanoparticles remove bacterial and fungal resistance, alter cell membrane potential, inhibit biofilm formation, trigger immune response, and include intracellular reactive oxygen species [17].

against different viruses, such as HIV, HSV, and respiratory viruses [18]. The antiviral mechanisms of nanoparticles include: direct contact with the virus; preventing the virus from linking to the receptor that is present in the host cells; and disrupting the processes through which the virus replicates. Silver nanoparticles have been found to possess broad-spectrum antiviral properties, as seen from studies done on several viruses. It has been shown that their activity is highly dependent on its size, shape, functionalization, and concentration. For instance, copper-silver and copper-zinc intermetallic nanoparticles were highly potent towards RNA viruses and DNA viruses, with viral reductions of more than 89% and above [19, 20].

2.2. *Mechanisms of action of nanoparticles against microbes*

Antimicrobial nanoparticles exhibit a number of anti-microbial activities through different modes of action and present novel approaches for controlling microbial infections and resistance [21]. Such mechanisms include the ability to generate reactive oxygen species, which in turn cause oxidative stress and damage to essential biomolecules and other structures, resulting in microbial cell death. It has also been widely reported that nanoparticles are capable of penetrating the membrane and damaging it in a manner that weakens the barrier [22, 23]. Metal-based nanoparticles release ions, which enter and interact with the membrane functions of microbes, thus enhancing the antimicrobial effects. Enzymes and proteins vital for cellular functions can be deactivated by nanoparticles, and this causes death amongst microbes [24]. Certain nanoparticles, namely the silver nanoparticles, alter the DNA of microbes, causing strain as well as hindering their ability to replicate and survive. Such DNA damage creates oxidative stress that plays roles in the antimicrobial mechanisms of nanoparticles. Other ways that nanoparticles can act against microbes are by inhibiting the synthesis of proteins that are essential in the growth and development of microbes. The capability to penetrate through

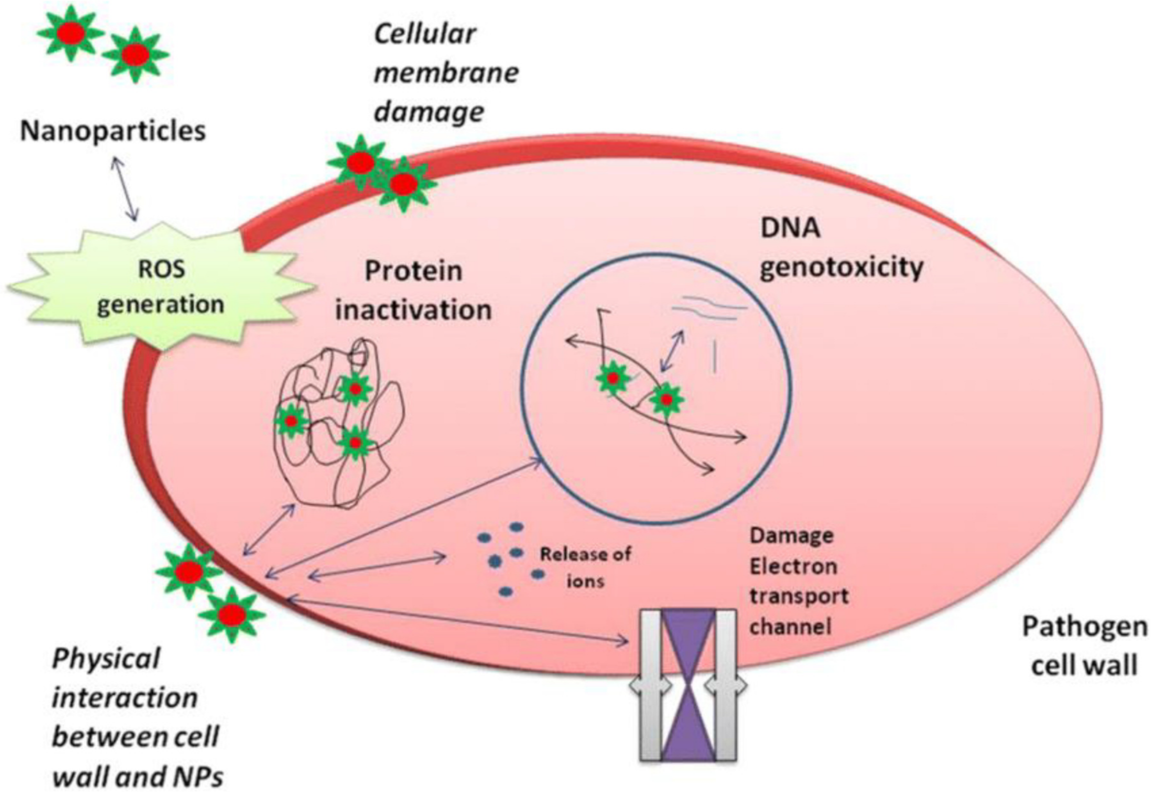

Fig. 2. Mechanism of action of nanoparticle in bacterial cell [29].

the membrane enables nanoparticles to get through the cell and membrane wall of microbes and thus provide an immediate intra-cell antimicrobial effect [25, 26]. It is necessary to comprehend these mechanisms in order to utilize the full potential of nanoparticles as the antimicrobial agents since they can interfere with the microbial resistance peculiarities and make contributions to the development of efficient approaches for the elimination of the microbial infection caused by bacteria, fungi, and viruses [27, 28]. Fig. 2 explain the mechanism of nanoparticle action in bacterial cells.

3. Applications of nanoparticles in biomedical field

The biomedical applications have become endless after the introduction of nanoparticles since they possess special features and size-dependent behavior. They vary in 1-100 nm, and due to their large surface area and small mass, the nanoparticles interact favorably with biological systems [30]. In diagnostics, the nanoparticles have been known to enhance most imaging procedures. For example, superparamagnetic iron oxide nanoparticles (SPIONs) may be employed as magnetic resonance imaging (MRI) contrast agents for early diagnosis of diseases [31]. Organic and inorganic nanoparticles like quantum dots and gold nanoparticles have found in bioimaging and as biosensors for biomolecule detection that show high sensitivity and specificity [32]. Another important area where nanoparticles play a great role is drug delivery. It can also be tailored to incorporate and deliver drugs in a controlled fashion for enhancing the effectiveness of drugs and minimizing side effects. It has been elicited that nanoparticles can conveniently permeate biological barriers, for example, the blood-brain barrier, hence allowing rightful delivery of the nanoparticles to the desired tissues or organs [33]. This is advantageous in cancer therapy because nanoparticles possess the capability to be trapped in the tumor tissues as a result of the well-known EPR effect [34]. In cancer treatment, nanoparticles are used for drug delivery, as well as in photothermal and photodynamic treatment; for instance, gold nanoparticles can produce heat when exposed to near-infrared light and would be able to kill cancer cells. Nanoparticles also have potential in the field of regenerative medicine as well as in tissue engineering. They can also be applied as templates for cell attachment and differentiation when applied as for tissue repair and regeneration [35, 36]. In addition,

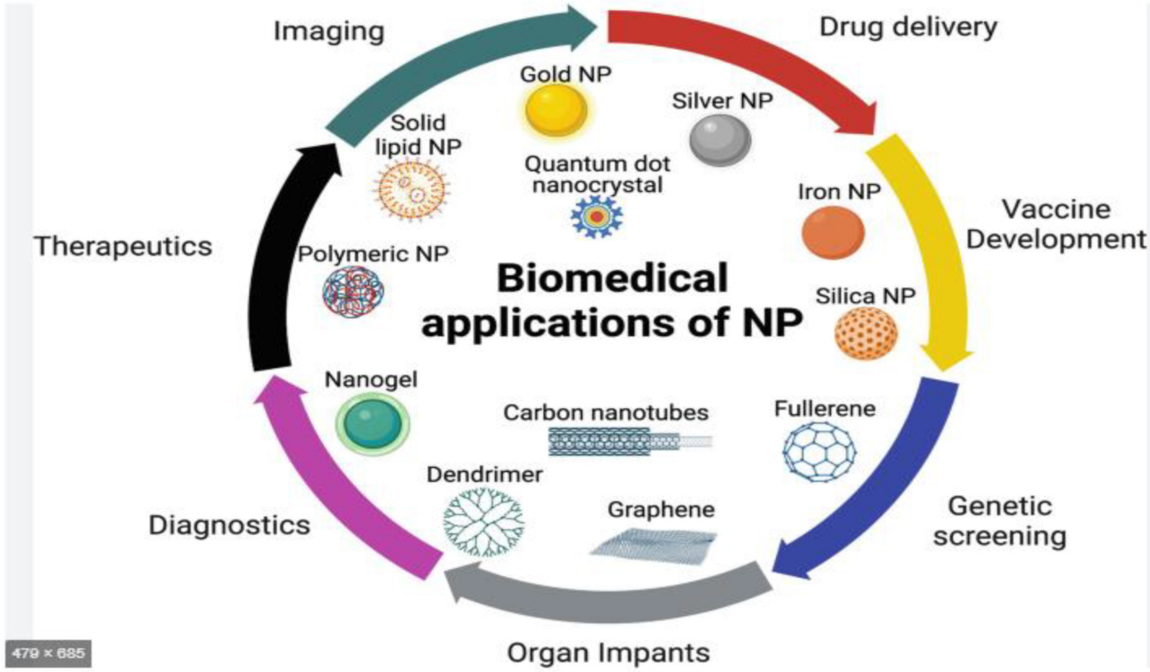

Fig. 3. Biomedical applications of nanoparticles [39].

particles, particularly in, display character, which can be helpful for usage against antibiotic-resistant bacteria. Among all the silver-containing compounds, it is the silver nanoparticles that demonstrated extremely high antimicrobial activity against various pathogens. However, the use of nanomaterials as reinforcement in polymer matrices has been found to possess many applications, but their safety and possible toxicity cannot be overemphasized. Current work is to make nanoparticles more biodegradable to eradicate most of the hazardous impacts [37, 38]. Fig. 3 illustrates the use of nanoparticles in biomedicine.

4. Nanoparticles in clinical settings

4.1. Impact of nanoparticles on drug-resistant bacteria

Many bacterial microbes are now becoming resistant to well-recognized antibiotics, and this is now a cause of severe illness, costly treatment, and increased mortality. Nanoparticles have recently been reported to be effective in improving the efficacy of antibiotics and lowering bacterial resistance in bacteria. Therefore, nanomaterial-based therapy may provide the ultimate solution to biofilm eradication and to dealing with extracellular and intracellular bacteria. The size and composition of the NPs exert significant influence on the extent of the bacterial-resistant organisms [40]. Interestingly, nanoparticles could also alter bacterial physiology in issues such as competence, and these have implications for the spread of antibiotic resistance in bacteria [41]. Examples of the impact of metallic nanoparticles include ZnO nanoparticles that have been found to cause the death of *E. coli* cells and raise the transformation frequency, although the latter effect may further facilitate the horizontal transfer of resistance genes [42]. However, metallic nanoparticles can also interact with the pathogens and increase their improvements, especially for the antibacterial effect against gram-positive pathogens. Nanoparticles application in fighting drug-resistant bacteria is crucial because the antimicrobial resistance rate is rising significantly all over the world [43]. The following properties associated with nanoparticles have proven to be very efficient in controlling the growth and existence of MDRAC bacteria in different sectors of healthcare. Both amorphous and crystalline nanostructures can act as positive antimicrobial agents and as drug carriers for antibacterial agents addressing planktonic bacteria and bacterial biofilms [44]. Nanoparticles are capable of counteracting the existing drug resistance factors, including reduced drug internalization and enhanced extrusion out of the microbial cell, microbial biofilm formation, and intracellular microbes. They can also deliver antimicrobial agents to the site of infection, thus enhancing the ability to apply a high dose of the drug in a localized area. The use of nanoparticles may offer a solution to fighting resistant infections through suppression of MDROs growth and survival in humans, animals, and the environment [45]. The behaviors of particles at the bacterial membrane level play a vital role in the effectiveness of the nanoparticles in countering DR bacteria. Concerning the last and most interesting point, it is possible to state that nanoparticles can encapsulate antibiotics and be protected from bacterial resistance mechanisms by the process of surface functionalization of nanocarriers. Nanoparticles in nanomedicine offer potential ways of addressing antimicrobial resistance since bacteria develop into resistant versions [46].

4.2. Examination of nanoparticles' antimicrobial properties and their clinical applications

Silver, chitosan metal nanoparticles, and other nanoparticles also have antibacterial properties against bacteria, fungi, and viruses. These nanoparticles provide certain distinct features and benefits, such as better drug delivery, increased solubility, and effectiveness against antibiotic-resistant bacteria [47]. For example, silver nanoparticles have strong biocidal properties, and they can also be efficient against antibiotic-resistant microorganisms. These chitosan nanoparticles have been known to exhibit antimicrobial properties against different microorganisms, and they have versatile uses in the pharmacological industry for use in antibiotics, wound dressing, and food conservation [48]. The ways through which nanoparticles exhibit antimicrobial action include the ability to produce reactive oxygen species, DNA destruction, disruption of the bacterial membrane, and protein synthesis [49]. These mechanisms help nanoparticles to successfully address infection diseases and avoid biofilm formation, which is a major problem in the treatment of bacterial infections [50]. In this work, the advancements made through the application of nanotechnology in the medical field for the treatment of resistant microbes, AMR, and infectious diseases have been discussed. Nanoparticles can be applied as drug delivery systems for antimicrobial drugs, as this will enhance the effectiveness of the drugs and reduce the impact on healthy cells. Consideration of how nanoparticles interact with conventional antimicrobial agents, including antibiotics, shows that they increase the overall effectiveness, decrease toxicity levels, and expand the antimicrobial action spectrum [51]. Nanoparticles in antimicrobial therapy involve topical application, wound healing, and infection control, as well as using antimicrobial coatings on medical equipment. In this case, nanoparticles have been deemed effective in treating bacterial infections, especially in the fight against both biofilms and antibiotic-resistant bacteria [52]. The application of bimetallic nanoparticles becomes a new method to combat the problem of antimicrobial resistance and find opportunities in the areas of wound healing and infection prevention [53]. Thus, it can be concluded that nanoparticles possess immense antimicrobial potential, and they have an assortment of uses in eradicating infectious diseases. Due to differences in mode of action, enhanced activity of conventional antibacterial agents, and biocompatibility aspects, these compounds have potential application in today's medicine [54].

5. Properties and drawbacks of nanoparticles in antimicrobial

Studies have shown promising results in using nanoparticles like iron oxide, gold, zinc oxide, and silver to combat microbial infections. However, Table 1 also highlights some drawbacks associated with their use.

Some possible disadvantages of nanoparticles in antimicrobial activities are cytotoxicity in normal cells and tissues, environmental accumulation and effects, unknown chronic effects to humans, lack of cost-effectiveness in large-scale manufacturing for therapies, and dependence on size, shape, and surface charge [59]. Nevertheless, nanoparticles can be regarded as one of the most promising substitutes for traditional antibiotics, particularly for treating the infections caused by drug-resistant bacteria and the formation of biofilms. More studies are required to

Table 1. Advantages and drawbacks on nanoparticles in antimicrobial actions.

Nanoparticles	Antimicrobial properties	Drawbacks
Iron oxide	Eliminates bacterial biofilms and fought against antibiotic-resistant bacteria [55].	Murine cytotoxicity, possibility of forming aggregates in biological fluids [56].
Gold	Selectively embedded in biofilm and can boost the effectiveness of using older antibiotics [55].	Expensive and can accumulate in the organs of the body over time [56].
Zinc oxide	A wide spectrum of antibacterial effects, relatively low toxicity [57].	Activities that may cause build up in the environment, low stability in certain situations [56].
Silver	This product has extremely effective bactericidal action against various microorganisms [57].	It has toxic affect to human cells at very high concentration and there is always chances of bacteria getting resistant to it [56, 58].

understand how they can be safely used for various treatments in health facilities [60, 61].

6. Conclusion

Thus, nanoparticles are proving their worth in serving as an effective tool against antimicrobial resistance. These nanoparticles possess the ability to act as biocides to different types of pathogens, such as those resistant to antibiotics, as well as inhibit the formation of biofilms. Nanoparticles of bimetallic composition have also been developed that are endowed with outstanding antibacterial properties and enhanced activity when used in combination with other usual antimicrobial agents. The approaches of nanoparticle incorporation with antimicrobial agents make more approaches available to combat antimicrobial resistance challenges. Earlier research has established that copper nanoparticles, especially in the nanoform, have prospects when used as bacterial adjuvants, including their ability to alter resistance in *Staphylococcus aureus*. The use of nanoparticle technology to overload resistance poses a step towards decreasing the public health risk associated with AMR.

Ethical issue

Not applicable.

Financial funding

The authors received no funding for this study.

Conflicts of interest

The authors have declared that no conflict of interest exists.

References

1. Ladenheim D. Role of nurses in supporting antimicrobial stewardship. Nurs Stand. 2018;33(6):55–58. https://doi.org/10.7748/ns.2018.e11245
2. Li X, Mowlaboccus S, Jackson B, Cai C, Coombs GW. Antimicrobial Resistance Among Clinically Significant Bacteria in Wildlife: An Overlooked One Health Concern. International Journal of Antimicrobial Agents. 2024;64(3):107251. https://doi.org/10.1016/j.ijantimicag.2024.107251
3. Gandra S, Alvarez-Uria G, Turner P, Joshi J, Limmathurotsakul D, van Doorn HR. Antimicrobial resistance surveillance in low-and middle-income countries: progress and challenges in eight South Asian and Southeast Asian countries. Clinical Microbiology Reviews. 2020;33(3):10–128. https://doi.org/10.1128/CMR.00048-19
4. Aljeldah MM. Antimicrobial resistance and its spread is a global threat. Antibiotics. 2022;11(8):1082. https://doi.org/10.3390/antibiotics11081082
5. Fleece ME, Pholwat S, Mathers AJ, Houpt ER. Molecular diagnosis of antimicrobial resistance in Escherichia coli. Expert Review of Molecular Diagnostics. 2018;18(3):207–217. https://doi.org/10.1080/14737159.2018.1439381
6. Mubeen B, Ansar AN, Rasool R, Ullah I, Imam SS, Alshehri S, Ghoneim MM, Alzarea SI, Nadeem MS, Kazmi I. Nanotechnology as a novel approach in combating microbes providing an alternative to antibiotics. Antibiotics. 2021;10(12):1473. https://doi.org/10.3390/antibiotics10121473
7. Mercan DA, Niculescu AG, Grumezescu AM. Nanoparticles for antimicrobial agents delivery—an up-to-date review. International Journal of Molecular Sciences. 2022;23(22):13862. https://doi.org/10.3390/ijms232213862
8. Khair-Allah DH, Al-Charrakh AH, Al-Dujaili NH. Antimicrobial activity of silver nanoparticles biosynthesized by Streptomyces spp. Annals of Tropical Medicine and Public Health. 2019;22(9):S301.
9. Dos Santos Ramos MA, Da Silva PB, Spósito L, De Toledo LG, Bonifacio BV, Rodero CF, Dos Santos KC, Chorilli M, Bauab TM. Nanotechnology-based drug delivery systems for control of microbial biofilms: a review. International Journal of Nanomedicine. 2018;13:1179–1213. https://doi.org/10.2147/IJN.S146195
10. Mohanta YK, Chakrabartty I, Mishra AK, Chopra H, Mahanta S, Avula SK, Patowary K, Ahmed R, Mishra B, Mohanta TK, Saravanan M. Nanotechnology in combating biofilm: A smart and promising therapeutic strategy. Frontiers in Microbiology. 2023;13:1028086. https://doi.org/10.3389/fmicb.2022.1028086
11. Rai M, Deshmukh SD, Ingle AP, Gupta IR, Galdiero M, Galdiero S. Metal nanoparticles: The protective nanoshield against virus infection. Critical Reviews in Microbiology. 2016;42(1):46–56. https://doi.org/10.3109/1040841X.2013.879849
12. Singh P, Garg A, Pandit S, Mokkapati VR, Mijakovic I. Antimicrobial effects of biogenic nanoparticles. Nanomaterials. 2018;8(12):1009. https://doi.org/10.3390/nano8121009
13. Munir S, Asghar F, Younis F, Tabassum S, Shah A, Khan SB. Assessing the potential biological activities of TiO 2 and Cu, Ni and Cr doped TiO 2 nanoparticles. RSC Advances. 2022;12(7):3856–3861. https://doi:10.1039/d1ra07336b
14. Ameh T, Zarzosa K, Dickinson J, Braswell WE, Sayes CM. Nanoparticle surface stabilizing agents influence antibacterial action. Frontiers in Microbiology. 2023;14:1119550. https://doi.org/10.3389/fmicb.2023.1119550
15. Kumar P, Mahajan P, Kaur R, Gautam S. Nanotechnology and its challenges in the food sector: A review. Materials Today Chemistry. 2020;17:100332. https://doi.org/10.1016/j.mtchem.2020.100332
16. Bayat M, Zargar M, Chudinova E, Astarkhanova T, Pakina E. In vitro evaluation of antibacterial and antifungal activity of biogenic silver and copper nanoparticles: The first report of applying biogenic nanoparticles against Pilidium concavum and Pestalotia sp. fungi. Molecules. 2021;26(17):5402. https://doi.org/10.3390/molecules26175402
17. Sharmin S, Rahaman MM, Sarkar C, Atolani O, Islam MT, Adeyemi OS. Nanoparticles as antimicrobial and antiviral agents: A literature-based perspective study. Heliyon. 2021;7(3):e06456. https://doi.org/10.1016/j.heliyon.2021.e06456
18. Muthulakshmi K, Uma C. Antimicrobial activity of Bacillus subtilis silver nanoparticles. Frontiers in Bioscience-Elite. 2019;11(1):89–101. https://doi:10.2741/E848
19. Tomaszewska E, Ranoszek-Soliwoda K, Bednarczyk K, Lech A, Janicka M, Chodkowski M, Psarski M, Celichowski G, Krzyzowska M, Grobelny J. Anti-HSV Activity of Metallic Nanoparticles Functionalized with Sulfonates vs. Polyphenols. International Journal of Molecular Sciences. 2022;23(21):13104. https://doi.org/10.3390/ijms232113104
20. Luceri A, Francese R, Lembo D, Ferraris M, Balagna C. Silver nanoparticles: review of antiviral properties, mechanism of action and applications. Microorganisms. 2023;11(3):629. https://doi.org/10.3390/microorganisms11030629
21. Nisar P, Ali N, Rahman L, Ali M, Shinwari ZK. Antimicrobial activities of biologically synthesized metal nanoparticles: an insight into the mechanism of action. JBIC Journal of

Biological Inorganic Chemistry. 2019;24:929–941. https://doi.org/10.1007/s00775-019-01717-7
22. Franco D, Calabrese G, Guglielmino SP, Conoci S. Metal-based nanoparticles: Antibacterial mechanisms and biomedical application. Microorganisms. 2022;10(9):1778. https://doi.org/10.3390/microorganisms10091778
23. Girma A. Alternative mechanisms of action of metallic nanoparticles to mitigate the global spread of antibiotic-resistant bacteria. The Cell Surface. 2023;10:100112. https://doi.org/10.1016/j.tcsw.2023.100112
24. Wang L, Hu C, Shao L. The antimicrobial activity of nanoparticles: present situation and prospects for the future. International Journal of Nanomedicine. 2017;12:1227–1249. https://doi.org/10.2147/IJN.S121956
25. Adeyemi OS, Shittu EO, Akpor OB, Rotimi D, Batiha GE. Silver nanoparticles restrict microbial growth by promoting oxidative stress and DNA damage. EXCLI Journal. 2020;19:492. https://doi.org/10.17179/excli2020-1244
26. Mohanbaba S, Gurunathan S. Differential biological activities of silver nanoparticles against Gram-negative and Gram-positive bacteria: A novel approach for antimicrobial therapy. In Nanobiomaterials in Anti microbial Therapy. 2016;6:193–227. https://doi.org/10.1016/B978-0-323-42864-4.00006-3
27. Ozdal M, Gurkok S. Recent advances in nanoparticles as antibacterial agent. ADMET and DMPK. 2022;10(2):115–129. https://doi.org/10.5599/admet.1172
28. Rosli NA, Teow YH, Mahmoudi E. Current approaches for the exploration of antimicrobial activities of nanoparticles. Science and Technology of Advanced Materials. 2021;22(1):885–907. https://doi.org/10.1080/14686996.2021.1978801
29. Fatima F, Siddiqui S, Khan WA. Nanoparticles as novel emerging therapeutic antibacterial agents in the antibiotics resistant era. Biological Trace Element Research. 2021;199(7):2552–2564. https://doi.org/10.1007/s12011-020-02394-3
30. Alshamrani M. Broad-spectrum theranostics and biomedical application of functionalized nanomaterials. Polymers. 2022;14(6):1221. https://doi.org/10.3390/polym14061221
31. Pieszka M, Bederska-Łojewska D, Szczurek P, Pieszka M. The membrane interactions of nano-silica and its potential application in animal nutrition. Animals. 2019;9(12):1041. https://doi.org/10.3390/ani9121041
32. Sharifi S, Seyednejad H, Laurent S, Atyabi F, Saei AA, Mahmoudi M. Superparamagnetic iron oxide nanoparticles for in vivo molecular and cellular imaging. Contrast Media & Molecular Imaging. 2015;10(5):329–355. https://doi.org/10.1002/cmmi.1638
33. Jenjob R, Phakkeeree T, Crespy D. Core–shell particles for drug-delivery, bioimaging, sensing, and tissue engineering. Biomaterials Science. 2020;8(10):2756–2770. https://doi.org/10.1039/c9bm01872g
34. Lopes TS, Alves GG, Pereira MR, Granjeiro JM, Leite PE. Advances and potential application of gold nanoparticles in nanomedicine. Journal of Cellular Biochemistry. 2019;120(10):16370–16378. https://doi.org/10.1002/jcb.29044
35. Kim T, Hyeon T. Applications of inorganic nanoparticles as therapeutic agents. Nanotechnology. 2013;25(1):012001. https://doi.org/10.1088/0957-4484/25/1/012001
36. Leng F, Liu F, Yang Y, Wu Y, Tian W. Strategies on nanodiagnostics and nanotherapies of the three common cancers. Nanomaterials. 2018;8(4):202. https://doi.org/10.3390/nano8040202
37. Cabuzu D, Cirja A, Puiu R, Mihai Grumezescu A. Biomedical applications of gold nanoparticles. Current Topics in Medicinal Chemistry. 2015;15(16):1605–1613. https://doi.org/10.2174/1568026615666150414144750
38. Su S, Kang PM. Systemic review of biodegradable nanomaterials in nanomedicine. Nanomaterials. 2020;10(4):656. https://doi.org/10.3390/nano10040656
39. Lambuk L, Ahmad S, Abdul Razak SK, Mohd Idris RA, Mohamud R. Progress in Biomedical Applications Using Sustainable Nanoparticles. In: Sustainable Material for Biomedical Engineering Application 2023 pp. 207–238. Singapore: Springer Nature Singapore.
40. Rai M, Ingle AP, Birla S, Yadav A, Santos CA. Strategic role of selected noble metal nanoparticles in medicine. Critical Reviews in Microbiology. 2016;42(5):696–719. https://doi.org/10.3109/1040841X.2015.1018131
41. Hasanzadeh A, Alamdaran M, Ahmadi S, Nourizadeh H, Bagherzadeh MA, Jahromi MA, Simon P, Karimi M, Hamblin MR. Nanotechnology against COVID-19: Immunization, diagnostic and therapeutic studies. Journal of Controlled Release. 2021;336:354–374. https://doi.org/10.1016/j.jconrel.2021.06.036
42. Uskoković V. Why have nanotechnologies been underutilized in the global uprising against the coronavirus pandemic? Nanomedicine. 2020;15(17):1719–1734. https://doi.org/10.2217/nnm-2020-0163
43. Solanki R, Shankar A, Modi U, Patel S. New insights from nanotechnology in SARS-CoV-2 detection, treatment strategy, and prevention. Materials Today Chemistry. 2023;29:101478. https://doi.org/10.1016/j.mtchem.2023.101478
44. Azhar A, Hassan N, Singh M, Al-Hosaini K, Kamal MA. Synopsis of pharmotechnological approaches in diagnostic and management strategies for fighting against COVID-19. Current Pharmaceutical Design. 2021;27(39):4086–4099. https://doi.org/10.2174/1381612827666210715154004
45. Moradialvand M, Asri N, Jahdkaran M, Beladi M, Houri H. Advancements in Nanoparticle-Based Strategies for Enhanced Antibacterial Interventions. Cell Biochemistry and Biophysics. 2024;82:3071–3090. https://doi.org/10.1007/s12013-024-01428-0
46. Chintagunta AD, Nalluru S, SK NS. Nanotechnology: an emerging approach to combat COVID-19. Emergent Materials. 2021;4(1):119–130. https://doi.org/10.1007/s42247-021-00178-6
47. Rozman NA, Yenn TW, Ring LC, Nee TW, Hasanolbasori MA, Abdullah SZ. Potential antimicrobial applications of chitosan nanoparticles (ChNP). Journal of Microbiology and Biotechnology. 2019;29(7):1009–1013. https://doi.org/10.4014/jmb.1904.04065
48. Ribeiro AI, Dias AM, Zille A. Synergistic effects between metal nanoparticles and commercial antimicrobial agents: A review. ACS Applied Nano Materials. 2022;5(3):3030–3064. https://doi.org/10.1021/acsanm.1c03891
49. Rodrigues AS, Batista JG, Rodrigues MÁ, Thipe VC, Minarini LA, Lopes PS, Lugão AB. Advances in silver nanoparticles: a comprehensive review on their potential as antimicrobial agents and their mechanisms of action elucidated by proteomics. Frontiers in Microbiology. 2024;15:1440065. https://doi.org/10.3389/fmicb.2024.1440065
50. Pokrowiecki R, Zareba T, Mielczarek A, Opalińska A, Wojnarowicz J, Majkowski M, Lojkowski W, Tyski S. Evaluation of biocidal properties of silver nanoparticles against cariogenic bacteria. Medycyna doswiadczalna i mikrobiologia. 2013;65(3):197–206.
51. Kemp MM, Kumar A, Clement D, Ajayan P, Mousa S, Linhardt RJ. Hyaluronan-and heparin-reduced silver nanoparticles with antimicrobial properties. Nanomedicine. 2009;4(4):421–429. https://doi.org/10.2217/nnm.09.24
52. Thambirajoo M, Maarof M, Lokanathan Y, Katas H, Ghazalli NF, Tabata Y, Fauzi MB. Potential of nanoparticles integrated with antibacterial properties in preventing biofilm and antibiotic resistance. Antibiotics. 2021;10(11):1338. https://doi.org/10.3390/antibiotics10111338
53. Ul-Islam M, Shehzad A, Khan S, Khattak WA, Ullah MW, Park JK. Antimicrobial and biocompatible properties of nanomaterials. Journal of Nanoscience and Nanotechnology. 2014;14(1):780–791. https://doi.org/10.1166/JNN.2014.8761
54. Bharti S. Harnessing the potential of bimetallic nanoparticles: Exploring a novel approach to address antimicrobial resistance. World Journal of Microbiology and Biotechnology. 2024;40(3):89. https://doi.org/10.1007/s11274-024-03923-1
55. Mohanta YK, Chakrabartty I, Mishra AK, Chopra H, Mahanta S, Avula SK, Patowary K, Ahmed R, Mishra B, Mohanta TK, Saravanan M. Nanotechnology in Combating Biofilm: A Smart

and Promising Therapeutic Strategy. Frontiers in Microbiology. 2023;13:1028086.
56. Engin AB, Engin A. Nanoantibiotics: A novel rational approach to antibiotic resistant infections. Current Drug Metabolism. 2019;20(9):720–741.
57. Rudramurthy GR, Swamy MK, Sinniah UR, Ghasemzadeh A. Nanoparticles: alternatives against drug-resistant pathogenic microbes. Molecules. 2016;21(7):836.
58. Mahmoudi M, Serpooshan V. Silver-coated engineered magnetic nanoparticles are promising for the success in the fight against antibacterial resistance threat. ACS Nano. 2012;6(3):2656–2664.
59. Singh S, Hussain A, Shakeel F, Ahsan MJ, Alshehri S, Webster TJ, Lal UR. Recent insights on nanomedicine for augmented infection control. International Journal of Nanomedicine. 2019;14:2301–2325.
60. Wang L, Hu C, Shao L. The antimicrobial activity of nanoparticles: present situation and prospects for the future. International Journal of Nanomedicine. 2017;12:1227–1249.
61. Vikal A, Maurya R, Patel P, Kurmi BD. Nano Revolution: Harnessing Nanoparticles to Combat Antibiotic-resistant Bacterial Infections. Current Pharmaceutical Design.