Heliyon 10 (2024) e37939

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Metal oxide nanoparticles as a promising method to reduce biotic stress in plant cell wall: A review

Yalew Yiblet [a,b,*], Miseganaw Sisay [a,b]

[a] Department of Biology, Mekdela Amba University, P.O. Box 32, Tuluawlia, Ethiopia
[b] Department of Biology, Debre Tabor University, P.O. Box 272, Debre Tabor, Ethiopia

ARTICLE INFO

Keywords:
Antimicrobial activity
Cell wall
Biotic stress
Protein
Gene expression
Nanoparticle

ABSTRACT

The application of metal-based nanoparticles in inhibiting plant pathogenic bacteria and fungi has gained significant attention in recent years. several nanoparticles, including silver (Ag), titanium dioxide (TiO_2), magnesium oxide (MgO), copper (Cu), and zinc oxide (ZnO), can generate reactive oxygen species (ROS) when exposed to light. The oxidative damage inflicted by ROS can disrupt the cellular structures and metabolic processes of pathogens, leading to their inactivation and inhibition. However, it is crucial to consider the potential environmental and health impacts of nanoparticle use. The safe and responsible use of nanoparticles and their potential risks should be thoroughly evaluated to ensure sustainable and effective plant disease management practices.

1. Introduction

Biotic stress in plants is characterized by the detrimental effects instigated by living organisms, including pathogens such as bacteria, fungi, and viruses, as well as pests. These stressors can negatively impact plant growth, development, and overall productivity [1]. Metal oxide nanoparticles (MNPs) have garnered considerable attention across various sectors, particularly in agriculture, due to their distinctive properties and potential applications [2].

Research indicates that plant resilience against biotic stress, which encompasses damage caused by pathogens, pests, and other biological factors, can be enhanced through the application of metal oxide nanoparticles (MNPs) [3]. The unique physical and chemical properties of these nanoparticles have the potential to improve plant health and productivity. However, despite the promising benefits, there remains a significant gap in understanding the interactions between MNPs and plant cell walls, as well as their overall efficacy in mitigating biotic stress [4].

Metal oxide nanoparticles, such as zinc oxide (ZnO), silver oxide (Ag_2O), titanium dioxide (TiO_2), Magnesium oxide (MgO) [5] and copper oxide (CuO), have been investigated for their ability to enhance plant defense mechanisms against biotic stress [6]. These NPs possess several properties that make them attractive for agricultural applications, including their small size, high surface area-to-volume ratio, and unique physicochemical characteristics [7]. Plant defense mechanisms can be activated through various pathways in response to exposure to metal oxide nanoparticles. For instance, these nanoparticles may enhance the activity of antioxidant enzymes such as catalase (CAT) and superoxide dismutase (SOD), as well as stimulate the synthesis of secondary metabolites [8]. Beyond fortifying the cell wall, these responses bolster the plant's defenses against pests and diseases, thereby contributing positively to the overall health of the plant [9].

* Corresponding author. Department of Biology, Mekdela Amba University, P.O. Box 32, Tuluawlia, Ethiopia.
E-mail address: yalewyiblet@gmail.com (Y. Yiblet).

https://doi.org/10.1016/j.heliyon.2024.e37939
Received 31 May 2024; Received in revised form 12 September 2024; Accepted 13 September 2024
Available online 20 September 2024
2405-8440/

Metal oxide nanoparticles (MNPs) possess the ability to penetrate the cell wall and enter plant cells, potentially inducing alterations in gene expression and triggering defense responses. Furthermore, these nanoparticles can generate reactive oxygen species (ROS) upon exposure to light, which may exert both direct and indirect effects on plant cells [10]. Additionally, metal oxide nanoparticles can modulate the defense signaling pathways within plants, thereby enhancing the production of defense-related compounds and stimulating the plant's resistance against biotic stressors [11].

According to the scholar [12] reported that zinc oxide nanoparticles have been demonstrated to inhibit the growth of various plant pathogens by disrupting their cellular membranes or interfering with their enzymatic functions. Similarly, titanium dioxide nanoparticles have exhibited antifungal activity against several pathogenic fungi affecting plants. The application of metal oxide nanoparticles offers multiple ways for the protection of plant cell walls. These nanoparticles can be utilized for structural reinforcement, antibacterial activity, induction of defense responses, reduction of stress, and enhancement of nutrient uptake. This review seeks to summarize the existing literature that may contribute to the advancement of sustainable farming practices designed to enhance crop resilience against biotic stresses.

2. Synthesis of metal oxide NPs

The synthesis of metal and metal oxide NPs can indeed be achieved through various methods, including chemical, physical, and biological synthesis [13]. Chemical synthesis involves chemical reactions and the use of various additives to control the nanoparticle properties. Physical synthesis methods utilize physical processes to break down larger materials into NPs. Biological synthesis methods make use of biological systems to produce NPs, offering eco-friendly and scalable approaches [14]. These different methods provide researchers with a range of options to tailor the synthesis process and achieve desired nanoparticle characteristics (Fig. 1).

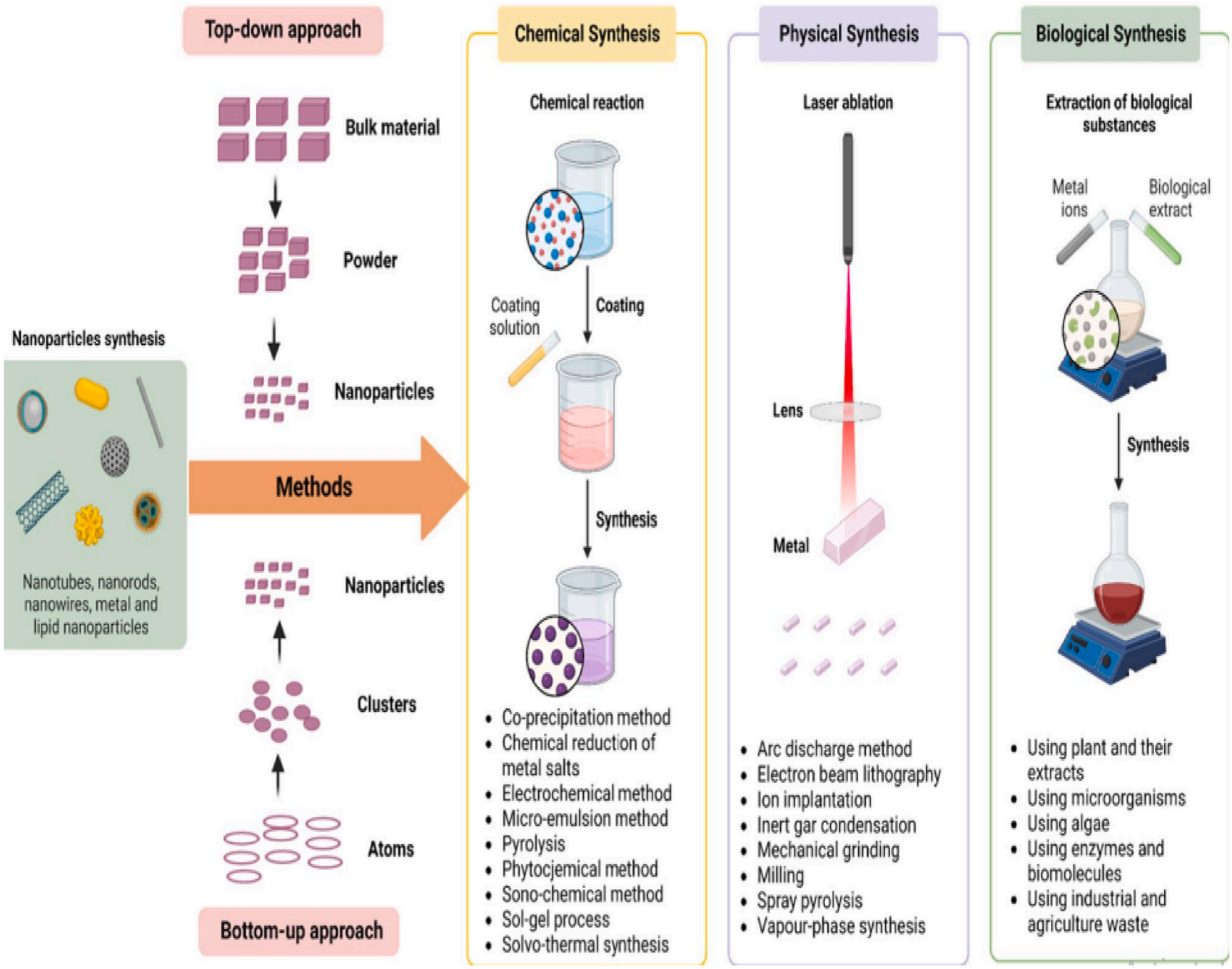

Fig. 1. Top-down and bottom-up approaches to the synthesis of metal oxide NPs demonstrating the chemical, physical, and biological synthesis processes [15].

3. Mechanisms of nanobiotechnology in enhancing biotic stress tolerance

Nanobiotechnology serves as a promising approach for enhancing tolerance to abiotic stresses in various organisms. This innovative field integrates nanotechnology with biological systems to develop strategies that bolster resilience against non-living environmental factors [16]. The structure and composition of the cell wall (CW) can be regulated during biotic interactions through meticulous and continuous post-synthetic remodeling, in addition to processes occurring at the biosynthetic stage [17]. Consequently, the CW should be regarded as a strategic domain wherein organisms either collaborate or engage in competition, employing advanced molecular strategies to facilitate specific physiological functions (Table 1) [18].

3.1. Cell wall reinforcement

Plant cell walls can be strengthened by using metal oxide-based nanoparticles (NPs), which increase the plant's resistance to diseases and pests [26]. They interact with cell wall components like cellulose, hemicellulose, and lignin, providing physical strength and making it harder for pathogens to invade [27]. Bidi et al. [28], Zhao et al. [29], and [26] reported that metal oxide (Ag, Au, Cu, Fe_2O_3, TiO_2, and ZnO) NPs can protect plants against biotic stress by physically interacting with the plant cell wall through adsorption or surface deposition, forming a protective layer that prevents direct contact between pathogens or pests and the plant cell wall. According to research by Refs. [29,30] metal oxide NPs can induce defense responses in plants by interacting with the cell wall, activating defense-related genes and synthesis of antimicrobial compounds, such as phytoalexins or proteins, which inhibit pathogen growth. Metal oxide NPs, such as silver, copper, zinc oxide, and titanium dioxide, are being explored for potential agricultural applications due to their nanoscale properties and antimicrobial properties [2]. Plants react to biotic stress by generating reactive oxygen species, activating signaling pathways through phytohormones, and releasing secondary metabolites that discourage herbivores or impede pathogen proliferation (Fig. 2) [31].

3.2. Reactive oxygen species (ROS) production

It has been demonstrated that metal oxide nanoparticles (NPs), especially those such as zinc oxide (ZnO) and titanium dioxide (TiO_2), can produce ROS when exposed to light [33]. ROS can have direct antimicrobial effects by causing oxidative damage to pathogenic microorganisms, impairing their growth or survival (Fig. 3) [34]. Additionally, ROS can act as signaling molecules, triggering defense responses in plants [35]. The production of ROS by metal oxide NPs can be localized to the cell wall, enhancing protection against biotic stress [36].

3.3. Binding to proteins

Through protein stabilization and the inhibition of enzymes involved in cell wall disintegration, metallic nanoparticles (NPs) provide protection for plant cell walls. The substance is good for plant health because it reduces denaturation of proteins, increases cell wall strength, and improves cell wall integrity [38]. Metallic NPs bind to enzymes or substrates, blocking their interaction and preventing cell wall degradation. They exhibit antioxidant properties, protecting proteins from oxidative damage and mitigating oxidative stress in the cell wall, thus preserving its structural integrity [39]. NPs binding to cell wall proteins enhances their stability and release, protecting the cell wall. An extra line of defense against environmental stressors including infections is offered by NPs' attachment to cell wall proteins [40]. Nanoparticles may influence cell wall biosynthesis metabolic processes, potentially upregulating genes related to lignin synthesis, thereby enhancing the mechanical strength of the cell wall [41].

3.4. Regulation of gene expression

When plants are exposed to metallic nanoparticles, they produce more defense-related genes, which fortifies their cell wall barriers

Table 1
The role of various nanoparticles in enhancing tolerance to biotic stresses across different plant species.

Plant species	Nanoparticles	Effect	References
lettuce (*Lactuca sativa*)	CuO	Promote the production of reactive oxygen species (ROS) within plant roots, subsequently triggering a series of modifications to cell wall polysaccharides.	[19]
Soybean (*Glycine max*)	Al_2O_3	The structure and properties of cell wall have been modified by aluminum oxide nanoparticles.	[20]
Watermelon(*Citrullus lanatus*)	MnO	When a pathogen attacks, manganese aids in the production of reactive oxygen species (ROS).	[21]
Rice (*Oryza sativa*)	SiO_2	Enhance the resistance of plants to rice fungal infections by activating salicylic acid signaling pathways.	[22]
(Canola)Brassica *napus*	ZnO	Alter the structure and composition of the cell walls to provide active protection against external threats.	[23]
Wheat (*Triticum aestivum*)	Se	Interfere with the genetic material of the fungi to inhibit their growth on the surfaces of plant cell walls.	[24]
Nem(*Azadirachta indica*)	TiO_2	Mutations or breaks in bacterial DNA caused by reactive oxygen species (ROS)-induced oxidative stress may impede bacterial proliferation and functionality.	[25]

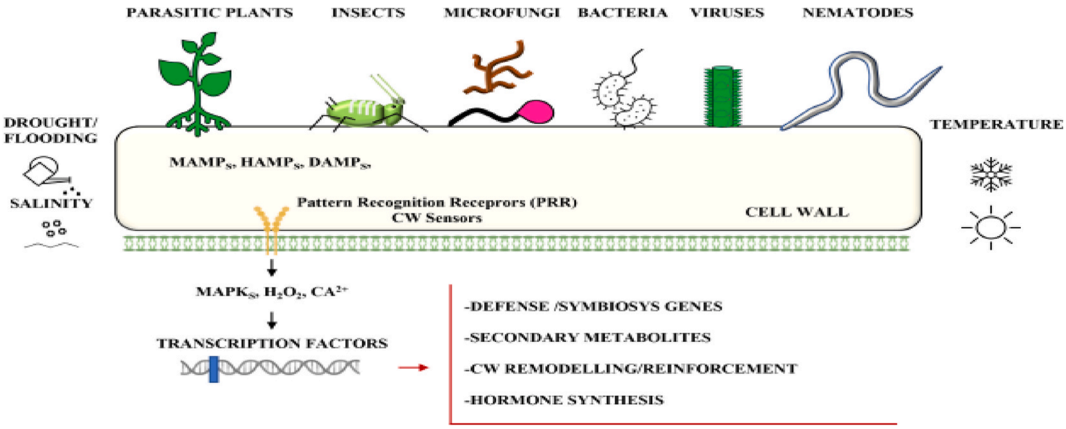

Fig. 2. An illustration of the primary sensory and response systems pertaining to the plant cell wall (CW) in the various biotic interactions. When biotic and abiotic stress are present together, CW may be crucial. Plant development, nutrition, and resistance to abiotic stressors can all be enhanced by symbiont-induced CW changes. Changes in abiotic stressor composition can impact the effectiveness of parasitism. The acronym stands for Microbe/Herbivore/Damage Associated Molecular Patterns [32].

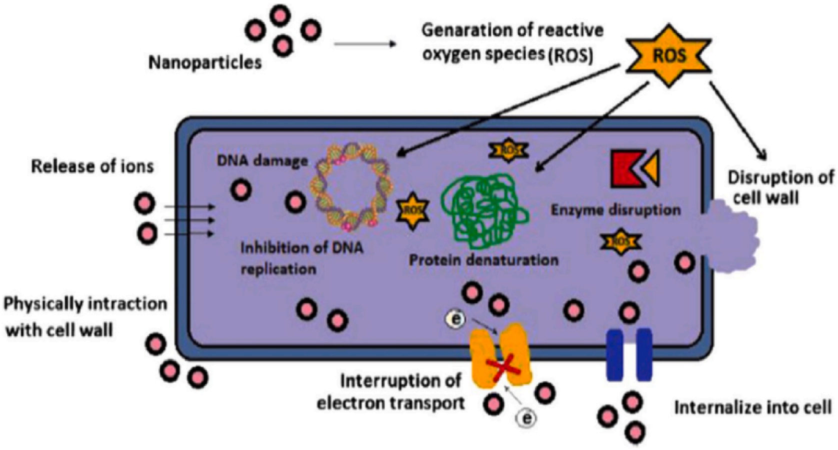

Fig. 3. The antibacterial properties of metal nanoparticles [37].

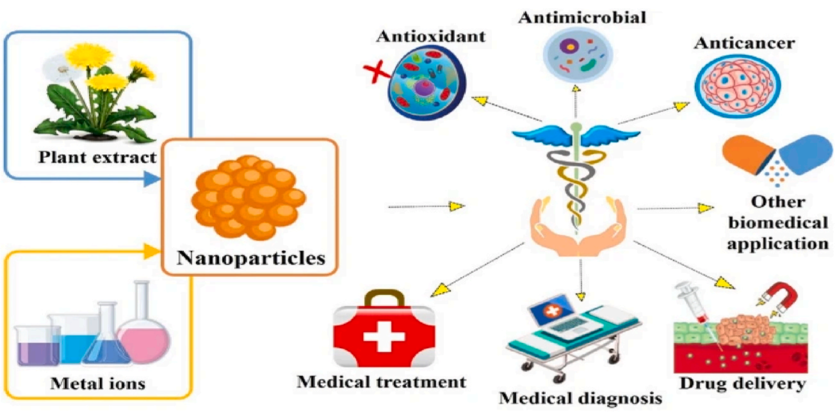

Fig. 4. The utilization of plant extracts for the synthesis of nanoparticles intended for medical applications [52].

and produces antimicrobial chemicals [42]. Research explores molecular mechanisms regulating gene expression by metallic NPs, potentially improving plant biotic stress resistance, cell wall reinforcement, and defense response activation [43].

Metal oxide NPs possess the capability to alter cellular signaling pathways through their interactions with proteins, nucleic acids, and cellular membranes [44]. These interactions can initiate a cascade of metabolic events that ultimately influence gene expression. For example, the size and surface charge of metal oxide NPs may significantly affect their cellular uptake, which in turn could impact their interactions with intracellular components [45]. Metal oxide NPs have the capacity to modify gene expression through epigenetic mechanisms, such as DNA methylation and histone acetylation, without altering the DNA sequence [46]. This process may lead to the activation or repression of genes that are crucial for cell division, growth, and responses to stress. The effects of metallic NPs on gene expression vary based on properties, concentration, exposure duration, and plant species, necessitating further research for optimal application [47].

3.5. *Delivery of bioactive compounds*

In order to improve the stability and targeted release of bioactive chemicals into plant cell walls, metallic nanoparticles (NPs) are being investigated as possible carriers [48]. These NPs transport antimicrobial agents or growth regulators, encapsulating them for stability [49]. Due to their unique properties, metallic nanoparticles particularly those composed of iron oxide (Fe_3O_4), silver (Ag), and gold (Au) serve as excellent carriers for bioactive agents such as proteins, DNA, and pharmaceuticals (Fig. 4) [50]. These properties include their diminutive size, high surface area-to-volume ratio, and ease of functionalization with various biomolecules [51].

3.6. *Antimicrobial activity*

Applying metallic nanoparticles (NPs) to plant cell walls efficiently inhibits the growth and multiplication of numerous plant pathogens, exhibiting antibacterial characteristics against microbes and shielding plants from diseases and infections. According to the researchers [53] zinc oxide (ZnO), manganese dioxide (MnO_2), and magnesium oxide (MgO) NPs possess antibacterial properties that enable them to combat plant diseases caused by bacteria, fungi, and viruses through various mechanisms. Similarly, Ag NPs have been shown by Ref. [54], to interact directly with pathogen cell walls, rupturing their integrity and causing cellular leakage, loss of function, and inhibition of pathogen growth. These NPs can disrupt cellular processes, inhibit pathogen growth, and modulate plant immune responses [55]. However, their effectiveness depends on factors like size, shape, surface charge, and composition.

4. Conclusion

Biotic stress in plants, caused by pathogens and pests, negatively impacts growth and productivity. Metal oxide NPs, with their unique properties, have shown promise in reducing biotic stress in plant cell walls. Metal oxide NPs, like TiO_2 and ZnO, generate reactive oxygen species (ROS) when exposed to light, causing oxidative damage to pathogenic microorganisms and triggering defense responses in plants. Metallic NPs have antimicrobial properties, effectively inhibiting plant pathogen growth and proliferation. They can interact with cell membranes, leading to cellular leakage and inhibition of pathogen growth. Metals like silver and copper can exhibit toxicity due to their antimicrobial properties. However, their effectiveness depends on factors like size, shape, surface charge, and composition.

Data availability

Throughout the review process, no new data were generated or analyzed; rather, individual studies were consolidated into a single entity to furnish readers with all necessary information.

CRediT authorship contribution statement

Yalew Yiblet: Methodology, Data curation, Conceptualization. **Miseganaw Sisay:** Writing – original draft, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors express their gratitude to all the scientists involved in developing a feasible worldwide healthcare system through the use of nanoparticles.

Abbreviations

NPs = Nanoparticles

MNPs = Metal oxide nanoparticles
ROS = Reactive oxygen species

References

[1] M. Moustafa-Farag, A. Almoneafy, A. Mahmoud, A. Elkelish, M.B. Arnao, L. Li, S. Ai, Melatonin and its protective role against biotic stress impacts on plants, Biomolecules 10 (1) (2019) 54.
[2] D. Maity, U. Gupta, S. Saha, Biosynthesized metal oxide nanoparticles for sustainable agriculture: next-generation nanotechnology for crop production, protection and management, Nanoscale 14 (38) (2022) 13950–13989.
[3] V.R. Rajpal, Y. Dhingra, L. Khungar, S. Mehta, T. Minkina, V.D. Rajput, A. Husen, Exploring Metal and metal-oxide nanoparticles for nanosensing and biotic stress management in plant systems, Current Research in Biotechnology (2024) 100219.
[4] M. Inam, I. Attique, M. Zahra, A.K. Khan, M. Hahim, C. Hano, S. Anjum, Metal oxide nanoparticles and plant secondary metabolism: unraveling the game-changer nano-elicitors, Plant Cell Tissue Organ Cult. 155 (2) (2023) 327–344.
[5] L. Xinghui, R. Periakaruppan, R. Mohanraj, S. Dhanasekaran, Nanometal Oxides in Horticulture and Agronomy, Elsevier, 2023.
[6] P. Dikshit, J. Kumar, A. Das, S. Sadhu, S. Sharma, S. Singh, P. Gupta, B. Kim, Green synthesis of metallic nanoparticles: applications and limitations, Catalysts 11 (2021) 902, 2021, s Note: MDPI stays neutral with regard to jurisdictional claims in published.
[7] M. Sajid, J. Płotka-Wasylka, Nanoparticles: synthesis, characteristics, and applications in analytical and other sciences, Microchem. J. 154 (2020) 104623.
[8] A.E. García-Ovando, J.E.R. Piña, E.U.E. Naranjo, J.A.C. Chávez, K. Esquivel, Biosynthesized nanoparticles and implications by their use in crops: effects over physiology, action mechanisms, plant stress responses and toxicity, Plant Stress 6 (2022) 100109.
[9] R.S. Riseh, F. Fathi, A. Lagzian, M. Vatankhah, J.F. Kennedy, Modifying lignin: a promising strategy for plant disease control, Int. J. Biol. Macromol. 271 (2024) 132696.
[10] S. Khan, N. Akhtar, S.U. Rehman, M. Jamil, Iron oxide nanoparticles: plant response, interaction, phytotoxicity and defense mechanisms, in: Nanomaterials and Nanocomposites Exposures to Plants: Response, Interaction, Phytotoxicity and Defense Mechanisms, Springer, 2023, pp. 227–245.
[11] M. Jabran, M.A. Ali, S. Muzammil, A. Zahoor, F. Ali, S. Hussain, G. Muhae-Ud-Din, M. Ijaz, L. Gao, Exploring the potential of nanomaterials (NMs) as diagnostic tools and disease resistance for crop pathogens, Chemical and Biological Technologies in Agriculture 11 (1) (2024) 75.
[12] C.R. Mendes, G. Dilarri, C.F. Forsan, V.d.M.R. Sapata, P.R.M. Lopes, P.B. de Moraes, R.N. Montagnolli, H. Ferreira, E.D. Bidoia, Antibacterial action and target mechanisms of zinc oxide nanoparticles against bacterial pathogens, Sci. Rep. 12 (1) (2022) 2658.
[13] S. Stankic, S. Suman, F. Haque, J. Vidic, Pure and multi metal oxide nanoparticles: synthesis, antibacterial and cytotoxic properties, J. Nanobiotechnol. 14 (2016) 1–20.
[14] N.M. Ishak, S. Kamarudin, S. Timmiati, Green synthesis of metal and metal oxide nanoparticles via plant extracts: an overview, Mater. Res. Express 6 (11) (2019) 112004.
[15] A. Nawaz, H.u. Rehman, M. Usman, A. Wakeel, M.S. Shahid, S. Alam, M. Sanaullah, M. Atiq, M. Farooq, Nanobiotechnology in crop stress management: an overview of novel applications, Discover nano 18 (1) (2023) 74.
[16] S.G. Thabet, A.M. Alqudah, Unraveling the role of nanoparticles in improving plant resilience under environmental stress condition, Plant Soil (2024) 1–18.
[17] L.A. Baez, T. Tichá, T. Hamann, Cell wall integrity regulation across plant species, Plant Mol. Biol. 109 (4) (2022) 483–504.
[18] R. Lorrai, S. Ferrari, Host cell wall damage during pathogen infection: mechanisms of perception and role in plant-pathogen interactions, Plants 10 (2) (2021) 399.
[19] X. Guo, J. Luo, R. Zhang, H. Gao, L. Peng, Y. Liang, T. Li, Root cell wall remodeling mediates copper oxide nanoparticles phytotoxicity on lettuce (Lactuca sativa L.), Environ. Exp. Bot. 200 (2022) 104906.
[20] G.H.G. de Almeida, R. de Cássia Siqueira-Soares, T.R. Mota, D.M. de Oliveira, J. Abrahão, M. de Paiva Foletto-Felipe, W.D. Dos Santos, O. Ferrarese-Filho, R. Marchiosi, Aluminum oxide nanoparticles affect the cell wall structure and lignin composition slightly altering the soybean growth, Plant physiology and biochemistry 159 (2021) 335–346.
[21] W. Elmer, R. De La Torre-Roche, L. Pagano, S. Majumdar, N. Zuverza-Mena, C. Dimkpa, J. Gardea-Torresdey, J.C. White, Effect of metalloid and metal oxide nanoparticles on Fusarium wilt of watermelon, Plant Dis. 102 (7) (2018) 1394–1401.
[22] J. Du, B. Liu, T. Zhao, X. Xu, H. Lin, Y. Ji, Y. Li, Z. Li, C. Lu, P. Li, Silica nanoparticles protect rice against biotic and abiotic stresses, J. Nanobiotechnol. 20 (1) (2022) 197.
[23] Á. Molnár, A. Rónavári, P. Bélteky, R. Szőllősi, E. Valyon, D. Oláh, Z. Rázga, A. Ördög, Z. Kónya, Z. Kolbert, ZnO nanoparticles induce cell wall remodeling and modify ROS/RNS signalling in roots of Brassica seedlings, Ecotoxicol. Environ. Saf. 206 (2020) 111158.
[24] M. Shahbaz, A. Akram, A. Mehak, E.u. Haq, N. Fatima, G. Wareen, B.N. Fitriatin, R. Sayyed, N. Ilyas, M.K. Sabullah, Evaluation of selenium nanoparticles in inducing disease resistance against spot blotch disease and promoting growth in wheat under biotic stress, Plants 12 (4) (2023) 761.
[25] C.L. de Dicastillo, M.G. Correa, F.B. Martínez, C. Streitt, M.J. Galotto, Antimicrobial effect of titanium dioxide nanoparticles, Antimicrob. Resist.-A One Health Perspect. 1 (2020) 488–494.
[26] H.K. Chandrashekar, G. Singh, A. Kaniyassery, S.A. Thorat, R. Nayak, T.S. Murali, A. Muthusamy, Nanoparticle-mediated amelioration of drought stress in plants: a systematic review, 3 Biotech 13 (10) (2023) 336.
[27] H. Jia, P. Ma, L. Huang, X. Wang, C. Chen, C. Liu, T. Wei, J. Yang, J. Guo, J. Li, Hydrogen sulphide regulates the growth of tomato root cells by affecting cell wall biosynthesis under CuO NPs stress, Plant Biol. 24 (4) (2022) 627–635.
[28] H. Bidi, H. Fallah, Y. Niknejad, D. Barari Tari, Iron oxide nanoparticles alleviate arsenic phytotoxicity in rice by improving iron uptake, oxidative stress tolerance and diminishing arsenic accumulation, Plant Physiol. Biochem. 163 (2021) 348–357.
[29] L. Zhao, J.R. Peralta-Videa, A. Varela-Ramirez, H. Castillo-Michel, C. Li, J. Zhang, R.J. Aguilera, A.A. Keller, J.L. Gardea-Torresdey, Effect of surface coating and organic matter on the uptake of CeO2 NPs by corn plants grown in soil: Insight into the uptake mechanism, J. Hazard Mater. 225–226 (2012) 131–138.
[30] S.M. Kamel, S.F. Elgobashy, R.I. Omara, A.S. Derbalah, M. Abdelfatah, A. El-Shaer, A.A. Al-Askar, A. Abdelkhalek, K.A. Abd-Elsalam, T. Essa, M. Kamran, M. M. Elsharkawy, Antifungal activity of copper oxide nanoparticles against root rot disease in cucumber, J Fungi (Basel) 8 (9) (2022).
[31] S. Tyagi, A. Shah, K. Karthik, M. Rathinam, V. Rai, N. Chaudhary, R. Sreevathsa, Reactive oxygen species in plants: an invincible fulcrum for biotic stress mitigation, Appl. Microbiol. Biotechnol. 106 (18) (2022) 5945–5955.
[32] V. Lionetti, J.-P. Métraux, Plant Cell Wall in Pathogenesis, Parasitism and Symbiosis, Frontiers Media SA, 2014, p. 612.
[33] A. Juárez-Maldonado, H. Ortega-Ortíz, A.B. Morales-Díaz, S. González-Morales, Á. Morelos-Moreno, M. Cabrera-De la Fuente, A. Sandoval-Rangel, G. Cadenas-Pliego, A. Benavides-Mendoza, Nanoparticles and nanomaterials as plant biostimulants, Int. J. Mol. Sci. 20 (1) (2019).
[34] D. Susanti, M.S. Haris, M. Taher, J. Khotib, Natural products-based metallic nanoparticles as antimicrobial agents, Front. Pharmacol. 13 (2022) 895616.
[35] G. Chichiriccò, A. Poma, Penetration and toxicity of nanomaterials in higher plants, Nanomaterials 5 (2) (2015) 851–873.
[36] L.F. Leopold, C. Coman, D. Clapa, I. Oprea, A. Toma, D. Iancu Ș, L. Barbu-Tudoran, M. Suciu, A. Ciorîță, A.I. Cadiș, L.E. Mureșan, I.M. Perhaița, L. Copolovici, D. M. Copolovici, F. Copaciu, N. Leopold, D.C. Vodnar, V. Coman, The effect of 100-200 nm ZnO and TiO(2) nanoparticles on the in vitro-grown soybean plants, Colloids Surf. B Biointerfaces 216 (2022) 112536.
[37] J. Singh, T. Dutta, K.-H. Kim, M. Rawat, P. Samddar, P. Kumar, 'Green'synthesis of metals and their oxide nanoparticles: applications for environmental remediation, J. Nanobiotechnol. 16 (2018) 1–24.

[38] A. Paul, A. Roychoudhury, Go green to protect plants: repurposing the antimicrobial activity of biosynthesized silver nanoparticles to combat phytopathogens, Nanotechnology for Environmental Engineering 6 (1) (2021) 10.
[39] R.K. Das, V.L. Pachapur, L. Lonappan, M. Naghdi, R. Pulicharla, S. Maiti, M. Cledon, L.M.A. Dalila, S.J. Sarma, S.K. Brar, Biological synthesis of metallic nanoparticles: plants, animals and microbial aspects, Nanotechnology for Environmental Engineering 2 (2017) 1–21.
[40] Y.N. Slavin, H. Bach, Mechanisms of antifungal properties of metal nanoparticles, Nanomaterials 12 (24) (2022) 4470.
[41] N. Munir, W. Gulzar, Z. Abideen, J.T. Hancock, A. El-Keblawy, E. Radicetti, Nanotechnology improves disease resistance in plants for food security: applications and challenges, Biocatal. Agric. Biotechnol. 51 (2023) 102781.
[42] Z.M. Almutairi, Plant Molecular Defense Mechanisms Promoted by Nanoparticles against Environmental Stresses, 2019.
[43] M. Mostafa, H. Almoammar, K.A. Abd-Elsalam, Nanoantimicrobials mechanism of action, Nanobiotechnology Applications in Plant Protection (2018) 281–322.
[44] M.P. Nikolova, M.S. Chavali, Metal oxide nanoparticles as biomedical materials, Biomimetics 5 (2) (2020) 27.
[45] R. Augustine, A.P. Mathew, A. Sosnik, Metal oxide nanoparticles as versatile therapeutic agents modulating cell signaling pathways: linking nanotechnology with molecular medicine, Appl. Mater. Today 7 (2017) 91–103.
[46] M. Wang, X. Lai, L. Shao, L. Li, Evaluation of immunoresponses and cytotoxicity from skin exposure to metallic nanoparticles, Int. J. Nanomed. (2018) 4445–4459.
[47] S.M. Joshi, S. De Britto, S. Jogaiah, Myco-engineered selenium nanoparticles elicit resistance against tomato late blight disease by regulating differential expression of cellular, biochemical and defense responsive genes, J. Biotechnol. 325 (2021) 196–206.
[48] M. Martínez-Ballesta, Á. Gil-Izquierdo, C. García-Viguera, R. Domínguez-Perles, Nanoparticles and controlled delivery for bioactive compounds: outlining challenges for new "smart-foods" for health, Foods 7 (5) (2018) 72.
[49] G. Guleria, S. Thakur, M. Shandilya, S. Sharma, S. Thakur, S. Kalia, Nanotechnology for sustainable agro-food systems: the need and role of nanoparticles in protecting plants and improving crop productivity, Plant Physiol. Biochem. 194 (2023) 533–549.
[50] N. Zafar, A. Madni, A. Khalid, T. Khan, R. Kousar, S.S. Naz, F. Wahid, Pharmaceutical and biomedical applications of green synthesized metal and metal oxide nanoparticles, Curr. Pharmaceut. Des. 26 (45) (2020) 5844–5865.
[51] F. Ahmad, M.M. Salem-Bekhit, F. Khan, S. Alshehri, A. Khan, M.M. Ghoneim, H.-F. Wu, E.I. Taha, I. Elbagory, Unique properties of surface-functionalized nanoparticles for bio-application: functionalization mechanisms and importance in application, Nanomaterials 12 (8) (2022) 1333.
[52] N.T.T. Nguyen, L.M. Nguyen, T.T.T. Nguyen, T.T. Nguyen, D.T.C. Nguyen, T.V. Tran, Formation, antimicrobial activity, and biomedical performance of plant-based nanoparticles: a review, Environ. Chem. Lett. 20 (4) (2022) 2531–2571.
[53] S.O. Ogunyemi, M. Zhang, Y. Abdallah, T. Ahmed, W. Qiu, M.A. Ali, C. Yan, Y. Yang, J. Chen, B. Li, The bio-synthesis of three metal oxide nanoparticles (ZnO, MnO2, and MgO) and their antibacterial activity against the bacterial leaf blight pathogen, Front. Microbiol. 11 (2020) 588326.
[54] L. Pradhan, P. Sah, M. Nayak, A. Upadhyay, P. Pragya, S. Tripathi, G. Singh, B. Mounika, P. Paik, S. Mukherjee, Biosynthesized silver nanoparticles prevent bacterial infection in chicken egg model and mitigate biofilm formation on medical catheters, JBIC Journal of Biological Inorganic Chemistry (2024) 1–21.
[55] I.H. Shah, M. Ashraf, A.R. Khan, M.A. Manzoor, K. Hayat, S. Arif, I.A. Sabir, M. Abdullah, Q. Niu, Y. Zhang, Controllable synthesis and stabilization of Tamarix aphylla-mediated copper oxide nanoparticles for the management of Fusarium wilt on musk melon, 3 Biotech 12 (6) (2022) 128.