Deep Science Publishing
https://doi.org/10.70593/978-93-49307-12-4_9

Chapter 9

Biosynthesized Nanoparticles from Endophytic bacteria: A Game-changer for Stress-resilient Crops

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Abstract: Environmental changes have significantly impacted global crop production. Both abiotic stress (such as drought, heat, salinity, heavy metals, cold and UV radiation) and biotic stress (including bacteria, fungi, parasites, weeds and insects) pose serious threats to crop growth and development. Endophytic bacteria play a crucial role in plant health by promoting growth and providing resistance against biotic and abiotic stresses. Recent advancements in nanotechnology have highlighted the potential of bacteria-derived nanoparticles (NPs) as a sustainable alternative for improving crop resilience by enhancing yield and stress tolerance. Bacteria-based nanoparticles [silver (AgNPs), zinc oxide (ZnO NPs), copper (CuNPs) and silicon (SiNPs)] offer a simple, reliable and environmentally friendly approach to mitigate stress-related damages and promote plant growth in adverse conditions through enhanced plant defence mechanisms, improved nutrient uptake and mitigate the effects of drought, salinity and pathogen attacks. The mechanisms underlying the induction of systemic resistance, modulation of defense-related enzymes and generation of reactive oxygen species (ROS). Additionally, bacteria-derived NPs contribute to soil health by reducing chemical residues via improving microbial diversity. The present book chapter highlights recent advancements in bacterial nanoparticle biosynthesis, showcasing successful applications of bacterial nanotechnology in enhancing both biotic and abiotic stress tolerance for sustainable agriculture. Lastly, also discussed about potential of bacterial nanoparticles to replace synthetic fertilizers and pesticides in cultivating stress-free crops.

Keywords: Endophytic bacteria, nanoparticles, biotic stress, abiotic stress, plant defence mechanisms.

Citation: Anand, V & Yadav, U. (2025). Biosynthesized Nanoparticles from Endophytic bacteria: A Game-Changer for Stress-Resilient Crops. In *Eco-Friendly Nanotechnology: Harnessing Small-Scale Technologies for a Cleaner and Healthier Planet* (pp. 116-132). Deep Science Publishing. https://doi.org/10.70593/978-93-49307-12-4_9

1 Introduction

The escalating challenges of biotic and abiotic stress in agriculture and environmental sustainability necessitate innovative solutions. Plants encounter two primary forms of stress: biotic, caused by various pathogenic bacteria, fungi, nematodes, oomycetes and herbivores and abiotic, arising from factors like salinity, drought, radiation, heavy metals and extreme temperatures (Dixit *et al.*, 2015). Plants experience water scarcity, ion toxicity, phytohormone imbalances and increased production of reactive oxygen species (ROS) under stress, leading to considerable decreases in crop production (Roychowdhury *et al.*, 2023). Conventional strategies, such as chemical pesticides and fertilizers, often lead to environmental degradation and resistance development in pests and pathogens (Omomowo & Babalola, 2021). In response to these challenges, sustainable approaches such as nanotechnology are gaining attention as potential solutions to enhance plant resilience and productivity.

Endophytic bacteria, which inhabit plant tissues without causing harm, have emerged as promising bioresources for plant growth promotion and stress tolerance. These bacteria produce a variety of beneficial compounds, including antimicrobial metabolites, phytohormones and enzymes, that enhance plant defence mechanisms (Vandana *et al.*, 2021). Recent advances in nanotechnology have highlighted the role of endophytic bacteria in biosynthesizing nanoparticles (NPs), offering an eco-friendly alternative to chemically synthesized nanomaterials (Samuel *et al.*, 2022). Biosynthesized nanoparticles from endophytic bacteria exhibit unique properties such as high biocompatibility, controlled size and eco-friendly production. These nanoparticles, including silver (Ag), gold (Au) and zinc oxide (ZnO), have demonstrated remarkable efficacy in mitigating both biotic and abiotic stresses in crops.

Endophytic bacteria-derived nanoparticles (EBNPs) exhibit potent antimicrobial, antioxidant and plant growth-promoting properties, making them highly effective in mitigating both biotic and abiotic stress. Studies have shown that silver nanoparticles (AgNPs) synthesized by endophytic bacteria possess strong antibacterial and antifungal activity against phytopathogens such as *Pseudomonas syringae* and *Alternaria solani*, reducing disease occurrence in crops (Lee *et al.*, 2022). Additionally, bacterial-derived nanoparticles such as zinc oxide (ZnO NPs) and selenium nanoparticles (SeNPs) have been reported to improve drought and salinity tolerance by enhancing osmotic regulation, promoting root development and activating stress-responsive genes (Bódalo *et al.*, 2023). Furthermore, EB-NPs contribute to heavy metal detoxification by chelating toxic elements, neutralizing oxidative stress and enhancing antioxidant enzyme activity, thereby protecting plants from heavy metal-induced toxicity (Bódalo *et al.*, 2023). Their ability to enhance plant resistance against multiple stressors underscores their potential as sustainable alternatives to conventional agrochemicals. However, challenges such as large-scale production, nanoparticle stability and regulatory approval must be addressed for their widespread adoption in agriculture (Hernandez *et al.*, 2023). This chapter explores the biosynthesis, mechanisms and applications of endophytic bacteria-derived nanoparticles in alleviating plant stress, emphasizing their role in sustainable agriculture. By integrating nanobiotechnology with plant-microbe interactions, EB-NPs provide an innovative and environmentally friendly strategy to enhance crop productivity.

2 Endophytic Bacteria: Natural Symbionts with Unique Capabilities

Endophytic bacteria are microorganisms that reside within plant tissues without causing harm. These bacteria establish symbiotic relationships with their host plants, playing a crucial role in plant health by improved growth, elevating nutrient availability, improved resistance to various stress, make them valuable allies in sustainable agriculture and stress management.

2.1 Plant Growth Promotion

Endophytic bacteria contribute to plant growth by producing phytohormones such as auxins, cytokinin and gibberellins. Plant hormones regulate root and shoot development, by improved nutrient uptake and overall plant growth (Ismail *et al.*, 2021). Ethylene, an imperative plant hormone and signalling molecule, is known to reduce stress in plants. Bacteria possess ACC deaminase that enhances the agronomic attributes of the host by metabolizing ACC, the compound that precedes ethylene production. As a consequence, ethylene levels are reduced and the host's immune system is stimulated. Scientists have discovered various bacteria which possessing the ability to metabolize ACC through ACC deaminase and are belongs to different genera like as *Streptomyces*, *Bacillus*, *Isoptericola*, *Serratia*, *Klebsiella*, *Arthrobacter*, *Microbacterium* and *Pseudomonas* (Miliute *et al.*, 2015). Additionally, some endophytes facilitate nitrogen fixation, making atmospheric nitrogen available to plants, reducing the need for synthetic fertilizers. Recent studies indicate that co-inoculating soybean with *Rhizobium* and AMF increases nodule formation, improves root structure and enhances grain yield, particularly in soils that are low in nitrogen and phosphorus (Adeyemi *et al.*, 2021).

2.2 Biocontrol Activity

Endophytes can act as biocontrol agents by producing antimicrobial compounds, lytic enzymes, or inducing systemic resistance (ISR) in plants, helping them fend off pathogens (Nguvo & Gao, 2019; Yadav *et al.*, 2023). Endophyte-plant interaction also plays a pivotal role in the ability of disease suppression by the host. For example, in *Solanum lycopersicum* (tomato), mycorrhizal fungi paired with *Pseudomonas fluorescens* inhibit *Fusarium oxysporum* (a soil born pathogen) infection. *Pseudomonas fluorescens*, categorized as a mycorrhiza helper bacterium (MHB), secrete several biologically active metabolites that trigger mycorrhizal colonization via strengthening the plant's defence responses through Induced Systemic Resistance (ISR) (Alizadeh *et al.*, 2013).

2.3 Stress Tolerance and Environmental Adaptation

Endophytic bacteria enhance plant resilience against abiotic stresses like drought, salinity and heavy metal toxicity by modulating stress-related gene expression, through production of osmo-protecting agents and detoxification of heavy metals through biosorption and biotransformation. Bacterial endophyte *Pseudomonas pseudoalcaligenes*, has been reported to enhance glycine betaine accumulation in rice resulting in reduced salinity stress in rice (Zeng *et al.*, 2023). Plant hormones are known to play important role in plant development, hydrological cycle and various stress responses Zhao et al. (2021) reported the role of endophyte *Azospirillum* spp. to cope up with water stress by accumulating abscisic acid in maize. Table- 1 represents the list of some bacterial endophytes along with their role in abiotic and biotic stress mitigation.

3 Biosynthesis of Nanoparticles by Endophytic Bacteria

Green synthesis or biological methods to synthesize metal NPs are becoming more popular. Among them, endophytic microorganisms viz., bacteria, fungi and actinomycetes have the ability to convert metal ions into metallic NPs such as Ag, Au, Zn and Cu with the help of secondary metabolites and cellular enzymes (Soliman *et al.*, 2018). Due to having metallic ion stress tolerance tendency, endophytic bacteria emerged as good entrant for NPs synthesis (Syed *et al.*, 2019). Under high metallic ion stress endophytic bacteria establish the defence mechanism to reduce the toxicity of metal ions through the precipitation of metallic ions at the nanometer scale to synthesize NPs (Iravani & Varma, 2020). Table- 2 summarizes the list of some bacteria mediated synthesis of nanoparticles. For instance, AgNPs with antibiofilm, antibacterial and antifungal activity has been synthesized from *Bacillus siamensis* C1, *Pseudomonas poae* CO (Ibrahim *et al.*, 2020), or *Aneurinibacillus migulanus* (Prathna *et al.*, 2010), while AuNPs (5–50 nm) synthesized by *Pseudomonas fluorescens* 417 (Syed *et al.*, 2019). AgNPs synthesized by *Pseudomonas aeruginosa* were reported as higher active NPs due to presence of metal uptake, their accumulation and toleration ability (Moghaddam *et al.*, 2015). *Streptomyces capillispiralis* and *Streptomyces zaomyceticus* Oc-5 have been used for the synthesis of CuNPs (Hassan *et al.*, 2019).

4 Exploration of Microbially Synthesized Nanoparticles for Producing Stress resilient Crops

The application of bacteria in the NPs synthesis is evolving as a promising method to develop nanoparticles that can improve both abiotic and biotic stress tolerance in plants. When certain types of metal and metal oxide NPs administered at low concentrations, have reported to boost plant defences against pathogens and pests. This section discusses about and an overview of recent studies focused on utilizing bacterial produced NPs to cultivate stress free crops that are resilient against environmental stress. Table. 3 represents the list of bacterial-mediated synthesized nanoparticles reported as plant biotic and abiotic stress tolerance.

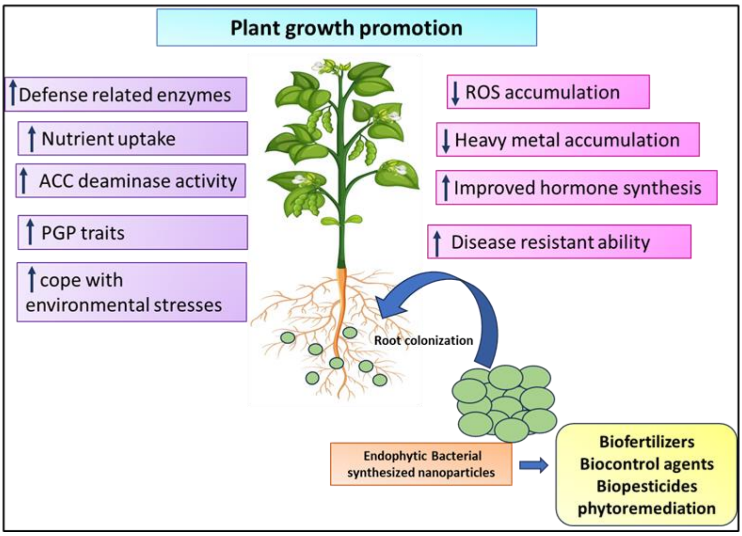

Fig. 1. Represents the application of bacteria-mediated synthesis of NPs for enhancing the plant abiotic and biotic stress tolerance.

4.1 Role of Bacteria-based Nanoparticles in Cope up with Abiotic Stress

Endophyte-based nanoparticles (EBNPs) have gained significant attention for their potential role in mitigating abiotic stress in plants, such as drought, salinity, heavy metal toxicity and temperature extremes. These nanoparticles, synthesized by beneficial bacteria like *Pseudomonas* spp., *Bacillus* spp. and *Rhizobium* spp., enhance plant resilience by modulating stress-related physiological and biochemical pathways. EBNPs facilitate nutrient uptake, regulate reactive oxygen species (ROS) levels and improve osmotic balance, thereby reducing oxidative damage under stressful conditions (Deep *et al.*, 2025). Additionally, bacterial nanoparticles can enhance stress tolerance by influencing phytohormonal signalling pathways, such as abscisic acid (ABA) and salicylic acid (SA), which play a crucial role in stress adaptation (Kumar *et al.*, 2023). The bioavailability of essential nutrients like iron and zinc is also improved through bacterial nanoparticle-mediated solubilization, further promoting plant growth in stress-prone environments. Given their eco-friendly nature and efficiency, bacteria-based nanoparticles offer a promising, sustainable solution to enhancing crop resilience against abiotic stressors in modern agriculture (Fig. 1).

4.2 Role of Bacteria-based Nanoparticles in Alleviating Biotic Stress

Endophyte-based nanoparticles (EBNPs) have emerged as a promising tool for mitigating biotic stress in plants by enhancing their defence mechanisms against pathogens and pests. These nanoparticles, synthesized using beneficial bacteria such as *Pseudomonas*, *Bacillus* and *Rhizobium*, exhibit antimicrobial properties, induce systemic resistance and promote plant growth. Their biocompatibility and eco-friendly nature make them an attractive alternative to chemical pesticides. Studies have shown that silver and zinc oxide nanoparticles synthesized using bacterial metabolites effectively inhibit the growth of fungal and bacterial pathogens, reducing disease incidence in crops (Verma *et al.*, 2024). Additionally, bacterial-derived nanoparticles can activate plant immune responses by modulating phytohormone signalling pathways, leading to enhanced resistance against biotic stressors (Kumar *et al.*, 2023). With increasing concerns over pesticide resistance and environmental toxicity, bacteria-based nanoparticles present a sustainable and efficient approach to crop protection in modern agriculture (Fig. 1).

5 Environmental and Economic Sustainability of Endophytic Bacteria-Derived Nanoparticles

The rapid advancement of nanotechnology has raised concerns about environmental impact and economic feasibility. However, the biosynthesis of nanoparticles (NPs) using endophytic bacteria presents a sustainable alternative that aligns with ecological conservation and cost-effective production (Kuppusamy *et al.*, 2025). The integration of endophyte-derived nanoparticles (EBNPs) in agriculture and environmental management offers a promising route to reduce dependency on hazardous chemicals, mitigate pollution and promote sustainable farming practices (Choudhary *et al.*, 2023).

5.1 Environmental Sustainability

5.1.1 Green Synthesis with Minimal Ecological Footprint: Traditional chemical and physical nanoparticle synthesis methods involve toxic solvents, high energy consumption and hazardous byproducts. In contrast, EBNPs are synthesized under ambient conditions using natural bacterial processes, making them environmentally friendly (Choudhary *et al.*, 2023). This green synthesis approach eliminates the need for toxic reducing and stabilizing agents, produces biodegradable nanoparticles that do not accumulate in ecosystems and also reduces risk of greenhouse gas emissions by lowering energy-intensive production steps (Tiwari & Park, 2024).

5.1.2 Biodegradability and Eco-Friendly Decomposition: EBNPs are inherently biodegradable, ensuring that they break down into non-toxic components over time. Unlike synthetic nanoparticles, which can persist in the environment and disrupt microbial communities, biosynthesized nanoparticles degrade naturally without causing soil or water contamination (Tiwari and Park, 2024).

5.1.3 Reduction in Chemical Pesticide and Fertilizer Use: The antimicrobial and growth-promoting properties of EBNPs offer a sustainable alternative to chemical pesticides and synthetic fertilizers. Their application in agriculture reduces chemical runoff into water bodies, preventing eutrophication and biodiversity loss. In addition, also minimizes soil degradation and microbial imbalance that is caused by prolonged chemical exposure and play important role in enhancing soil fertility by promoting beneficial microbial activity (Choudhary *et al.*, 2023).

5.1.4 Support for Climate-Resilient Agriculture: EBNPs enhance plant resilience against climate change-related stresses such as drought, salinity and extreme temperatures. By strengthening plant defence mechanisms, these nanoparticles contribute to sustainable food production systems that require fewer resources while maintaining high yields (Tiwari & Park, 2024).

5.2 Economic Sustainability

5.2.1 Cost-Effective Production and Scalability: Traditional nanoparticle synthesis involves expensive chemicals, sophisticated equipment and energy-intensive processes. Biosynthesis using endophytic bacteria is significantly more cost-effective because their production utilizes readily available biological resources (Gupta *et al.*, 2024). Bacterial endophytes also minimize the need for complex purification and post-synthesis processing. Therefore, by optimizing bacterial cultures in bioreactors, large-scale production of EBNPs can be achieved at a fraction of the cost compared to conventional nanoparticle synthesis (Khanam *et al.*, 2020).

5.2.2 Increased Agricultural Productivity and Profitability: The use of endophytic bacterial nanoparticles (EBNP)s in agriculture leads to improved crop yields, disease resistance and soil health, translating into economic benefits for farmers, resulting in higher crop production, thereby reducing input cost (Khanam *et al.,* 2020).

5.2.3 Potential for Commercialization and Job Creation: The development of EBNP-based biofertilizers, biopesticides and plant growth enhancers presents new avenues for commercial production and employment generation. Small- and large-scale industries can benefit from establishing microbial nanotechnology-based startups (Nazir *et al.*, 2024).

6 Future Prospects and Challenges

Bacterial endophyte nanoparticles hold promise for sustainable agriculture, medicine and industry, but face challenges in understanding their mechanisms, safety and environmental impact. Future prospects include developing novel therapeutics and agricultural practices, while challenges include scaling up production, ensuring safety and establishing robust regulatory frameworks. Future research should focus on genetic and metabolic engineering of endophytic bacteria to enhance nanoparticle synthesis efficiency. Additionally, integrating biosynthesized nanoparticles into modern agricultural practices can revolutionize stress mitigation strategies, ensuring a sustainable future for global food production.

Conclusions

Endophytic bacteria-derived nanoparticles represent a sustainable and innovative solution for mitigating biotic and abiotic stress in agriculture. By harnessing the natural capabilities of these microbes, researchers and farmers can develop eco-friendly strategies to enhance crop resilience and productivity while reducing environmental harm. Continued research and technological advancements in this field will pave the way for widespread adoption of EBNPs in sustainable agriculture.

Table 1: List of bacterial endophytes that can mitigate abiotic and biotic stress in host plants.

S. No.	Bacterial Endophyte	Characteristics	References
Abiotic Stress			
1.	*Achromobacter* spp.	Osmotic stress, heavy metals	Das et al. (2024)
2.	*Actinobacteria* spp.	Drought tolerance, secondary metabolite production	Dinesh et al. (2017)
3.	*Alcaligenes* spp.	Metal tolerance, stress resistance	Jan et al. (2019)
4.	*Bacillus altitudinis*	Drought tolerance, growth promotion	Arun et al. (2020)
5.	*Bacillus* spp.	Drought resistance, growth promotion	Vardharajula et al. (2011)
6.	*Brevundimonas* spp.	Osmotic stress, growth promotion	Bakhtiyarifar et al. (2021)
7.	*Chitinophaga* spp.	Metal tolerance, organic matter degradation	Tiwari and Bae (2023)
8.	*Flavobacterium* spp.	Salinity, metal tolerance	Kim et al. (2020)
9.	*Marinobacter* spp.	Salinity tolerance, osmotic stress	Amara et al. (2025)
10.	*Massilia* spp.	Metal tolerance, stress resistance	Gonzalez et al. (2021)
11.	*Methylobacillus* spp.	Cold, heat tolerance, growth promotion	Gamit and Amaresan (2023)
12.	*Weissella* spp.	Heat, cold tolerance, plant growth promotion	Akhtar et al. (2023)
13.	*Xanthomonadaceae*	Abiotic stress mitigation, biocontrol	Rizvi et al. (2024)
14.	*Streptococcus* spp.	Cold, heat tolerance, stress resistance	Ashwini et al. (2023)
15.	*Rhodococcus* spp.	Drought tolerance, biodegradation	Hnaka et al. (2021)
Biotic Stress			
1.	*Achromobacter* spp.	Enhances nutrient uptake, induces systemic resistance	Kaur & Karnwal (2023)
2.	*Acinetobacter* spp.	Promotes plant growth, reduces pathogen infection	Dinesh et al. (2017)
3.	*Aeromonas* spp.	Enhances stress tolerance, reduces pathogen infection	Eid et al. (2019)
4.	*Agrobacterium tumefaciens*	Causes crown gall disease but can be used in genetic engineering	Li et al. (2019)
5.	*Arthrobacter* spp.	Produces antifungal and antibacterial metabolites	Ashitha et al. (2019)
6.	*Azospirillum* spp.	Enhances root growth, improves nutrient uptake	Rana et al. (2020)
7.	*Bradyrhizobium* spp.	Nitrogen fixation influences plant health	Kumawat et al. (2019)
8.	*Burkholderia* spp.	Produces antifungal metabolites, enhances root growth	Pal et al. (2022)
9.	*Pseudomonas fluorescens*	Antifungal compounds, induces plant defence mechanisms	Mengistu (2020)

10.	*Serratia marcescens*	Produces antifungal and antibacterial compounds	Clements et al. (2019)
11.	*Variovorax paradoxus*	Enhances plant growth, may compete with pathogens	Han et al. (2011)
12.	*Streptomyces* spp.	Produces antibiotics, induces plant resistance	Vurukonda et al. (2018)
13.	*Mesorhizobium* spp.	Nitrogen fixation influences plant health	Chen et al. (2025)
14.	*Pantoea agglomerans*	Triggers plant defences, reduces pathogen infection	Lorenzi et al. (2022)
15.	*Xanthomonas citri*	Induces systemic resistance against certain pathogens	Rabbee et al. (2019)

Table 2: List of bacteria-mediated synthesis of nanoparticles.

S. No.	**Microorganism**	**Type of Nanoparticle**	**Size (nm)**	**Shape**	**Site of synthesis**	**Reference**
2.	*Bacillus paramycoids*	Silver Oxide (Ag_2O)	25–70	Spherical	Extracellular using culture supernatant	(Nchoe, 2023)
1.	*Bacillus subtilis* ZBP4	Zinc Oxide (ZnO)	22–59	Spherical	Extracellular	(Hamk *et al.*, 2023)
5.	*Escherichia coli, Exiguobacterium aurantiacumm,* and *Brevundimonas diminuta*	Silver (Ag)	5–50	Spherical	Extracellular using secondary metabolites	(Saeed *et al.*, 2020)
4.	*Lactobacillus plantarum TA4*	Silver (Ag)	14.0 ± 4.7	Spherical	Cell membrane	(Yusof *et al.*, 2020)
6.	*Lactococcus lactis* NCDO1281(T) and *Bacillus* sp. PTCC 1538	Zinc Oxide (ZnO)	55–60 and 99	Nanospheres and Nanorods	Extracellular using culture broth	(Mahdi *et al.*, 2021)
3.	*Proteus vulgaris*	Iron Oxide	19.23–30.51	Spherical	Extracellular	(Majeed *et al.*, 2021)

Table 3: List highlighting the study of bacterial-mediated synthesized nanoparticles reported as plant biotic and abiotic stress tolerance.

Sr. No.	**Nanoparticle**	**Microbe used for synthesis**	**Plant**	**Improved Stress resistance**	**Characteristics**	**Reference**
Biotic Stress						
1	Silver	*Bacillus cereus* SZT1	Rice	*Xanthomonas oryzae* pv	Increased nutrient uptake and antioxidant enzyme levels, improved the plant health	Ahmed et al. (2020)
2	Magnesium Oxide	*Bacillus* strain *RNT3*	Rice	*Acidovorax oryzae*	CS-Mg nanocomposite showed remarkable antimicrobial activity by	Ahmed et al. (2021b)

					inhibiting growth compared to control	
3	Magnesium Oxide	*Acinetobacter johnsonii RTN1*	Rice	*Acidovorax oryzae*	Biogenic MgONPs showed significant antibacterial activity at concentration of 20 µg mL^{-1}	Ahmed et al. (2021c)
			Abiotic Stress			
1	Iron oxide	*Pantoea ananatis*	Wheat	Salinity and Cadmium	FeO-NPs in soil increased the nutrient concentrations of N, P and K, along with length of plants by 36.7%, while reduced uptake of Cd by 72.5% and Na^{+} and Cl^{-}	Manzoor et al. (2021)
2	Iron oxide	*Bacillus* strain (RNT1)	Rice	Drought and Cadmium	Increased biomass, antioxidant contents, nutrient acquisition and decreased Cd translocation and expression of Cd transporters.	Ahmed et al. (2021a)
3	Copper	*Shigella flexneri* SNT22	Wheat	Cadmium	100 mg kg^{-1} of CuNPs increased plant length shoot dry weight nitrogen, phosphorus K^{+}, $Ca^{2+,}$ K^{+}/Na^{+} and Ca^{2+} /Na^{+} contents. While decreased in Cd translocation.	Noman et al. (2020)
4	Copper	*Klebsiella pneumoniae*	Wheat	Chromium	Decrease in reactive oxygen species and Cr translocation from soil to roots and shoots.	Noman et al. (2021)

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