

Fabricated *Fusarium* species-mediated nanoparticles against Gram-negative pathogen (Review)

RAZHAN BAKHTYAR¹, ROZHGAR TOFIQ¹, HAIDER HAMZAH¹ and KARZAN QURBANI^{2,3}

¹Department of Biology, College of Science, University of Sulaimani, Sulaymaniyah, Kurdistan 46001, Iraq;

²Department of Biology, College of Science, University of Raparin, Sulaymaniyah, Kurdistan 46012, Iraq;

³Department of Medical Microbiology, College of Health Science, Cihan University of Sulaimaniya, Sulaymaniyah, Kurdistan 46001, Iraq

Received August 2, 2024; Accepted October 11, 2024

DOI: 10.3892/wasj.2024.289

Abstract. Nanoparticles (NPs) exhibit a broad spectrum of highly efficient activities, including antimicrobial, anticancer, anticoagulant, anti-inflammatory and antibiofilm effects. With the rapid increase in antibiotic resistance, Gram-negative pathogens have become particularly resilient against antibiotics, posing a significant challenge to public health. Numerous studies have demonstrated that NPs possess substantial antimicrobial properties. The present review focuses specifically on the biosynthesis of nanoparticles using *Fusarium* and their notable antibacterial activity against Gram-negative pathogens. The antibacterial potential of metal-based nanoparticles is attributed to several mechanisms, including oxidative stress, protein dysfunction, and membrane and DNA damage, all of which contribute to microbial cell destruction. By summarizing the importance of NPs and various methods for their preparation, the present review highlights the promising role of *Fusarium*-derived NPs in combating antibiotic-resistant bacterial infections.

Contents

1. Introduction
2. *Fusaria* as a key element for the construction of nanoparticles
3. Characterization of nanoparticles
4. *Fusaria* nano-weapons against Gram-negative pathogens
5. Effect of *Fusaria* nanoparticles
6. Conclusion and future perspectives

Correspondence to: Dr Karzan Qurbani, Department of Biology, College of Science, University of Raparin, 12 Darwaza Street, Rania, Sulaymaniyah, Kurdistan 46012, Iraq
E-mail: karzan.qurbani@uor.edu.krd

Key words: *Fusarium* species, metals, nanoparticle, multidrug-resistant bacteria

1. Introduction

The study of nanotechnology is an intriguing field of current research that is primarily concerned with the production, alteration and application of minuscule particle structures. These structures usually vary in size from ~1 to 100 nanometers. Nanotechnology presents a novel method of technological progress that involves controlling materials on an extremely small scale, which is equivalent to one billionth of a meter (1-3). The field of nanotechnology is a captivating area of expertise that encompasses physics, chemistry, engineering and biology. Over the past few years, nanotechnologies have displayed encouraging outcomes in the domain of human health, especially in the cure of cancer (4).

Nanotechnology is dependent on the production and modulation of nanoparticles (NPs); this process involves marked changes in the properties of metals formed as by-products of combustion reactions. The peculiar properties of NPs render them ideally suited for the design of electrochemical sensors and biosensors (5). At this size, atoms and molecules function differently and have various unexpected and fascinating applications. It provides resources for the production of products, including medical applications (6). NPs have been used in numerous fields, including cosmetics, food medicine and genetics, and have led to a number of discoveries, including fluorescent biological markers, DNA structure testing, tissue engineering, tumor destruction, separation and purification of biological molecules, anticancer agents to tumor sites (7,8). NPs also have antimicrobial activity against pathogenic bacteria, such as multidrug-resistant pathogens (4,9,10).

NPs can be synthesized by using various methods, including physical and chemical approaches. The key physical methods employed to synthesize NPs are evaporation-condensation and laser ablation. Physical synthesis methods provide advantages, such as the absence of solvent contamination in the produced thin films and the uniform distribution of NPs. However, physical methods can be costly, and only a small quantity of powder is produced each time. On the other hand, chemical reduction by organic and inorganic reducing agents is the most common approach for synthesizing NPs using chemical methods; while chemical methods can be expensive, they have low yields and use toxic chemicals (11). Due to issues associated with physical and chemical methods, scientists have turned to biological methods

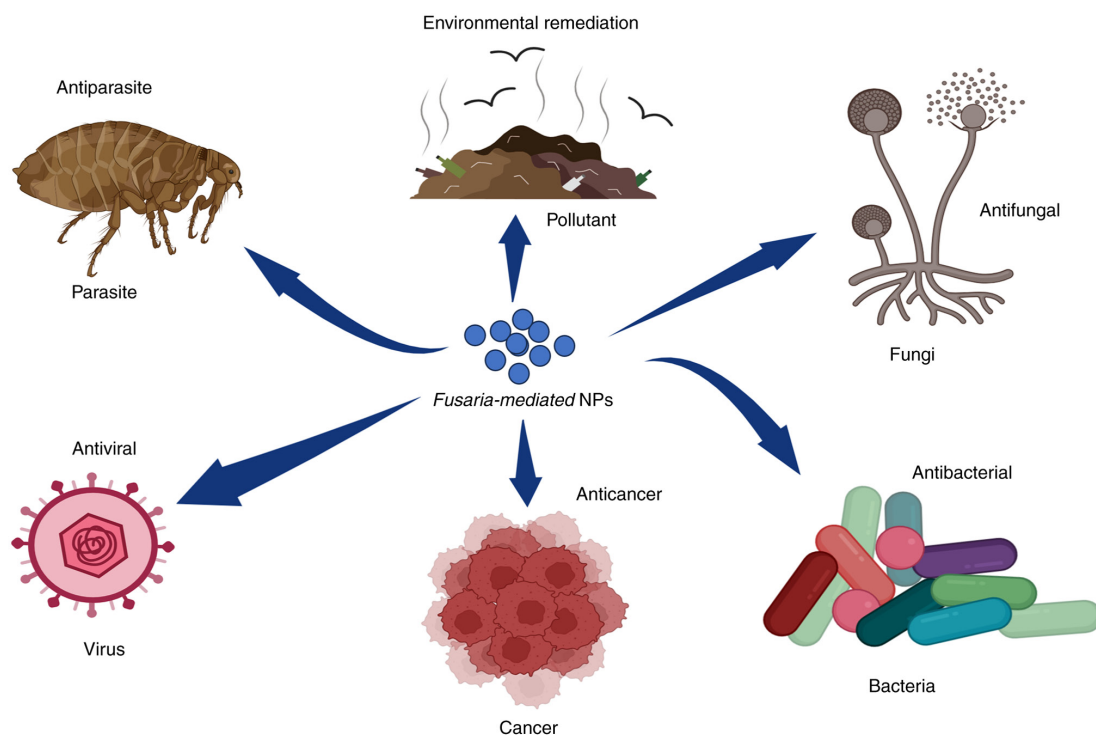


Figure 1. The applications of biogenic nanoparticles synthesized from diverse strains of *Fusaria*.

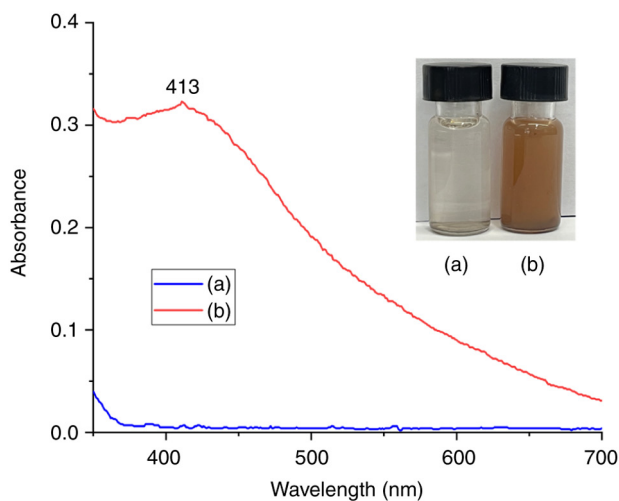


Figure 2. UV-visible absorption spectra of AgNPs are presented for (a) AgNO_3 solution as a control; and (b) biosynthesized AgNPs by *Fusarium solani* KQ-21. Inset: The filtrate changes color from white (a) to light brown (b) following the synthesis of AgNPs. AgNPs, silver nanoparticles.

of synthase; biological methods (also known as biosynthesis, green synthesis, biogenic synthesis and biofabricate) provide an environmentally benign, low toxic, cost-effective and efficient protocol to synthesize and fabricate NPs (9,10). These methods employ microorganisms, such as bacteria, fungi, viruses, yeast, actinomycetes, or their by-product and plant extract (12,13).

Fungi are an extraordinary group of microorganisms that are capable of producing a vast array of metabolites. This renders them an ideal candidate for the biogenic synthesis of nanoparticles. The reason behind this is that fungi secrete a substantial amount of extracellular proteins that assist in stabilizing the

negative charge of NPs (14,15). Fungal NPs can be effectively synthesized using *Fusarium* species due to their filamentous nature and easy extraction from plants and soil. This genus is well-studied and can grow on a simple medium at moderate temperatures, rendering it a popular choice for nanoparticle synthesis. The medical applications of NPs synthesized through the *Fusarium*-mediated method are illustrated in (Fig. 1) (16,17).

The present review discusses the synthesis of NPs using *Fusarium* species and their potential as antimicrobial agents against multidrug-resistant Gram-negative bacteria. In addition, the current methods for NP characterization are summarized and the mechanisms through which these NPs exert their antimicrobial activity are discussed.

2. *Fusaria* as a key element for the construction of nanoparticles

NPs synthesized from fungal sources are used as novel antibacterial and antifungal agents (18). *Fusarium* is a filamentous, well-studied genus that is widely distributed on plants and in soil. It is easy to isolate this bacterium from soil and it grows on simple media at normal temperatures, as it is not a fastidious microorganism (19,20). Of note, one method which can be used to synthesize NPs from the mycelia of *Fusarium* spp. fungus would involve growth in Erlenmeyer flasks filled with potato dextrose broth. The flasks would be kept at an ideal temperature of $25 \pm 2^\circ\text{C}$ for 72 h. Once the growth is complete, the mycelia would be collected by filtering them through Whatman filter paper to separate them from the medium and other components. The collected mycelia would then be purified and washed several times with distilled water (21,22).

Subsequently, a suspension would be made by blending the mycelia with distilled water and incubating it again at $25 \pm 2^\circ\text{C}$

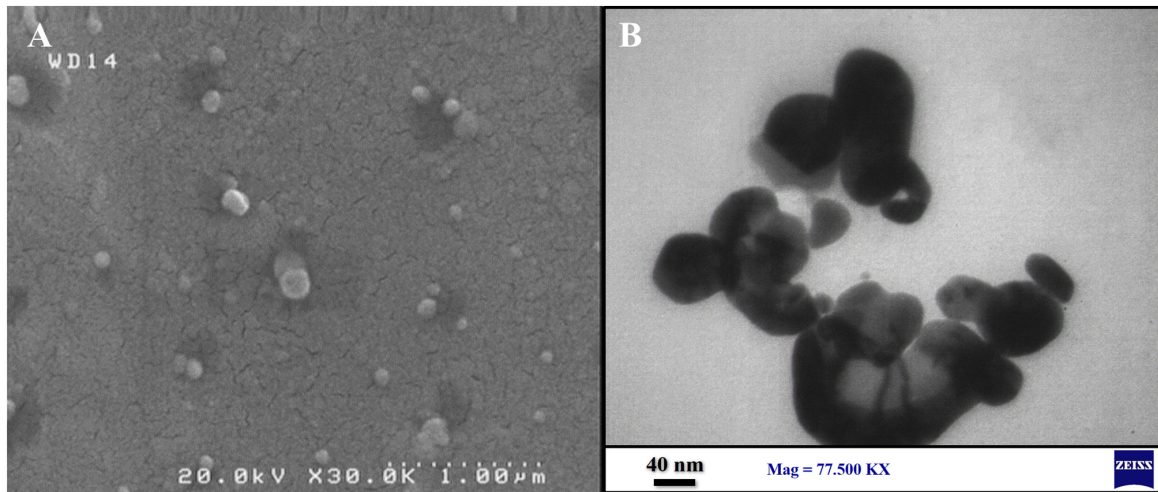


Figure 3. Micrographs of silver nanoparticles synthesized by *Fusarium solani*. (A) Scanning electron microscope image; (B) transmission electron microscopy image.

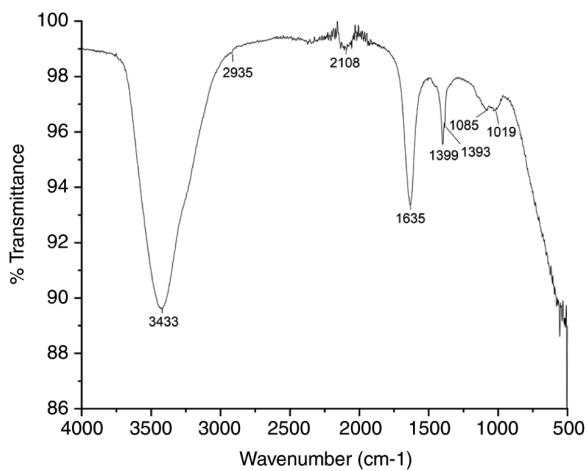


Figure 4. Fourier transform infrared spectroscopy spectrum of silver nanoparticles synthesized by *Fusarium solani*.

for 24 h. After the incubation period was complete, the cell filtrate would be separated by filtration and then treated with varying concentrations of metal salts. The mixture would be left to incubate at room temperature until a noticeable color change was observed (21,22). A list of the *Fusarium* species that are used in the production of NPs are presented in Table I.

3. Characterization of nanoparticles

There are numerous techniques used to detect the presence of NPs. The main techniques used for the characterization of NPs are presented in Table II. The primary technique for detecting the formation of silver NPs (AgNPs) or gold NPs is visual observation. For instance, when the fungal cell filtrate changes from yellowish to dark brown, it indicates the formation of silver NPs. Similarly, the solution color changes from yellow to dark red when gold NPs are formed (18,23,24). UV-visible absorption spectra of AgNPs are presented in Fig. 2 [only fungal extract and silver nitrate (AgNO_3) were used as controls in this case].

The scanning electron microscope (SEM) is a highly versatile instrument that allows for the examination and analysis of

microstructure, morphology and chemical composition. The naked eye can only distinguish objects subtending about $1/60^\circ$ visual angle, corresponds to a resolution of ~ 0.1 mm (when viewed from an optimal distance of 25 cm). Optical microscopy can enlarge the visual angle through its lens, although it has a resolution limit of $\sim 2,000 \text{ \AA}$ (25). The NPs are observed by transmission electron microscopy (TEM) characterization and are cleaned through plasma treatment using oxygen for <1 min. The sample is placed on the grid and allowed to dry at room temperature. The samples are then inspected by operating at 120 KV (16). An example of the characterization of NPs using both SEM and TEM is illustrated in Fig. 3.

The UV-visible spectrophotometer is a method used to detect NPs shown in Fig. 2. To analyze the NPs, their liquid samples were scanned in the range of 200-800 nm, with fungal filtrate and AgNO_3 used as controls. A scattering cell was used in this range, through which a laser beam (~ 40 mW at $\lambda=635$ nm) was passed. To observe the nanoparticles via the path of the laser beam, a dedicated no-microscope optical instrument (LM-20, NanoSight) was used, which has a charge-coupled device camera. The motion of the particles in the field of view ($\sim 100 \times 100 \mu\text{m}$) was recorded (at 30 fps), and the subsequent video and images were analyzed to determine the size distribution of the nanoparticles (26,27).

The characterization of NPs can also be carried out using Fourier transform infrared spectroscopy (FTIR). FTIR aims to analyze the biomolecules responsible for reducing silver ions and stabilizing NPs in the solution, as illustrated in Fig. 4. For the sample preparation, a colloidal NP solution would be mixed with potassium bromide (KBr) in a clean crucible until a fine powder is produced. The dried powder of NPs is then prepared and dried in an oven to remove any traces of moisture and analyzed in the ranges of $1,000\text{-}2,000 \text{ cm}^{-1}$ at a resolution of 4 cm^{-1} (16).

4. *Fusaria* nano-weapons against Gram-negative pathogens

Due to the discovery that some NPs display intriguing anti-bacterial properties, there has been an increased interest in the manufacture and research of NPs in recent years (8,28).

Table I. Synthesis of nanoparticles from different *Fusarium* species.

Species	Nanoparticles	Size	Shape	Application	(Refs.)
<i>F. acuminatum</i>	Silver	5-40	Spherical	Antibacterial	(49)
<i>F. culmorum</i>	Silver	5-25	Spherical	Antibacterial	(16)
<i>F. chlamydosporum</i>	Silver	6-26	Spherical	Antifungal	(50)
<i>F. equiseti</i>	Silver	85.74	Spherical	Antibacterial	(48)
<i>F. graminearum</i>	Silver	40-50	Spherical	Antibacterial	(51)
<i>F. keratoplasticum</i>	Silver	6-36	Spherical	Antimicrobial	(52)
<i>F. mangiferae</i>	Silver	25-52	Spherical	Protector for cotton fabric Antigrowth Ant biofilm Cytotoxicity	(26)
<i>F. oxysporum</i>	Silver	10-25	Spherical	Antibacterial	(53)
	Silver	20-50	Spherical	-	(54)
	Silver	5-13	Spherical	Antibacterial Cytotoxicity	(55)
	Silver	21.3-37.3	Spherical	Antimicrobial	(24)
	Silver	8-25	Spherical	Antibacterial Antifungal	(21)
<i>F. oxysporum</i>	Silver	5-15	-	-	(56)
	Silver	1-50	Spherical	Antibacterial	(57)
	Silver	30-36.1	Spherical	Antibacterial	(58)
	Platinum	5-30	Spherical	-	(59)
	Platinum	25	-	Antimicrobial, antioxidant photocatalytic	(60)
	Platinum	10-100	Hexagons pentagons circle squares rectangles	-	(61)
	Zinc	42	Spherical	-	(62)
	Gold	-	Spherical Hexagonal	Antibacterial	(63)
	Gold	20-50	Spherical, hexagonal	Nano toxicity	(64)
	Gold	-	-	-	(23)
<i>F. pseudonygamai</i>	Silver	5-20	Almost spherical	Antibacterial Anti-biofilm Antioxidant Cytotoxicity	(65)
	Gold	8-60	Spherical	Antibacterial Anti-biofilm Antioxidant Cytotoxicity	
<i>F. scirpi</i>	Silver	2-20	Quasispherical	Antibacterial	(66)
<i>F. solani</i>	Gold	40-45	-	Anticancer Biomedical applications	(67)
<i>F. solani</i>	Gold	20-50	Spherical	-	(68)
	Silver	5-35	Spherical	-	(69)
	Silver	130.6	Spherical	-	(48)

Table I. Continued.

Species	Nanoparticles	Size	Shape	Application	(Refs.)
	Silver	8.27	Spherical	Agriculture Seed germination Seedling growth promoters	(70)
	Silver	7.65- 18.89	Spherical	Antimicrobial	(71)
	Copper	9.97- 19.49	Spherical	Antimicrobial	
	Zink	8.55- 21.76	Spherical	Antimicrobial	
	Zink	117.79- 175.12	Irregular	Agriculture Seed germination Seedling growth promoters	(70)
<i>F. semitectum</i>	Silver	8-50	Spherical ellipsoidal	Antibacterial	(72)
	Silver	10-60	Spherical	-	(73)
	Silver	5-30	Spherical	Treatment of grain-born fungi	(74)
	Silver	130.6	Spherical	Antibacterial	(48)
	Silver	5-35	Spherical	-	(69)
	Silver and gold	10-35	Spherical	-	(75)
	Silver	18-80	Spherical	-	

Table II. The main techniques used for the characterization of nanoparticles.

Technique	Purpose	(Refs.)
TEM	It uses an electron beam to image a nanoparticle sample	(76)
SEM	Scans a sample with an electron beam to produce a magnified image for analysis	(25)
UV-Vis	Identifies the absorption of ultraviolet light or visible light by chemical compounds	(27)
XRD	Determines the crystallographic structure of a material	(77)
FTIR	Identifies chemical bonds in a molecule by producing an infrared absorption spectrum	(78)
EDX	Identifies the elemental composition of materials	(79)
Zeta potential	Determines the surface charge of nanoparticles in a solution	(80)
AFM	Assists for the visualization and measurement of nanostructures	(81)

TEM, transmission electron microscopy; SEM, scanning electron microscope; XRD, X-ray diffraction; FTIR, Fourier transform infrared spectroscopy; EDX, energy-dispersive X-ray spectroscopy; AFM, atomic force microscopy.

Antimicrobial resistance poses a major threat to humanity and one of the most severe health crises of the current era. Certain bacterial strains have become resistant to almost all antibiotics, thus rendering it crucial to identify new

antibacterial drugs to fight these microorganisms (29,30). In 2017, the World Health Organization (WHO) released a list of priority antibiotic-resistant illnesses, divided into three categories: Critical, high and medium. The majority of the bacteria on

Table III. Different *Fusaria* species against Gram-negative pathogens.

Species	Nanoparticle	Gram-negative pathogen	Size (nm)	Concentration ($\mu\text{g/ml}$)	Inhibition zone (mm)	(Refs.)
<i>F. acuminatum</i>	Silver	<i>Escherichia coli</i>	5-40	20	10 mm	(49)
		<i>Salmonella typhi</i>	5-40	20	17 mm	
<i>F. culmorum</i>	Silver	<i>Klebsiella pneumoniae</i>	5-25	20	16	(16)
		<i>Enterobacter aerogenes</i>	5-25	20	17	
<i>F. graminearum</i>	Silver	<i>Pseudomonas aeruginosa</i>	40-50	20-50	12-14.5	(51)
		<i>Salmonella sp.</i>	40-50	20-50	7.3-9.5	
		<i>E. coli</i>	40-50	20-50	7.5-8	
<i>F. oxysporum</i>	Silver	<i>E. coli</i>	10-25	100		(53)
<i>F. semitectum</i>	Silver	<i>K. pneumonia</i>	8-50	50	16	(24)
		<i>P. aeruginosa</i>	8-50	50	15	
		<i>K. pneumonia</i>	8-50	50	16	
		<i>P. aeruginosa</i>	8-50	50	15	
<i>F. solani</i>	Silver	<i>E. coli</i>	130	50	7	(48)
		<i>Pseudomonas sp.</i>	130	50	11	
		<i>Klebsiella sp.</i>	130	50	15	
<i>F. equiseti</i>	Silver	<i>E. coli</i>	85.74	50	7	(48)
		<i>Pseudomonas sp.</i>	85.74	50	11	
		<i>Klebsiella sp.</i>	85.74	50	7	

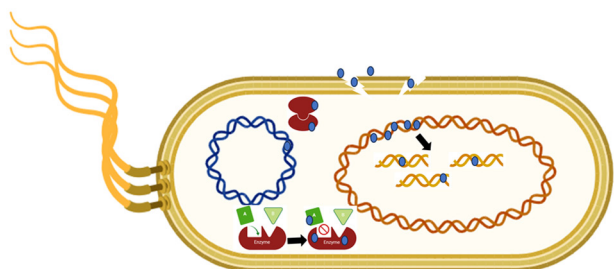


Figure 5. Schematic diagram of the mode of action of nanoparticles against Gram-negative bacteria treated with nanoparticles; nanoparticles accumulate on the cell wall and in the cytoplasm.

the list are Gram-negative pathogens, which are more resistant than Gram-positive bacteria due to their unique structure. This has resulted in a significant global disease and mortality burden (31-33).

Gram-negative bacteria have developed various mechanisms to resist a wide range of antibiotics, such as tetracycline, aminoglycosides and cotrimoxazole. The development of nano-sized particles with antibacterial properties is highly desirable for the creation of novel pharmaceuticals (28,34). Consequently, scholars are actively exploring alternatives to conventional antibiotics in response to rising antibiotic resistance. Their investigations encompass a diverse range of solutions, including plant extracts known for their antimicrobial properties, the development of new antibiotic derivatives with enhanced efficacy, and the use of NPs that can target bacteria more precisely (35,36). However, there has been insufficient research conducted on the toxicity of NPs, particularly regarding their mechanisms of action. This is

a matter of concern, particularly as the field of nanomedicine continues to grow. In recent decades, NPs have been widely used in various industries, including as food additives and for drug delivery purposes (37). With the persistent rise of bacterial resistance, there is a growing need for the development of new antibiotics. One of the most promising emerging antibiotic drugs is metal NPs, which have demonstrated potent antibacterial action in the majority of trials (7,38).

In general, smaller NPs tend to exhibit greater antibacterial activity. However, there are conflicting findings regarding the effectiveness of larger-sized NPs, and size alone is not always the most critical factor in determining their toxicity. Other factors that can affect the antibacterial properties of NPs include the formulation process, the surrounding environment, bacterial defense mechanisms and the physical properties of the NPs themselves (39).

NPs that are smaller in size have a higher surface area-to-volume ratio compared with larger NPs. This explains why they are more toxic than larger ones. A larger surface area of small NPs increases the proportion of contact with bacterial cells. NPs <10 nm in size have a higher proportion of contact with bacteria. The interaction between the NP and bacterial surface causes an electrical impact that enhances the reactivity of NPs (38,40,41). Various-sized silver NPs have different antimicrobial activities against different Gram-negative pathogenic bacteria, as illustrated in Table III.

5. Effect of *Fusaria* nanoparticles

There are various theories regarding the specific mechanisms of the antibacterial action of AgNPs. However, the precise

mechanisms involved continue to be under investigation. Some proposed possibilities include the generation of free metal ion toxicity from the surface of synthesized nano-metals and oxidative stress from the reactive oxygen species (ROS) on the surface of NPs (42-44).

NPs can cause a deletion activity on the cell wall of organisms, reduce oxidative stress, inactivate protein synthesis, penetrate the cell membrane and modify essential proteins, thereby increasing cell signal processes and hindering the formation of biofilm (17,45). The mode of action of NPs in damaging the bacterial membrane, bacterial protein and bacterial DNA remains a topic of research. The possible mechanism relies on the interaction of NPs with bacteria, excessive ROS generation and the precipitation of NPs on the bacterial exterior; which disrupts the cellular activities, resulting in membrane disruption (44,46,47).

NPs can cause intracellular alterations by inhibiting DNA replication ability. NPs which are <10 nm in size can diffuse into the nucleus, causing DNA damage, chromosomal abnormalities and cell cycle arrest, leading to genotoxicity in human cell lines (17,48).

NPs have different mechanisms against Gram-negative pathogens. Nano-silver can interact with the bacterial membrane, which is considered the main mechanism for its antimicrobial toxicity. NPs anchor themselves to the bacterial membrane, penetrate it and trigger the destruction of the cell membrane. This can lead to the release of ions into the intracellular medium, which further increases the toxicity level. NPs located on an *Escherichia coli* membrane can hold fast to the bacterial cell wall, enter it, and cause structural changes in the cell film such as the penetrability of the cell layer (17,48). Copper NPs and zinc oxide NPs can also cause damage to the bacterial membrane (17,43).

Gold NPs, for example, exploit their antibacterial powers against multidrug-resistant (Gram-negative) bacteria via two ways: Degrading membrane potential to lower ATP levels by reducing ATPase activity and preventing ribosomal subunit interaction with tRNA (43).

Metal reacts with sulfhydryl group proteins in cells, inactivating the proteins. Silver ions and AgNPs can interact with chemical groups like sulfide and chloride (43). NPs have different mechanisms of action against Gram-negative pathogens, as illustrated in Fig. 5).

NPs derived from *Fusarium* species provide a cost-effective and eco-friendly alternative to traditional physical and chemical synthesis methods, demonstrating prominent antimicrobial properties, particularly against Gram-negative bacteria. They can be easily produced using simple media, rendering them an appealing option for large-scale manufacturing. However, challenges include variations in size and stability, the potential for fungal contamination, and the necessity for comprehensive toxicity assessments to guarantee safe clinical application.

6. Conclusion and future perspectives

The present mini-view demonstrates the immense promise of biological synthesis for the production of NPs. In particular, the production of NPs using fungi that are produced from *Fusarium* species has a wide range of applications. These NPs

are noteworthy for their potent antibacterial action against a range of pathogenic bacteria, including those that show resistance to several drugs.

Further research on the mechanisms of action of NPs produced from *Fusarium* against bacteria resistant to several drugs is essential going forward. By conducting thorough research in this field, it is possible to deepen the understanding of the underlying mechanisms and develop more effective strategies to address the increasing problem of antibiotic resistance.

Acknowledgements

Not applicable.

Funding

No funding was received.

Availability of data and materials

Not applicable.

Authors' contributions

All authors (RB, RT, HH and KQ) contributed equally to the preparation and design of the manuscript. RB, RT and HH were involved in the conception and design of the study. All authors (RB, RT, HH and KQ) participated in articulating the content and in drafting and editing the manuscript. Specifically, RB, HH, and KQ focused on manuscript editing, while HH and KQ handled the technical aspects. RB, RT and KQ organized the data included in the review. All authors have read and approved the final manuscript.

Ethics approval and consent to participate

Not applicable.

Patient consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

References

1. Kader DA, Aziz DM, Mohammed SJ, Maarof NNN, Karim WO, Mhamad SA, Rashid RM, Ayoob MM, Kayani KF and Qurbani K: Green synthesis of ZnO/catechin nanocomposite: Comprehensive characterization, optical study, computational analysis, biological applications and molecular docking. *Mater Chem Phys* 319: 129408, 2024.
2. Qurbani KA, Amiri O, Othman GM, Fatah AA, Yunis NJ, Joshaghani M, Ahmed S and Abdulrahman N: Enhanced antibacterial efficacy through piezoelectric effect of CaTiO₃/TiO₂ nano-composite. *Inorg Chem Commun* 165: 112470, 2024.
3. Ibrahim WM, Amiri O, Ahmed SS, Muhammed HY, Mahmood PH, Qurbani KA, Abdulrahman NA, Younis KA and Omer PK: Enhanced asphaltene degradation using piezocatalytic technology: A novel approach for sustainable oilfield operations. *Results Eng* 21: 101938, 2024.

4. Bayda S, Adeel M, Tuccinardi T, Cordani M and Rizzolio F: The history of nanoscience and nanotechnology: From chemical-physical applications to nanomedicine. *Molecules* 25: 112, 2019.
5. Alagarasi A: Chapter-introduction to nanomaterials. Indian Institute of Technology Madras, pp1-24, 2013.
6. Singh P, Kim YJ, Zhang D and Yang DC: Biological synthesis of nanoparticles from plants and microorganisms. *Trends Biotechnol* 34: 588-599, 2016.
7. Salata OV: Applications of nanoparticles in biology and medicine. *J Nanobiotechnology* 2: 3, 2004.
8. Kyriacou SV, Brownlow WJ and Xu XHN: Using nanoparticle optics assay for direct observation of the function of antimicrobial agents in single live bacterial cells. *Biochemistry* 43: 140-147, 2004.
9. Hussein S, Sulaiman S, Ali S, Pirot R, Qurbani K, Hamzah H, Hassan O, Ismail T, Ahmed SK and Azizi Z: Synthesis of silver nanoparticles from aeromonas caviae for antibacterial activity and in vivo effects in rats. *Biol Trace Elem Res* 202: 2764-2775, 2024.
10. Qurbani K, Hussein S, Hamzah H, Sulaiman S, Pirot R, Motevaseli E and Azizi Z: Synthesis of silver nanoparticles by raoultella planticola and their potential antibacterial activity against multidrug-resistant isolates. *Iran J Biotechnol* 20: e3121, 2022.
11. Dhand C, Dwivedi N, Loh XJ, Ying AJ, Verma NK, Beuerman RW, Lakshminarayanan R and Ramakrishna S: Methods and strategies for the synthesis of diverse nanoparticles and their applications: A comprehensive overview. *RSC Adv* 5: 105003-105037, 2015.
12. Hulkoti NI and Taranath TC: Biosynthesis of nanoparticles using microbes-a review. *Colloids Surf B Biointerfaces* 121: 474-483, 2014.
13. Iravani S, Korbekandi H, Mirmohammadi SV and Zolfaghari B: Synthesis of silver nanoparticles: Chemical, physical and biological methods. *Res Pharm Sci* 9: 385-406, 2014.
14. Molnár Z, Bóday V, Szakacs G, Erdélyi B, Fogarassy Z, Sáfrán G, Varga T, Kónya Z, Tóth-Szeles E, Szűcs R and Lagzi I: Green synthesis of gold nanoparticles by thermophilic filamentous fungi. *Sci Rep* 8: 3943, 2018.
15. Guilger-Casagrande M and de Lima R: Synthesis of silver nanoparticles mediated by fungi: A review. *Front Bioeng Biotechnol* 7: 287, 2019.
16. Bawaskar M, Gaikwad S, Ingle A, Rathod D, Gade A, Duran N, Marcato PD and Rai M: A new report on mycosynthesis of silver nanoparticles by *Fusarium culmorum*. *Curr Nanosci* 6: 376-380, 2010.
17. Rai M, Bonde S, Golinska P, Trzcińska-Wencel J, Gade A, Abd-Elsalam KA, Shende S, Gaikwad S and Ingle AP: *Fusarium* as a novel fungus for the synthesis of nanoparticles: Mechanism and applications. *J Fungi (Basel)* 7: 139, 2021.
18. Birla S, Gaikwad SC, Gade AK and Rai MK: Rapid synthesis of silver nanoparticles from *Fusarium oxysporum* by optimizing physiocultural conditions. *ScientificWorldJournal* 2013: 796018, 2013.
19. Kalman B, Abraham D, Graph S, Perl-Treves R, Meller Harel Y and Degani O: Isolation and identification of *Fusarium* spp., the causal agents of onion (*Allium cepa*) basal rot in Northeastern Israel. *Biology (Basel)* 9: 69, 2020.
20. Qurbani K and Hamzah H: Intimate communication between *Comamonas aquatica* and *Fusarium solani* in remediation of heavy metal-polluted environments. *Arch Microbiol* 202: 1397-1406, 2020.
21. Joshi P, Bonde S, Gaikwad S, Gade A, Abd-Elsalam K and Rai M: Comparative studies on synthesis of silver nanoparticles by *Fusarium oxysporum* and *Macrophomina phaseolina* and its efficacy against bacteria and *Malassezia furfur*. *J Bionanosci* 7: 378-385, 2013.
22. Hussein SM, Salah TA and Anter HA: Biosynthesis of size controlled silver nanoparticles by *Fusarium oxysporum*, their antibacterial and antitumor activities. *Beni Suef Univ J Basic Appl Sci* 4: 225-231, 2015.
23. Mukherjee P, Senapati S, Mandal D, Ahmad A, Khan MI, Kumar R and Sastry M: Extracellular synthesis of gold nanoparticles by the fungus *Fusarium oxysporum*. *Chembiochem* 3: 461-463, 2002.
24. Ahmed AA, Hamzah H and Maarooof M: Analyzing formation of silver nanoparticles from the filamentous fungus *Fusarium oxysporum* and their antimicrobial activity. *Turk J Biol* 42: 54-62, 2018.
25. Zhou W, Apkarian R, Wang ZL and Joy D: Fundamentals of scanning electron microscopy (SEM). In: *Scanning Microscopy for Nanotechnology: Techniques and applications*. Zhou W and Wang ZL (eds). Springer, New York, NY, pp1-40, 2007.
26. Hamzah HM, Salah RF and Maroof MN: *Fusarium mangiferae* as new cell factories for producing silver nanoparticles. *J Microbiol Biotechnol* 28: 1654-1663, 2018.
27. Penner MH: Ultraviolet, visible, and fluorescence spectroscopy. In: Nielsen SS (ed) *Food Analysis*. Food Science Text Series. Springer, pp89-106, 2017.
28. Guzman M, Dille J and Godet S: Synthesis and antibacterial activity of silver nanoparticles against gram-positive and gram-negative bacteria. *Nanomedicine* 8: 37-45, 2012.
29. Ahmed SK, Hussein S, Qurbani K, Ibrahim RH, Fareeq A, Mahmood KA and Mohamed MG: Antimicrobial resistance: Impacts, challenges, and future prospects. *J Med Surg Public Health* 2: 100081, 2024.
30. Qurbani K, Ali S, Hussein S and Hamzah H: Antibiotic resistance in Kurdistan, Iraq: A growing concern. *New Microbes New Infect* 57: 101221, 2024.
31. Livermore DM: Current epidemiology and growing resistance of gram-negative pathogens. *Korean J Intern Med* 27: 128-142, 2012.
32. World Health Organization: Global diffusion of eHealth: making universal health coverage achievable: Report of the third global survey on eHealth. World Health Organization, 2017.
33. Breijyeh Z, Jubeh B and Karaman R: Resistance of gram-negative bacteria to current antibacterial agents and approaches to resolve it. *Molecules* 25: 1340, 2020.
34. Pfeifer Y, Cullik A and Witte W: Resistance to cephalosporins and carbapenems in Gram-negative bacterial pathogens. *Int J Med Microbiol* 300: 371-379, 2010.
35. Muhammed Aziz D, Hassan SA, Mamand DM and Qurbani K: New azo-azomethine derivatives: Synthesis, characterization, computational, solvatochromic UV-Vis absorption and antibacterial studies. *J Mol Struct* 1284: 135451, 2023.
36. Muhammed Aziz D, Hassan SA, Amin AAM, Abdullah MN, Qurbani K and Aziz SB: A synergistic investigation of azo-thiazole derivatives incorporating thiazole moieties: A comprehensive exploration of their synthesis, characterization, computational insights, solvatochromism, and multimodal biological activity assessment. *RSC Adv* 13: 34534-34555, 2023.
37. Carvalho PM, Felício MR, Santos NC, Gonçalves S and Domingues MM: Application of light scattering techniques to nanoparticle characterization and development. *Front Chem* 6: 237, 2018.
38. Slavin YN, Asnis J, Háfeli UO and Bach H: Metal nanoparticles: Understanding the mechanisms behind antibacterial activity. *J Nanobiotechnology* 15: 65, 2017.
39. Osonga FJ, Akgul A, Yazgan I, Akgul A, Eshun GB, Sakhaee L and Sadik OA: Size and shape-dependent antimicrobial activities of silver and gold nanoparticles: A model study as potential fungicides. *Molecules* 25: 2682, 2020.
40. Rai MK, Deshmukh S, Ingle A and Gade A: Silver nanoparticles: The powerful nanoweapon against multidrug-resistant bacteria. *J Appl Microbiol* 112: 841-852, 2012.
41. Salomoni R, Léo P, Montemor A, Rinaldi B and Rodrigues M: Antibacterial effect of silver nanoparticles in *Pseudomonas aeruginosa*. *Nanotechnol Sci Appl* 10: 115-121, 2017.
42. Gudikandula K and Charya Maringanti S: Synthesis of silver nanoparticles by chemical and biological methods and their antimicrobial properties. *J Exp Nanosci* 11: 714-721, 2016.
43. Nisar P, Ali N, Rahman L, Ali M and Shinwari ZK: Antimicrobial activities of biologically synthesized metal nanoparticles: An insight into the mechanism of action. *J Biol Inorg Chem* 24: 929-941, 2019.
44. Lamri M, Bhattacharya T, Boukid F, Chentir I, Dib AL, Das D, Djenane D and Gagaoua M: Nanotechnology as a processing and packaging tool to improve meat quality and safety. *Foods* 10: 2633, 2021.
45. Xu L, Wang YY, Huang J, Chen CY, Wang ZX and Xie H: Silver nanoparticles: Synthesis, medical applications and biosafety. *Theranostics* 10: 8996-9031, 2020.
46. Liao S, Zhang Y, Pan X, Zhu F, Jiang C, Liu Q, Cheng Z, Dai G, Wu G, Wang L and Chen L: Antibacterial activity and mechanism of silver nanoparticles against multidrug-resistant *Pseudomonas aeruginosa*. *Int J Nanomedicine* 14: 1469-1487, 2019.
47. Shahzad K and Manzoof F: Nanoformulations and their mode of action in insects: A review of biological interactions. *Drug Chem Toxicol* 44: 1-11, 2021.

48. Saha P, Rajkumar K and Abraham J: Comparative study on antimicrobial property of silver nanoparticles synthesized by *Fusarium equiseti* and *Fusarium solani*. *Bionanoscience* 6: 28-32, 2012.
49. Ingle A, Gade A, Pierrat S, Sonnichsen C and Rai M: Mycosynthesis of silver nanoparticles using the fungus *Fusarium acuminatum* and its activity against some human pathogenic bacteria. *Curr Nanosci* 4: 141-144, 2008.
50. Khalil NM, Abd El-Ghany MN and Rodríguez-Couto S: Antifungal and anti-mycotoxin efficacy of biogenic silver nanoparticles produced by *Fusarium chlamydosporum* and *Penicillium chrysogenum* at non-cytotoxic doses. *Chemosphere* 218: 477-486, 2019.
51. Shafiq SA, Al-Shammari RH and Majeed HZ: Study of biosynthesis silver nanoparticles by *Fusarium graminearum* and test their antimicrobial activity. *Int J Innov Appl Stud* 15: 43-50, 2016.
52. Mohamed AA, Fouda A, Elgamal MA, EL-Din Hassan S, Shaheen TI and Salem SS: Enhancing of cotton fabric antibacterial properties by silver nanoparticles synthesized by new Egyptian strain *Fusarium keratoplasticum* A1-3. *Egypt J Chem* 60: 63-71, 2017.
53. El Domany E, Essam T, Ahmed A and Farghli A: Biosynthesis, characterization, antibacterial and synergistic effect of silver nanoparticles using *Fusarium oxysporum*. *J Pure Appl Microbiol* 11: 1441-1446, 2017.
54. Marcato P, De Souza G, Alves O, Esposito E and Durán N: Antibacterial activity of silver nanoparticles synthesized by *Fusarium oxysporum* strain. In: *Proceedings of 2nd Mercosur Congr on Chem. Eng, 4th Mercosur Congr on Process Sys Eng*, pp1-5, 2005.
55. Vijayan S, Divya K, George TK and Jisha MS: Biogenic synthesis of silver nanoparticles using endophytic fungi *Fusarium oxysporum* isolated from *Withania somnifera* (L.), its antibacterial and cytotoxic activity. *J Bionanosci* 10: 369-376, 2016.
56. Ahmad A, Mukherjee P, Senapati S, Mandal D, Khan MI, Kumar R and Sastry M: Extracellular biosynthesis of silver nanoparticles using the fungus *Fusarium oxysporum*. *Colloids Surf B Biointerfaces* 28: 313-318, 2003.
57. Srivastava S, Bhargava A, Pathak N and Srivastava P: Production, characterization and antibacterial activity of silver nanoparticles produced by *Fusarium oxysporum* and monitoring of protein-ligand interaction through in-silico approaches. *Microb Pathog* 129: 136-145, 2019.
58. Kaabo HE, Saied E, Hassan SED, Mahdy HM and Sultan MH: *Penicillium oxalicum*-mediated the green synthesis of silica nanoparticles: characterization and environmental applications. *Biomass Conver Biorefin*, pp1-18, 2024.
59. Syed A and Ahmad A: Extracellular biosynthesis of platinum nanoparticles using the fungus *Fusarium oxysporum*. *Colloids Surf B Biointerfaces* 97: 27-31, 2012.
60. Gupta K and Chundawat TS: Bio-inspired synthesis of platinum nanoparticles from fungus *Fusarium oxysporum*: its characteristics, potential antimicrobial, antioxidant and photocatalytic activities. *Mater Res Express* 6: 1050d6, 2019.
61. Riddin TL, Gericke M and Whiteley CG: Analysis of the inter- and extracellular formation of platinum nanoparticles by *Fusarium oxysporum* f. sp. *lycopersici* using response surface methodology. *Nanotechnology* 17: 3482-3489, 2006.
62. Mirzadeh S, Darezereshki E, Bakhtiari F, Fazelipour MH and Hosseini MR: Characterization of zinc sulfide (ZnS) nanoparticles biosynthesized by *Fusarium oxysporum*. *Mater Sci Semicond Process* 16: 374-378, 2013.
63. Naimi-Shamel N, Pourali P and Dolatabadi S: Green synthesis of gold nanoparticles using *Fusarium oxysporum* and antibacterial activity of its tetracycline conjugant. *J Mycol Med* 29: 7-13, 2019.
64. Pourali P, Badiee SH, Manafi S, Noorani T, Rezaei A and Yahyaei B: Biosynthesis of gold nanoparticles by two bacterial and fungal strains, *Bacillus cereus* and *Fusarium oxysporum*, and assessment and comparison of their nanotoxicity in vitro by direct and indirect assays. *Electron J Biotechnol* 29: 86-93, 2017.
65. Soliman MKY, Abu-Elghait M, Salem SS and Azab MS: Multifunctional properties of silver and gold nanoparticles synthesis by *Fusarium pseudonygamai*. *Biomass Convers Biorefin*, pp1-18, 2022.
66. Rodríguez-Serrano C, Guzmán-Moreno J, Ángeles-Chávez C, Rodríguez-González V, Ortega-Sigala JJ, Ramírez-Santoyo RM and Vidales-Rodríguez LE: Biosynthesis of silver nanoparticles by *Fusarium scirpi* and its potential as antimicrobial agent against uropathogenic *Escherichia coli* biofilms. *PLoS One* 15: e0230275, 2020.
67. Clarence P, Luvankar B, Sales J, Khusro A, Agastian P, Tack JC, Al Khulaifi MM, Al-Shwaiman HA, Elgorban AM, Syed A and Kim HJ: Green synthesis and characterization of gold nanoparticles using endophytic fungi *Fusarium solani* and its in-vitro anticancer and biomedical applications. *Saudi J Biol Sci* 27: 706-712, 2020.
68. Gopinath K and Arumugam A: Extracellular mycosynthesis of gold nanoparticles using *Fusarium solani*. *Appl Nanosci* 4: 657-662, 2014.
69. Ingle A, Rai M, Gade A and Bawaskar M: *Fusarium solani*: A novel biological agent for the extracellular synthesis of silver nanoparticles. *J Nanoparticle Res* 11: 2079-2085, 2009.
70. Trzcńska-Wencel J, Wypij M, Terzyk AP, Rai M and Golińska P: Biofabrication of novel silver and zinc oxide nanoparticles from *Fusarium solani* IOR 825 and their potential application in agriculture as biocontrol agents of phytopathogens, and seed germination and seedling growth promoters. *Front Chem* 11: 1235437, 2023.
71. El Sayed MT and El-Sayed AS: Biocidal activity of metal nanoparticles synthesized by *Fusarium solani* against multi-drug-resistant bacteria and mycotoxigenic fungi. *J Microbiol Biotechnol* 30: 226-236, 2020.
72. Shelar GB and Chavan AM: *Fusarium semitectum* mediated extracellular synthesis of silver nanoparticles and their antibacterial activity. *Int J Biomed Adv Res* 5: 20-24, 2014.
73. Basavaraja S, Balaji SD, Lagashetty A, Rajasab AH and Venkataraman A: Extracellular biosynthesis of silver nanoparticles using the fungus *Fusarium semitectum*. *Mater Res Bull* 43: 1164-1170, 2008.
74. ABD El-Aziz ARM, Al-Othman MR, Mahmoud MA and Metwally HA: Biosynthesis of silver nanoparticles using *Fusarium solani* and its impact on grain borne fungi. *Dig J Nanomater Biostruct* 10: 655-662, 2015.
75. Dasaratrao Sawle B, Salimath B, Deshpande R, Dhondojirao Bedre M, Krishnamurthy Prabhakar B and Venkataraman A: Biosynthesis and stabilization of Au and Au-Ag alloy nanoparticles by fungus, *Fusarium semitectum*. *Sci Technol Adv Mater* 9: 035012, 2008.
76. Evans JE, Jungjohann KL, Browning ND and Arslan I: Controlled growth of nanoparticles from solution with in situ liquid transmission electron microscopy. *Nano Lett* 11: 2809-2813, 2011.
77. Bunaciu AA, Udriștiu EG and Aboul-Enein HY: X-ray diffraction: instrumentation and applications. *Crit Rev Anal Chem* 45: 289-299, 2015.
78. Ismail AA, van de Voort FR and Sedman J: Fourier transform infrared spectroscopy: Principles and applications. *Tech Instrum Anal Chem* 18: 93-139, 1997.
79. Khan MSI, Oh SW and Kim YJ: Power of scanning electron microscopy and energy dispersive X-ray analysis in rapid microbial detection and identification at the single cell level. *Sci Rep* 10: 2368, 2020.
80. Zhang Y, Yang M, Portney NG, Cui D, Budak G, Ozbay E, Ozkan M and Ozkan CS: Zeta potential: A surface electrical characteristic to probe the interaction of nanoparticles with normal and cancer human breast epithelial cells. *Biomed Microdevices* 10: 321-328, 2008.
81. Magonov SN and Reneker DH: Characterization of polymer surfaces with atomic force microscopy. *Annu Rev Mater Res* 27: 175-222, 1997.

