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Synergistic relationship of endophyte-nanomaterials to alleviate abiotic stress in plants

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Plant responses to abiotic stresses through diverse mechanisms and strategic measures in utilizing nanomaterials have positively impacted crop productivity. Stress can cause membrane depletion, reactive oxygen species formation, cell toxicity and death, and reduction in plant growth. However, nanomaterials can mitigate some of the negative impacts of abiotic stresses and enhance crop yield. Some endophytic microbes can synthesize nanomaterials, which can maintain and enhance plant health and growth *via* nitrogen fixation, siderophore production, phytohormones synthesis, and enzyme production without any pathological effects. Nanoparticle-synthesizing endophytes also help boost plant biochemical and physiological functions by ameliorating the impact of abiotic stresses. The increase in the use and implementation of nano-growth enhancers from beneficial microbes, such as nano-biofertilizers, nano-pesticides, nano-herbicides, and nano-fungicides are considered safe and eco-friendly in ensuring sustainable agriculture and reduction of agrochemical usage. Promisingly, nanotechnology concepts in agriculture aim to sustain plant health and protect plants from oxidative stresses through the activation of anti-oxidative enzymes. The mechanisms and the use of nanomaterials to relieve abiotic plant stress still require further discussion in the literature. Therefore, this review is focused on endophytic microbes, the induction of abiotic stress tolerance in plants, and the use of nanomaterials to relieve abiotic plant stresses.

KEYWORDS

environmental stressors, food security, plant health management, soil-plant microbe interactions, sustainable development goal 2, zero hunger

Introduction

The environmental problems linked to climate abiotic-induced stresses pose serious threats and ecological pressures on soils and plant health, limiting crop productivity (Varshney et al., 2011). Thus, the need to devise a problem-solving approach to enhance crop yield under stress becomes imperative. The biotic factors, such as bacterial and fungal pathogens, insect and nematode pests as well as abiotic factors such as temperature, salinity, drought, flooding, heavy metals, and pH cause a large number of modifications in plant biochemical and physiological processes (Kumar et al., 2019). The approaches to mitigate these stresses in crops should be targeted to maximally address the food supply and demand of the world population. Over time, the use of chemical fertilizers to improve crop productivity has been employed, but with profound detrimental effects on the ecosystems (Adeleke and Babalola, 2022). Hence, developing modern technology remains important to ensure Sustainable Development Goals (SDGs) without any significant negative impact on the ecosystem.

Nanotechnological approaches have been employed in agriculture, industry, and medicine (Audah, 2019; Elemike et al., 2019; Zulfiqar et al., 2019). Nanoparticles (NPs), are characterized by sizes ranging from 1 to 100 nm in diameter, various physical, chemical features, biochemical activity, and increased reactivity (Dutta and Sugumaran, 2021). Different methods have been employed in the synthesis of NPs, which include inert gas condensation, physical ball milling, biological and chemical processes (Aboyewa et al., 2021). The biological means of synthesizing NPs can be achieved by harnessing some endophytic microbes, such as bacteria and fungi (Ahmad F. et al., 2012; Eid et al., 2021). Some examples of NPs produced by endophytic microbes include titanium, platinum, cadmium, gold, zirconium, selenium, magnetite, usnic acid, gold-silver alloy, uraninite, tellurium, and palladium (Aboyewa et al., 2021). NPs from endophytic fungi have been reported to play an important role in plant disease management due to the presence of NP-assisted genes (Sonawane et al., 2022).

Endophytic microbes are microbes inhabiting the internal tissues of plants, which can be beneficial or pathogenic (Adeleke and Babalola, 2022). The beneficial types help ensure sustainable plant and soil health under a variety of stresses including drought stress (Premachandra et al., 2020). Some of these microbes also possess the ability to synthesize nanomaterials, which can be exploited in maintaining plant health without any pathological effects (Sonawane et al., 2022). Promisingly, NP-synthesizing endophytic microbes can help boost plant physiological functions and can be used as bioinoculants in developing eco-friendly agriculture. Nevertheless, information on the actual mechanisms and the use of nanomaterials to relieve abiotic plant stresses have not been fully discussed in the literature. Depending on the type, application and use, various NPs of carbon-based, metallic and non-metallic and organic polymers have been developed (Kumar et al., 2021; Fadiji et al., 2022b). The use and implementation of known nano-growth enhancers, nano-biofertilizers, nano-pesticides, nano-herbicides, and nano-fungicides are on the increase in modern agricultural systems (Imade et al., 2022; Sonawane et al., 2022). Based on experience to date, this approach is considered safe, eco-friendly for improved soil nutrition and crop yield.

Plants are prone to different environmental stressors, such as ultraviolent light, drought, flooding, salinity, temperature extremes (low or high), and the presence of heavy metals (Chaudhary et al., 2021c). All of these factors can induce oxidative stress causing membrane depletion, reactive oxygen species formation, cell toxicity and death, which cause a reduction in plant growth (Thomas and Puthur, 2017; Hasanuzzaman et al., 2019). Regardless of the nature of the abiotic stress, NPs may be involved in plant cellular metabolism, growth, and stress protection (Ajilogba et al., 2021). Also, some NPs exhibit the ability to modify the expression of genes involved in electron transport, energy transport, cell biosynthesis, and cell organization under stress conditions (Pandey, 2018; Sonawane et al., 2022). Thus, many studies have validated the multifunctional attributes of NPs in crop improvement (Abd-Alla et al., 2019; Chavan and Nadanathangam, 2019; Kibbey and Strevett, 2019).

Notwithstanding the positive attributes of NPs, information on the mechanisms of how NPs alleviate stresses and how endophytic microbes induce plant stress tolerance are still required. Consequently, this review addresses the role of endophytic microbes in inducing abiotic stress tolerance in plants, and the use of nanomaterials to relive abiotic plant stresses.

Microbe-nanomaterial interactions

Biological activities through alterations in the function and structure of bacteria can be unveiled using modern and advanced nano-technological processes (Chaudhary et al., 2021b). Recent methods are been used to assess the surface chemistry, structural form of NPs and their effects on biocidal activities (Noukelag et al., 2022; Rehman et al., 2022). Examples of ecofriendly nano-sized agents include a variety of phyto/zooplankton, fungal spores, bacteria, and other microorganisms. NPs react differently with microbes, which shows that the microbial cell surfaces can differ substantially in their reactivity and attraction (Gangadoo et al., 2022). Silica NPs react effectively with microorganisms of different groups (Wang et al., 2020). For instance, bacteria and microalgae are smaller with less reactive attributes compared to fungal spores. A comprehensive mechanism showing the harmful effect of metallic nano-sized particles on bacteria cells is still required. In addition, there is a need for special attention to the structural alteration of bacterial cells using *in vitro* studies.

The continuous upsurge in the cases of fungal infections in immunocompromised patients, which require urgent medical treatment has caught the attention of most researchers. Meanwhile, the need for an ecofriendly measure for treating mycoses and identification of the source of infection has prompted researchers toward the use of metallic NPs (Singh et al., 2019; Soliman et al., 2021). Several studies have assessed the antifungal effects of NPs (Khatoon et al., 2018; Ahmadpour et al., 2021; Sadek et al., 2022). A study by Masoumizadeh et al. (2022) reported the effect of AgNPs on fungal pathogens, *Candida spp*. Also, the findings of Santhoshkumar et al. (2019) on the toxicological ad antidermatophytic activity of AgNPs synthesized using leaf extract of *Passiflora caerulea* revealed the maximum antifungal activities against dermatophyte, *Trichophyton rubrum.*

Nanomaterial-microbial compatibility

Bacteria and NPs

Plasmolysis of bacteria is a slaying event that involves the breakdown of cytoplasmic components and morphological reduction of cytoplasm due to the loss of intracellular components and plasma membrane contraction from the cell wall. It has been reported that metallic NPs induce pleiotrophic effect on bacteria cells. Nanomaterials bind with bacteria proteins (thiol moieties) hindering their activities, forming an attachment with the cell membrane and causing cell death. Consequently, altering cell permeability by obstructing the activities of electrons in cells and obstructing respiration (Radzig et al., 2013; Mohanty et al., 2014). ROS generated as a result also inhibits respiratory enzymes. Oxidized DNA precursors result in DNA lesions (Park et al., 2009).

Advances in the cell to the non-cell formation, the reaction against resistant, persistent strains and swarming motility have encouraged researchers about bacterial genes encoding guanine nucleotide exchange factors. NPs enhance the activities and response of genes encoding guanine nucleotide exchange factors, which gives scientists better insights into improved NPs applications as antibacterial agents. Because of these highlighted responses, several studies have been conducted to verify the expression of bacterial genes to nano-sized particles (Khati et al., 2018). Exposure to metallic NPs revealed consistent gene patterns using transcriptional analytical methods such as RT qPCR or microarray. For instance, when *E. coli* was subjected to AgNPs, it exhibited a distinctive expression in gene functions, such as homeostasis of iron, silver and copper, which regulate the oxidative balance *via* the use of microarray experiment and its features to metabolize sulfur (Nagy et al., 2011; McQuillan and Shaw, 2014). In other studies, researchers assessed alterations in gene expression of bacteria subjected to the treatment with carbon NPs. A study by Kang et al. (2008) showed the leakage of cellular material, disrupted membrane, reduced viability and metabolism of *E. coli* when subjected to single-walled nanotubes. In another study by Pelletier et al. (2010) using microarray, *E. coli* was exposed to cerium oxide NPs, the NPs upregulated several oxidoreductases sowing depletion in iron deficiency, oxidation stress and cellular respiration. Yang et al. (2012b) exposed *Pseudomonas aeruginosa* to quantum dots and genes controlling metal efflux transporters and oxidative stress were upregulated.

To check the compatibility of nanomaterials and bacterial cells, Dimkpa et al. (2012) showed that NPs could also affect microorganisms and plants by causing modifications in cellular levels of siderophores (pyoverdine) of plant growth-promoting bacterium (Dimkpa et al., 2012).

Fungi and NPs

Almost all NPs are capable of creating holes in the membrane of most fungal cells. The alteration in physiological traits of fungi releases biomolecules resulting in cell death. In a study by Kim et al. (2009), Kim and co. observed the reaction between AgNPS and *Candida albicans* and discovered membrane depolarization in *C. albicans*. Pits and pores were formed on the cell wall of the organism. This leads to the release of trehalose and glucose into the prepared suspension. The antifungal activity of AgNPs was also performed on other fungal species such as *Saccharomyces cerevisiae*, *Candida tropicalis*, *Phomopsis spp*., *Penicillium expansum*, *Botrytis cinerea* and *Trichophyton rubrum* (He et al., 2011; Nasrollahi et al., 2011; Mallmann et al., 2015). The effect of Fe_3O_4NPs was tested against *Candida* spp and perforation of cell membranes was observed (Prucek et al., 2011). The cell wall and the membrane of *Cryptoccocus neoformans* were also depleted when *C. neoformans* was exposed to AgNPs in a study by Ishida et al. (2013).

The use of *In silico* and mathematical modelling could help provide a better understanding of microbe-nanomaterial compatibility and interactions. Studies to experiment with the interaction between microbes and NPs are extremely important to unveil the details of these interactions. Meanwhile, bioinformatics tools are also needed to ensure statistical analysis and data curation about the future occurrences of microbial interaction with NPs (Singh et al., 2019; Adeleke et al., 2022).

Synergistic relationship: Endophyte-induced NPs

Recent developments required to ensure an ecofriendly interface for nanoscience studies have delivered exciting results by revealing multifaceted metal-based NPs with numerous applications and functions (Baker et al., 2015a; Kumari et al., 2020). Ecofriendly biological resources viz. algae, fungi, bacteria and plants have been adopted to synthesize NPs, with each bio-factory having its pros and cons (Iravani et al., 2014; Rahman et al., 2019). Microorganisms are said to be an attractive option because of their dependable and unlimited metabolite production which are useful as reducing agents. In the case of plants, the disturbing plant diversity/species most times complicate the usage (because of selection problem) (Baker et al., 2015b). Even though microorganisms have been identified as the best option for the ecofriendly synthesis of NPs, the potential of endophytes remains under-explored. Adopting endophytes as reducing agents for the biosynthesis of nanomaterials opens new opportunities for the discovery of novel NPs with various applications (Rahman et al., 2019). Microorganisms (e.g., endophytes) remain the biological agents with harmless, clean and the most commercially available approach for NPs synthesis. That said, limitations faced by often synthesized endophyte NPs affect the stability of NPs because microbes are retarded overtime. With the variation in parameters such as substrate condition, synthesis condition, growth on media, pH, temperature and physicochemical parameters (stability, shape, and size) of NPs, which might change easily (Ovais et al., 2018).

The diverse endophytic microbes from different sources have been used in the synthesis of NPs. These include; the biosynthesis of AgNPs using *Bacillus cereus* isolated from *Adhatoda beddomei* and *Garcinia xanthocymus* as recapping agents to produce AgNPs with antibacterial properties (Sunkar and Nachiyar, 2012a; b). A study by Devi and Joshi (2015) also reported the use of *Cryptosporiopsis ericae* isolated from *Poteotilla fulgens* L. in the synthesis of NPs. The synthesized nanomaterial had an absorbance peek of ≈430 nm, spherical, and a diameter ranging between 2 nm and 16 nm. Rahi and Parmar (2014) and Singh et al. (2013) also synthesized AgNPs using *Penicillium* spp. isolated from the tissue of *Curcuma longa* and *Aloe vera* root. The synthesized NPs had a size range between 15 nm and 45 nm with immense antibacterial activity against antibiotic-resistant pathogens. Several studies have used endophytes as an ecofriendly route for the biosynthesis of multifunctional metal-based NPs. These include; Hulikere and Joshi (2019)—*Cladosporium cladosporoides*, Ramalingmam et al. (2015)—*Cochliobolus lunatus*, Qian et al. (2013)—*Epicoccum nigrum*, Yashavantha Rao et al. (2016)—Endophytic bacterium EH419, Neethu et al. (2018)—*Penicillium polonicum* and Abdel-Aziz et al. (2018)—*Aspergillus* spp.

Impact of nanomaterials on microbial diversity and soil health

In natural ecosystems, microorganisms drive ecological processes (Chaudhary et al., 2022). These processes include; anaerobic digestion, removal of nutrients in wastewater treatment, and biogeochemical cycling (Ahmed et al., 2012). On a single cell or population of microbes, antimicrobial activities and the potency of nanomaterials have been studied extensively elucidating their effects on the microbial community. As a result, there is an extensive understanding of the pros and cons associated with the ecotoxicity of NPs. Recently, scientists have studied the effect of nanomaterials on the community structure and functions of microorganisms in natural environments, such as water treatment facilities, marine, rivers and soils (Mohanty et al., 2014).

Effect of nanomaterials on microbial diversity

Microbial diversity in the soil plays a crucial role in nutrient cycling, plant diversity and agricultural output (Mohanty et al., 2014). Scientists have shown that important nanomaterials properties viz., aggregation, size, shape and charge, could be influenced by the environment (Lowry et al., 2012; Liu et al., 2014). NPs migrate at different levels in the soil matrix, and as such altering the microbial community structure in the soil. Also, the type of soil affects the impact of NPs. In a study by Frenk et al. (2013), the microbial community in clay and sandy soils were shown to respond differently to magnetite and copper oxide NPs. In a related study by Pawlett et al. (2013), a similar result was obtained from the reaction of microorganisms in the sandy soil to zero-valent iron nanomaterials. Herein, the microbial groups obtained from the combination of sandy soil and FeNPs were more susceptible than microbial communities in clay soil. Also, AgNPs were suspected to affect the community profile of freshwater microbial habitat in a study by Das et al. (2012). Both microbial biofilms and planktonic communities were influenced by nanomaterials as related in the study by Flemming and Wingender (2010) and Ding et al. (2014). Although, planktonic communities most times exhibit low tolerance to antimicrobial agents and toxic environments compared to their biofilm counterparts (Cao et al., 2012). For instance, the exposure of marine biofilm to AgNPs does not affect the community structure, succession and biofilm development of the community (Fabrega et al., 2011). However, apart from the reduction in microbial communities associated with a biofilm, the integrity of cells in a biofilm could be compromised because of its exposure to NPs (Battin et al., 2009).

In an engineered ecosystem using nanomaterials, most researchers adopt microbial communities associated with waste plants as model systems. Often, the impact of microbial communities and their community composition is of utmost interest to researchers. Meanwhile, most studies concentrate on the impact of NPs on commonly studied bioprocesses with the inclusion of methanogenesis, phosphorus and nitrogen removal. Even though most studies have reported the negative of nanomaterials on microbial community structure (Liang et al., 2010; Ahmed and Rodrigues, 2013), some other studies showed that the microbial communities associated with sludge digester were not affected by nanomaterials (Nyberg et al., 2008; Yang et al., 2012a). This discrepancy could be associated with variations in the physical and chemical properties of nanomaterials and their complex reaction with several other materials from either organic or inorganic sources (Mohanty et al., 2014).

Impact of nanomaterials on microbial community functions

The effect of nanomaterials on microbial community functions is another important aspect of NPs-induced community variation yet to be explored. Some studies have further highlighted possible alterations in microbial functions induced by the exposure of the environment to nanomaterials. These include functions associated with nutrient removal and methanogenesis in wastewater treatment plants. In a study by Alvarez and Cervantes (2012), the process of methane production was significantly inhibited by nanomaterials such as Al_2O_3 and its toxicity was reduced when coated with humic acids. In a similar study, Yang et al. (2012a) reported the effect of AgNPs on methane production in landfill bioreactors at different concentrations.

Several studies viz., Masrahi et al. (2014), Liang et al. (2010), and Li et al. (2014) also reported nitrogen removal processes using nanomaterials such as TiO_2 and AgNPs. The negative impact of graphene oxide was also reported on wastewater treatment by removing nitrogen and phosphorus from waste materials (Ahmed and Rodrigues, 2013). To discuss the effect of nanomaterials on microbial diversity, structure and functions, organism-determined toxicity of nanomaterials is required i.e., each microorganism with susceptible nanomaterials because bacteria tolerate nanomaterials differently. For instance, Gram-positive bacteria react positively to single-walled carbon nanotubes by changing their membrane lipid composition. The mechanism of nanomaterials-microbe specificity is widely unknown and there is a need to further investigate the process (Jin et al., 2014; Mohanty et al., 2014).

Mechanisms of mitigating abiotic stress in plants

Abiotic stresses remain one of the most significant factors limiting the growth and yield of plant crops (Yadav, 2017). There is a need for plants to resist stressful edaphic and environmental conditions using either innate or induced biological mechanisms. For induced biological mechanisms to relieve the plant of unwanted stressors, an environmentally friendly method is needed to avoid complications associated with the use of synthetic chemicals. In this regard, the use of endophytic microbes remains one of the more reliable methods to mitigate the effects of abiotic stresses. Microbes are ubiquitous in diverse natural environments and exhibit diverse metabolic responses to manage soil stressors (Meena et al., 2017; Akinola and Babalola, 2020; Akinola et al., 2021b). Due to the proximity between plants and microbes in the soil, the plant microbiome induces local and systemic mechanisms in crop plants to cope with continuous changes to the environment. This synergism (plant-microbe) in the agroecosystem induces complex mechanisms within the plant cellular system (Figure 1). Interestingly, the continuous change in climatic conditions has paved the way for a better understanding of plant cellular complexity; researchers are constantly ruminating on questions associated with the physiological, molecular, and biochemical processes related to plant-microbe interplay (Glick, 2020; Akanmu et al., 2021).

Because of the growing concern about climate change, it is important to explicitly explicate the synergy between plant-soil-microbe about protection against abiotic stressors. Understanding the changes in different abiotic stresses induced by either anthropogenic or natural means is crucial to reducing the negative effects of environmental stress as it impacts agricultural productivity (Jalil and Ansari, 2019). A report by the Food and Agriculture Organization (FAO) of the United Nations on the challenges limiting global food productivity argued that one of the major problems faced by the scientific community in the effort to increase crop production is unwanted abiotic stressors (FAO, 2009). As such, there is a need to address the challenges associated with plant growth sustainably. These include eco-friendly technological processes and the efficient use of bioproducts to address the constraints posed by environmental stresses (FAO, 2009).

Several abiotic factors can limit plant growth and development including low or high temperature, heavy metal toxicity, soil alkalinity or acidity, drought, flooding and salinity (Emamverdian et al., 2015; Pasala et al., 2016; Jalil and Ansari, 2019). Abnormal soil acidity can lead to nutrient deficiency in plants thereby reducing essential physiological attributes needed to improve plant growth and development (Jalil and Ansari, 2019; Akinola and Babalola, 2020). Similarly, salt treatment induces toxicity in plant tissues, leading to osmotic imbalance and stress which hinders plant growth. In addition, abiotic stressors increase the production of ROS and induce phytotoxicity by negatively impacting protein structure and functions (Baral and Izaguirre-Mayoral, 2017; Mukhtar et al., 2018; Komaresofla et al., 2019).

Naturally, plant cell organelles *viz*., chloroplasts, peroxisomes and mitochondria help in producing ROS, with hydrogen peroxide and oxygen radicals being produced in the mitochondria. Hydrogen peroxide and oxygen are produced in the chloroplast (Jalil and Ansari,

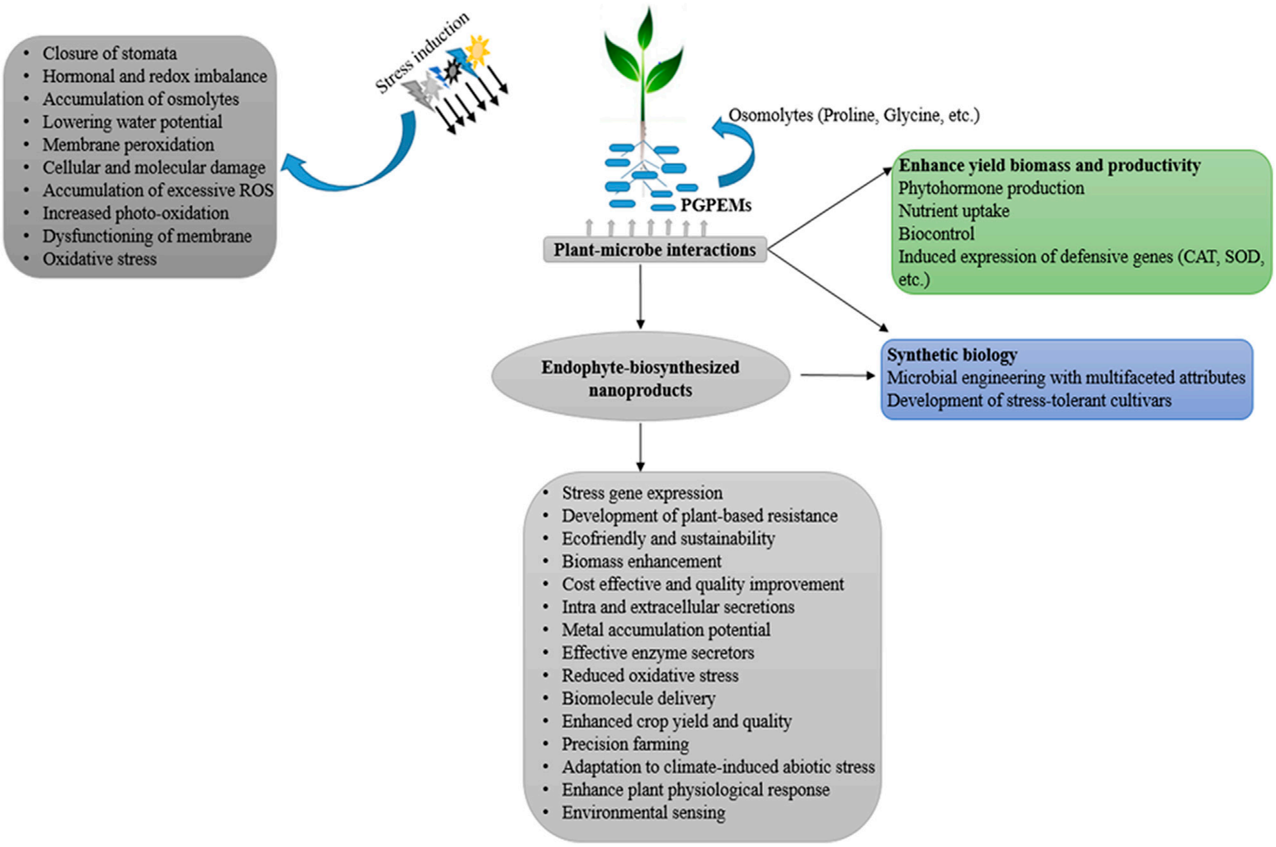

FIGURE 1
Concept of endophyte interactions and biosynthesized nanoproducts to alleviate abiotic stress and enhance crop yield.

2019). Using peroxidase dismutase, the peroxides are transformed into hydrogen peroxide (H_2O_2). The oxidation process involved in the conversion of xanthine and hypoxanthine to uric acid is achieved in the peroxisomal matrix using xanthine oxidase to generate oxygen radicals (Halliwell and Gutteridge, 2015; Jalil and Ansari, 2019). These radicals destroy cell biomolecules, such as DNA, carbohydrates, lipids, and proteins, resulting in cell death.

Plants can rapidly acclimatize to an abrupt change in the environment, such as unwanted abiotic conditions. A shift in the soil condition alters plant metabolic equilibrium and causes plant cells to modify genetic and metabolic processes (Tuteja and Mahajan, 2007; Tuteja and Sopory, 2008; Simontacchi et al., 2015). Plants then activate defense mechanisms needed to relieve unwanted stress conditions, reprogramming metabolic processes within the plant cell, thus facilitating bio-physicochemical relief of abiotic stress conditions (Massad et al., 2012; Mickelbart et al., 2015; Yolcu et al., 2016).

Due to uncertainty surrounding the mechanism of action of metallic NPs, different hypothetical mechanisms were frequently mentioned in different studies. These include that:

a) NPs aggregate and dissolve the cell membrane, resulting in the alteration of cell permeability and dissolution of the PMF—Proton motive force (McQuillan, 2010; Singh et al., 2019).
b) ROS—Reactive oxygen species that help in the destruction of the cellular structure are produced by metallic NPs and ions (Singh et al., 2019).
c) Absorption of metal ions by cells helps in the degradation of intracellular ATP and the disruption of DNA synthesis (Singh et al., 2019).

Oxidation reactions attributed to metallic ions in cells induce responses such as ROS—due to cell signal differentiation and cell death (Mueller et al., 2005). The integral components of ROS include peroxomonocarbonate ($HOOCO_2^-$), peroxynitrate (O_2NOO^-), peroxynitrite ($ONOO^-$), nitric compounds, hypochlorite and hypochlorous acids, peroxyl (RO_2^-), and hydroperoxyl (HO_2^-), and other oxygen-related compounds (Wu et al., 2014). With the catalysis of superoxidase dismutase (SOD), oxygen ions have a short lifespan due to instant reduction. NADPH—nicotinamide adenine dinucleotide phosphate oxidase in the mitochondria induces lipid peroxidation of the cell membrane (Singh et al., 2019). SOD initiates the complete conversion of oxygen into hydrogen peroxide. Physiologically, different detoxifying enzymes *viz*., glutathione peroxidase, catalase, SOD and antioxidants (flavonoids, vitamin E and ascorbic acids) modulate intracellular stages. Meanwhile, ROS activated by NPs of either CuO, ZnO or Ag plays a crucial role in genotoxicity. Oxidative stress degraded genetic materials are associated with different biological mechanisms *viz*., mutagenesis. Stress activation due to oxidative species results in nanotoxicity and the accumulation of oxidative stress leading to DNA destruction (Fu et al., 2014). The destruction of DNA because of OS; involves the breakage of single and double-stranded sugar bases, the generation of basic sites and DNA-protein crosslinks. Closely, hydroxyl radicals cause rapid damage to cells, whereas, from a distance, less-reactive ROS may interact easily (Fu et al., 2014).

Microbe-induced abiotic stress tolerance

An adaptation used in the process of abiotic stress tolerance is often referred to as induced systemic tolerance/resistance (IST/ISR). The intrinsic genetic and metabolic potential of microbes contribute immensely to the relief of plants from abiotic stresses (Gopalakrishnan et al., 2015). The role of endosphere and rhizosphere inhabitants belonging to different genera *viz*., *Cyanobacteria* (Singh et al., 2011), *Trichoderma* (Pandey et al., 2016; Igiehon and Babalola, 2021), *Burkholderia* (Naveed et al., 2014a; Naveed et al., 2014b), *Methylobacterium* (Meena et al., 2012), *Bradyrhizobium* (Tittabutr et al., 2013), *Enterobacter* (Sorty et al., 2016), *Bacillus* (Ashraf et al., 2004; Sorty et al., 2016), *Pantoea* (Sorty et al., 2016), *Rhizobium* (Igiehon and Babalola, 2021; Igiehon et al., 2021), *Azospirillum* (Omar et al., 2009), *Azotobacter*, and *Pseudomonas* (Ndeddy Aka and Babalola, 2016) have functional traits useful in improving plant growth under abiotic stresses. The functional role of *Trichoderma harzianum* in alleviating soil stresses through the upregulation of genes such as malonialdehyde, dehydrin, and aquaporin genes, has been reported by Pandey et al. (2016) on different serotypes of rice. Also, the synthesis of exopolysaccharides, antioxidants, protein defensins and phytohormones may be induced using plant growth-promoting rhizobacteria. Most of these functions are effective against drought and other abiotic stressors (Kaushal and Wani, 2016). Therefore, the effective productivity monitoring parameters, *viz*., screening, selection and inoculation of stress-mitigating microbes, can be helpful as a viable option to increase crop productivity to solve the problem of a growing world population with insufficient food (Akinola and Babalola, 2021). *Trichoderma harzianum* inoculation enhances the oil content of *Brassica juncea* inhibited by salinity stress and improves the plant's physiological traits, such as reducing sodium ion uptake, enhancing osmolyte synthesis, antioxidant accumulation, and facilitating the uptake of essential plant nutrients (Ahmad et al., 2015). Similarly, ACC deaminase production was shown to be responsible for the upregulation of monodehydroascorbate reductase in *B. juncea* (Brotman et al., 2013). Also, the addition of *Acinetobacter* sp. and *Pseudomonas* sp. have been used to increase the production of ACC deaminase and indole-3-acetic acid (IAA) in oat and barley grown in salinity-stressed soil (Chang et al., 2014). *Streptomyces* sp. strain PGPA39 has also been used to alleviate salinity stress in tomato plants (Palaniyandi et al., 2014). In *Arabidopsis*, wheat, and maize plants, *Burkholderia sp*., has been used to relieve plants and soil of salt and drought stresses (Naveed et al. (2014a); Naveed et al. (2014b); Pinedo et al. (2015).

There are a large number of microorganisms within proximity to plant tissues and across the vicinity of plant roots because the plant root exudates provide diverse metabolites and nutrients which attract beneficial microorganisms. These metabolites are crucial to the microbial presence surrounding and attached to plants (Akinola et al., 2021a; Akinola and Babalola, 2021) with chemoattraction being associated with microbial movement toward these compounds (Meena et al., 2017). While utilizing these plant exudates, plant growth-beneficial microorganisms associated with the plant endosphere induce both direct and indirect mechanisms, such as biocontrol agents, phytostimulation, and biofertilization (Hayat et al., 2010; Akinola and Babalola, 2020).

Indirect mechanisms of plant growth promotion include the production of antimicrobial agents, hydrogen cyanide (HCN), and antibiotics, which exert antagonistic effects against plant pathogens. Direct mechanisms include nitrogen fixation, stimulation of plant hormone synthesis, solubilization of potassium and phosphorus, synthesis of siderophores which facilitate iron uptake, and sequestration of zinc and other micro-and macronutrients from the soil (Meena et al., 2017). In addition, many plant-associated microbes also induce systemic resistance against various phytopathogens triggered by plant secondary metabolites (Meena et al., 2017; Omomowo and Babalola, 2019). Apart from bacteria, mycorrhizal fungi are also good to plant growth promoters. These include both vesicular-arbuscular mycorrhiza (VAM) and other ectomycorrhizal fungi (Akinola and Babalola, 2021). These fungi use their extensive hyphal networking to increase plant nutrient uptake. For instance, in studies by Sun et al. (2010) and Baltruschat et al. (2008), an endophytic fungus—*Piriformospora indica* was used to improve drought and salinity tolerance in Chinese cabbage and barley, respectively. These processes were achieved by improving both physiological traits and the level of plant antioxidants. At some point, microbes activate systemic or local stress responses in plants under abiotic stress. In other instances, they activate direct

TABLE 1 Examples from the recent literature of the effect of plant growth-promoting microbes in the relief of plant stress.

Crop type	Adopted organism(s)			Stress	Inference	References
	Fungi	Bacteria	Archaea			
Wheat		*Bacillus pumilus* (FAB10)		Salinity	Enhanced wheat growth with improvement in photosynthesis, plant tissue proline content, and transpiration	Ansari et al. (2019)
Paddy plants		*Curtobacterium albidum* (SRV4)		Salinity	Improved plant proline content, membrane solubilization index, and photosynthetic pigment efficiency	Vimal et al. (2019)
Wheat		*Bacillus megaterium* + *B. licheniformis* + Fulvic acid		Alkalinity	Improved plant growth, reduction in soil cadmium, increase in organic matter	Li et al. (2019)
Guinea grass (*Megathyrsus maximus*)		*Bacillus* spp.		Drought	Increased accumulation of proline and glutathione reductase activity	Moreno-Galván et al. (2020)
Maize (*Zea mays* L.)		*Azotobacter salinestris*, *A. chroococum*		Drought	Increase in shoot dry weight, chlorophyll content, plant height and N, P, Fe concentration	Shirinbayan et al. (2019)
Lettuce *Latuca sativa*		*Curtobacterium herbarum* (CAH5)		Drought	Reduction in oxidative stress and lipid peroxidation	Silambarasan et al. (2019)
Common ice-plant (*Mesembryanthemum crystallinum* L.)		*Streptomyces diastaticus* WZ902 (LC390202), *Bacillus subtilis subsp. Inaquosorum* LM03-B (LC390203)		Salinity	Increased plant growth, and elongated roots. ACC deaminase activity, phosphorus solubilization, and siderophore production	Mahmood et al. (2019)
Sorghum and sudan grass seedlings on red mud	*Trichoderma asperellum* RM-28			Sodic/saline-Alkalinity	Decreased pH and EC of red mud, and improved plant chlorophyll content, growth, and oxidative stress	Anam et al. (2019)
Salicornia sp		*Staphylococcus* sp. (rhizosphere strain) + *Staph*. sp. (endophytic strain)		Salinity	Enhanced growth and high salt tolerance with both strains. Increased phosphate solubilization and IAA production	Komaresofla et al. (2019)
Thale cress *Arabidopsis thaliana*		*Pantoea stewartii* JZ2, *Bacillus* sp. JZ34, *Microbacterium barkeri* JZ37, *Arthrobacter* sp. JZ12, *Cellulomonas* sp. JZ18		Salinity	Endophytic bacteria from the desert help reduce Na^+/K^+ ratio and increase plant shoot and root biomass	Eida et al. (2019)
Sulla carnosa		*Actinobacter* sp. (Br3) + *Pseudomonas putuda* (Br18) + *Curtobacterium* sp. (Br20)		Salinity	Enhanced soluble sugar, oxidative enzyme activities, ameliorated induced soil salinity and increased plant growth	Hmaeid et al. (2019)
Wheat (*Triticum aestivum*)		1-aminocyclopropane-1-carboxylate dismutase (ACCD)-producing *Klebsiella* spp. (8IJA, 27IJA)		Salinity	Increase in plant biomass and superoxidase dismutase activity	Acuña et al. (2019)
Maize (*Zea mays* L.)	*Glomus tortuosum*			Salinity	Increased crop output, chlorophyll content, and rubisco activity	Xu et al. (2018)
Finger millet (*Eleusine coracana L. Gaertn*)		*Pseudomonas* spp.		Drought	Improved growth performance and foliar nutrient content and increased antioxidant properties	Chandra et al. (2018)

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TABLE 1 (*Continued*) Examples from the recent literature of the effect of plant growth-promoting microbes in the relief of plant stress.

Crop type	Adopted organism(s)			Stress	Inference	References
	Fungi	Bacteria	Archaea			
Ice plant (*Aizoaceae* spp.)		*Mesembryanthemum crystallinum*		Salinity	Increase in rubisco activity, crop output, and chlorophyll content	Zhang et al. (2018)
White clover (*Trifolium repens*)		*Azospirillum brasilense*		Salinity	Polyphenols and phenol production	Khalid et al. (2017)
Lettuce (*Latuca sativa*)		*Curtobacterium herbarum* (CAH5)		Drought and Aluminium stress	Increased plant root and shoot growth, enhanced plant growth under 4-nitroaniline	Silambarasan and Vangnai (2017)
Maize (*Zea mays* L.)		*Pseudomonas putida* (FBKV2)		Drought	Increase in root length and dry biomass	Vurukonda et al. (2016)
Mung beans (*Vigna radiata*)		*Bacillus drentensis*, *Enterobacter cloacae*		Salinity	Increase in plant height, seed yield, dry biomass, chlorophyll content, water absorption rate, transpiration, and salt tolerance	Mahmood et al. (2016)
Tomato (*Solanum lycopersicum*)		*Arthrobacter* strains (TF1, TF7), *Bacillus megaterium* (TF2, TF3)		Salinity	Increase in seedling length, vigor index, dry weight, and tomato seed germination	Fan et al. (2016)
Maize (*Zea mays* L.)		*Chryseobacterium humi* ECP37 + *Pseudomonas reactans* EDP28		Salinity	Increased seedling and plant yield	Moreira et al. (2016)
Maize (*Zea mays* L.)	Glomus etunicatum +	*Methylobacterium oryzae* CBMB20			Improved crop yield after the *in vivo* application of organisms	Lee et al. (2015)
Garden thyme (*Thymus vulgaris*)		*Enterobacter* sp. + *Bacillus* sp. + *Bacillus thuringensis* + agrowaste		Drought	Optimal nutrition and better physiological traits compared to control	Armada et al. (2015a)
French lavender (*Lavandula dentate*), Common sage (*Salvia officinalis*), Lavender-cotton (*Santolina chamaecyparissus*)						
Maize (*Zea mays* L.)	Consortium of AMF	*Bacillus thuringensis*		Drought	Increased plant growth, photosynthesis efficiency, decreased oxidative damage to lipids, increased accumulation of proline and nutrient	Armada et al. (2015b)
Chicken pea (*Cicer arietinum*) cultivars BG-3629, BG-1003		*Pseudomonas putida*		Drought	Conferred drought tolerance by improving several biochemical and physiological parameters	Tiwari et al. (2016)
Mung beans (*Vigna radiata*)		*Pseudomonas putida* (SB21)		Acidity	The large increase in plant growth	Saluja et al. (2014)
Mung beans (*Vigna radiata*)		*Comamonas* spp. (SB20)		Alkalinity	Increase in plant yield after exposure to alkaline soil	Saluja et al. (2014)
White clover (*Trifolium repens*)	Arbuscular mycorrhiza fungi (AMF) +	Combination of any two of *Bacillus thuringensis*, *Rhizophagus intraradices*, *Pseudomonas putida*		Drought	Increased root and shoot weight with high superoxidase dismutase (SOD) activity	Ortiz et al. (2015)
Common bean (*Phaseolus vulgaris*)		*Pseudomonas fluorescens*		Salinity	Na^+ exclusion, proline production, increased SOD, catalase activity and shoot biomass	Younesi and Moradi (2014)

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TABLE 1 (*Continued*) Examples from the recent literature of the effect of plant growth-promoting microbes in the relief of plant stress.

Crop type	Adopted organism(s)			Stress	Inference	References
	Fungi	Bacteria	Archaea			
Barley (*Hordeum vulgare*), Oats (*Avena sativa*)		*Pseudomonas* sp., *Acinetobacter* spp.		Salinity	Increased IAA and ACC deaminase production	Chang et al. (2014)
Rice sensitive to salt (GJ-17)		*Bacillus pumilus*, *Pseudomonas pseudoalcaligenes*		Salinity	Increased SOD activity and reduced lipid peroxidase	Jha and Subramanian (2014)
Tomato (*Solanum lycopersicum*)		*Streptomyces* sp. (PGPA39)		Salinity	Phosphate solubilization, increased plant yield, IAA production, and ACC deaminase activity	Palaniyandi et al. (2014)
Mung beans (*Vigna radiata* L)		*Pseudomonas* sp. + *Rhizobium* sp		Salinity	Increased ACC deaminase activity and IAA production	Ahmad et al. (2013)
Wheat (*Triticum aestivum*)		*Serratia ficaria*, *Enterobacter cloacae*, *Pseudomonas fluorescens*, *P. putida*		Salinity	Improved nutrient uptake and enhanced plant growth	Nadeem et al. (2013)
Rice (*Oryza sativa*)		*Bacillus amyloliquefaciens* NBRISN13 (SN13)		Salinity	Increased colonization of osmoprotectant utilizing microbes to induce salt tolerance in rice	Nautiyal et al. (2013)
Wheat (*T. aestivum*)		*Halobacillus* spp *Bacillus halodenitrificans*		Salinity	Increase in dry weight and root length of the plant	Ramadoss et al. (2013)
Tomato (*Solanum lycopersicum*)		*Bacillus pumilis*, *Bacillus subtilis*		Salinity	High PGP traits, vigor index, and ability to tolerate saline soil	Damodaran et al. (2013)
Wheat (*T. aestivum*)		*Streptomyces* sp		Salinity	Increase in N, P, Fe, and Mn of the wheat shoots and alleviation of salt inhibition	Sadeghi et al. (2018)
Rice (*Oryza sativa*)		*Bacillus* sp., *Alcaligenes* sp., *Ochrobactrum* sp		Salinity	Increased germination, root, shoot growth, and chlorophyll content. ACC deaminase reduces ethylene production under salt stress	Bal et al. (2013)
Groundnut (*Arachis hypogaea* L.)		*Haererohalobacter* sp. (JG-11), *Bravibacterium casei* (JG-08), *Brachybacterium saurashtrense* (JG-06)		Salinity	Increase in phosphorus, nitrogen content, High Ca^{2+} and balanced K^{+}/Na^{+} ratio. ACC deaminase activity	Shukla et al. (2012)
		Raoultella planticola Rs-2		Salinity	ACC deaminase activity and high plant yield	Wu et al. (2012)
Mung bean (*Vigna radiata*)		*Rhizobium phaseoli* + PGPR (*Pseudomonas fluorescens* (MK20), *P. syringae* MK1)		Salinity	Increased efficiency of water use and ACC deaminase activity	Ahmad et al. (2012b)
Wheat (*T. aestivum*)		*Bacillus* sp. (SKU-3), *Paenibacillus* sp. (SKU-11)		Salinity	Exopolysaccharides produced by test organisms mitigate soil salinity	Upadhyay et al. (2011)
Sunflower treated with NaCl		*Pseudomonas fluorescens* biotype F, *P. fluorescens* $CECT378^{T}$		Salinity	Balanced K^{+}/Na^{+} ratio, siderophore, and IAA production	Shilev et al. (2012)
Wheat (*T. aestivum*)		*Pseudomonas extremorientalis* (TSAU6), *P. aureantiaca* (TSAU22), *P. extremorientalis* (TSAU20)		Salinity	Production of phytohormones such as gibberellin, auxin, zeatin, and alleviation of salinity inhibition	Egamberdieva (2009)
Soybean (*Glycine max*)		*P. putida* (62BN)		Acidity	Reduction in cadmium concentration and increased plant growth in acidic soil	Rani et al. (2009)
Soybean (*Glycine max*)		*P. monteilli* (97AN)		Alkalinity	Increased plant growth and amelioration of soil alkalinity	Rani et al. (2009)

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TABLE 1 (*Continued*) Examples from the recent literature of the effect of plant growth-promoting microbes in the relief of plant stress.

Crop type	**Adopted organism(s)**			**Stress**	**Inference**	**References**
	Fungi	**Bacteria**	**Archaea**			
Wheat seedling		Exopolysaccharides producing bacterial strains *viz.* *Aeromonas hydrophila/caviae* (MAS-765), *Bacillus insolitus* (MAS17), *Bacillus* sp. (MAS617, MAS620, MAS820)		Salinity	Increased physiological properties (root, shoot, and yield) in a saline environment and reduced Na + uptake by the plant	Ashraf et al. (2004)
Indian mustard (*Brassica juncea* L.) Barley (*Hordeum vulgare*)	*Trichoderma harzianum* *Piriformospora indica*			Salinity	An antioxidative defense system was used to mitigate the effect of NaCl on plant	Ahmad et al. (2015)
				Salinity	Microorganism induces desaturation of fatty acids in leaves, attenuated NaCl-induced lipid peroxidation and metabolic heat efflux useful in salt tolerance	Baltruschat et al. (2008)
Arabidopsis thaliana	*Trichoderma* spp.			Salinity	Activation of antioxidative compounds *viz.* ACC deaminase for tolerance against salt stress	Brotman et al. (2013)
Soybean (*Glycine max*)	AMF	*Rhizobium* spp		Drought	The synergy between AMF and *Rhizobium* spp. Relieve plants of drought stress by increasing the level of plant proline	Igiehon and Babalola (2021)
Rice (*Oryza sativa* L)		*Bacillus pumilus*		Salinity and heavy metal	The bacterium reduces the antioxidative activity of the plant due to the limited uptake of Na^+	Khan et al. (2016)
Rice (*Oryza sativa* L)	*Trichoderma harzianum* Th-56			Drought	*T. harzianum* modulates the activation of essential compounds such as lipid, peroxidase, SOD, and proline, needed to improve drought tolerance in tice	Pandey et al. (2016)
Micro Tom Tomato		*Streptomyces* sp. PGPA 39		Salinity	Reduction in leaf proline content increased chlorophyll content and plant biomass after inoculating the plant with *Streptomyces* sp	Palaniyandi et al. (2014)
Piptatherum miliaceum L. *Thymus vulgaris* Letc.	AMF	*Bacillus thuringensis*		Drought	Decreased stomatal conductance, electrolyte leakage, proline activity, increased water content, and nutrient uptake	Ortiz et al. (2015)
Brassica juncea		*Pseudomonas aeruginosa*, *Bacillus subtilis*, *Alcaligenes faecalis*		Heavy metal	Organisms reduce the uptake, toxic effect of heavy metals and also increase plant growth	Ndeddy Aka and Babalola (2016)
Maize (*Zea mays* L)		Endophytes *Burkholderia phytofirmans* (PsJN), *Enterobacter* sp. FD17		Drought	Endophytes relieve the effect of drought by increasing root-shoot biomass, chlorophyll content, photosynthesis, leaf area, and other physiological traits	Naveed et al. (2014b)
Wheat		*Burkholderia phytofirmans* PsJN		Drought	*B. phytofirmans* increases ionic balance, antioxidant level, nutrient uptake, and	Naveed et al. (2014a)

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TABLE 1 (*Continued*) Examples from the recent literature of the effect of plant growth-promoting microbes in the relief of plant stress.

Crop type	Adopted organism(s)			Stress	Inference	References
	Fungi	Bacteria	Archaea			
					protein concentration in grains	
Legume		*Bradyrhizobium, Rhizobacteria* containing stress-induced ACC deaminase		High temperature, Drought, and salinity	Synergism between used organisms mitigated different plant stressors by adjusting the expression of ACC deaminase to varying levels of stress conditions	Tittabutr et al. (2013)
Chinese cabbage	*Piriformospora indica*			Drought	Plastid-localized CAS proteins, drought-related genes and antioxidant enzymes were stimulated	Sun et al. (2010)
Rice (*Oryza sativa* L.)		*Pseudomonas putida* MTCC102		Nutrient deficiency	*P. putida* strain relieved the stress of iron deficiency	Sharma et al. (2013)
Rice (*Oryza sativa* L.)		*Pseudomonas* strains PF1, TDK1		Salinity	*Pseudomonas* strains relieved the plant of salt stress, increased physiological parameters, such as root and shoot length, dry weight, and plant height	Sen and Chandrasekhar (2014)
Arabidopsis thaliana		*Burkholderia phytofirmans* PsJN		Salinity	*B. phytofirmans* induces long-term transcriptional and metabolic changes in plants, suggesting the need to understand spatiotemporal mechanisms associated with the process	Pinedo et al. (2015)
Wheat (*Triticum aestivum* L.)		*Sinorhizobium* strains, *Rhizobium* sp., *Pseudomonas* sp., *Enterobacter* sp., *Acinetobacter* sp., *Bacillus, Pantoea* sp		Salinity	Plant growth-promoting bacteria isolated from halophytic weeds help germination and seedling wheat growth under saline stress	Sorty et al. (2016)
Chinese cabbage	*Piriformospora indica*			Drought	The upregulation of the expression level of drought-related genes, *viz.* RD290A, ANACO72, CBLI, and DREB2A in the leaves of Chinese cabbage help relieve plants of imposed drought stress	Sun et al. (2010)
Barley (*Hordeum vulgare* L.)		*Hartmannibacter diazotrophicus* E19^{T}		Salinity	*H. diazotrophicus* increased the root and shoot ratio of barley under salt stress. This growth promotion was associated with ACC-deaminase production	Suarez et al. (2015)

responses to support plant growth and development. This complex and multipronged action of soil microbes makes them a vital and viable choice for disease suppression and abiotic stress control in plants (Franken, 2012; Meena et al., 2017).

Several mechanisms have highlighted the enormous benefit of plant-associated microbiomes (Kushwaha et al., 2020; Glick and Gamalero, 2021; Adeleke and Babalola, 2022). The microbes found in the plant root environment typically belong to the genera *Pseudomonas*, *Klebsiella*, *Aeromonas*, *Azotobacter*, *Enterobacter*, *Bacillus*, *Azospirillum*, and *Achromobacter* (Ortiz et al., 2015; Kaushal and Wani, 2016; Sorty et al., 2016; Babalola et al., 2021; Fasusi et al., 2021) (Table 1).

All rhizosphere and endosphere bacteria with the ability to maintain plant growth under different adverse soil conditions are referred to as plant growth-promoting bacteria (PGPB) (Agri

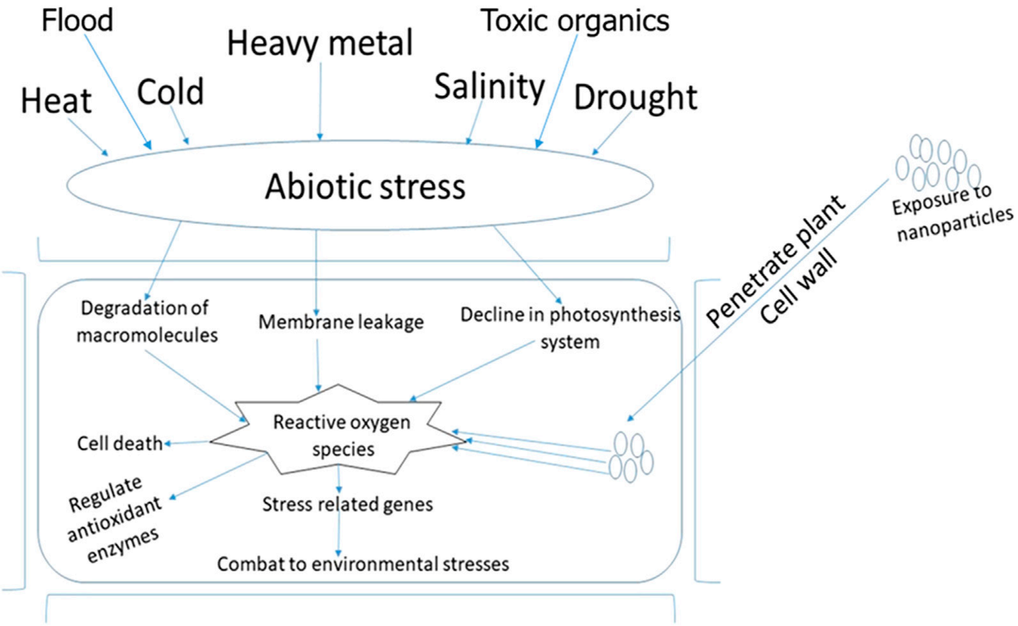

FIGURE 2
The use of nanotechnology to suppress abiotic stress conditions in a plant cell.

et al., 2022). There are other mechanisms plant microbes use to promote plant growth and development. IAA is produced to improve plant root development (Meena et al., 2017) where auxins initiate root growth and cell elongation. However, the high production of auxin may negatively affect root growth (Sorty et al., 2016; Akinola and Babalola, 2020). High auxin secretion also has drawbacks because of the increased ethylene production. In addition, the enzyme ACC deaminase is a key component in lowering the stress ethylene that results from both biotic and abiotic stress (Glick, 2004).

The mechanisms mentioned above have been reported in rhizosphere bacteria and fungi with enhanced phytohormones production for sustainable plant growth (Belimov et al., 2007; Ojuederie et al., 2019; Akinola et al., 2021c). Other studies have employed rhizobiomes to mitigate environmental stresses and improve the growth of crop plants in maize (Rojas-Tapias et al., 2012; Akinola et al., 2021a; Chaudhary A. et al., 2021), rice (Sharma et al., 2013), soybean (Sen and Chandrasekhar, 2014), and barley (Suarez et al., 2015).

The use of nanomaterials to relieve abiotic plant stresses

Plants possess several mechanisms needed to cope with unwanted soil conditions, including heat stress, drought, flooding, salinity, and chilling. Several researchers have studied molecular and cellular plant responses to abiotic stress (Gepstein and Glick, 2013; Ali and Glick, 2019; Santoyo et al., 2021a). Primarily, plants respond to abiotic stress using methods, such as an increase in MAPK (mitogen-activated protein kinase), abscisic acid, ROS, increased intracellular messenger *viz*., polyphosphate, inositol and raised Ca^{2+} in the cytoplasm as shown in Figure 2.

Meanwhile, stress relief responses, such as regulation of the expression of specific stress genes, and the proteins involved in the protection from cellular damage are involved in the advanced level of plant response. In addition, secondary metabolites ensure physiological processes to reduce abiotic stress conditions by activating the biosynthesis of polyamines signal transduction, ROS-induced photosystem protection and stabilizing cellular structure (Oh et al., 2009; Jalil and Ansari, 2019).

In mitigating soil stresses, the plant cell wall helps in plant adaptation and guides against stress perception. Induced peroxidases modify plant cell walls, which bring together oxidative stress and ROS when in contact with plant stressors (Rouet et al., 2006; Daudi et al., 2012). When plants encounter oxidative stress, immediate defense responses, such as the regulation of gene expression, enzyme production, phenylpropanoid aggregation, and ROS are produced (Daudi et al., 2012; Jalil and Ansari, 2019).

Although plants develop various mechanisms to initiate responses against adverse conditions. Nevertheless, their responses may differ even among the same plant species. Consequently, augmentation of stress tolerance in plants and identification of tolerant plant material remains conservative and ecofriendly methods towards sustainable agricultural practices and crop production (Akinola et al., 2022; Chaudhary et al., 2022). Nanoscience is an emerging multi-disciplinary area that involved the use of nanomaterials in different fields at the nano-level. The most promising application of nanoscience could be exploited in agroecosystem practices, food processing and packaging materials. In the current scenario, nanomaterials can be used as a tool to effectively promote plant growth and also ameliorate plant stressors (Saxena et al., 2016; Chaudhary et al., 2021b).

A lot has been done on the use of nanotechnological approaches to stress responses (Shabnam et al., 2014; Tripathi et al., 2015; Singh and Lee, 2016). The effect of NPs on sustainable plant growth and development is concentration-dependent, which also increases antioxidant enzyme activity. For example, in a study to assess the effect of TiO_2 NPs on onion seedlings, TiO_2 NPs increased the activity of the superoxidase dismutase enzyme (Laware and Raskar, 2014). Meanwhile, a drastic change in the physiological traits of the onion plant was noticed with an increased concentration of TiO_2 NPs (Laware and Raskar, 2014). Under these conditions, the activities of the catalase and amylase enzymes decreased at lower concentrations of TiO_2. In another study by Changmei et al. (2002), SiO_2 and TiO_2 NPs showed significant positive effects on the growth and sprouting of *Glycine max* seedlings.

Effect of NPs on heavy metal stressed plants

Contamination of the plant-soil environment by metallic ions is a severe menace to sustainable agricultural practices worldwide. Heavy metal stress increases plant toxicity, thus leading to retarded plant growth (Chibuike and Obiora, 2014; Jalil and Ansari, 2019). This happens due to decreased enzymatic activities induced by a continuous decrease in essential nutrients available in the soil (Sharma et al., 2012). Furthermore, heavy metal ions induce ROS production affecting the plant's physiological properties; *viz*., membrane permeability reduction, cell structure deformation, and degradation of available plant cell protein. To relieve the constraints attributed to heavy metal stress, plants induce defense mechanisms including the production of polyphosphates, organic acids, and metal chelates, which all reduce the influx of metal ions and activate the synthesis of antioxidants to lower ROS production. The activation of these defense mechanisms ensures resistance against heavy metal stress. Moreover, the use of synthesized NPs can reduce the burden of phytotoxicity induced by heavy metals on plants (Sharma et al., 2012; Gunjan and Zaidi, 2014; Tripathi et al., 2015).

Because of the small size and surface area of synthesized NPs, they can easily penetrate plant cells and retain a high affinity for metallic ions. In a study by Worms et al. (2012), it was reported that quantum dots (i.e., the nanoparticles of a semiconductor) reduce Pb and Cu accessibility to plant cells. The report of Singh and Lee (2016) showed TiO_2 NPs reduce Cd toxicity and improve physiological traits, *viz*., plant growth, and photosynthetic rate. The study of Li and Huang (2014) with *Brassica juncea* revealed the effect of hydroxyapatite NPs in the relief of cadmium toxicity. Similarly, synthesized SiNPs helped to reduce chromium toxicity in peas (Tripathi et al., 2015). Shabnam et al. (2014) also discovered that the treatment of cowpea with AuNPs induces a reduction of Au ions to a nontoxic form by phenolic compounds of cowpea seeds (Table 2).

Effect of NPs on heat stress

Exposing a plant to an extreme temperature for a long period results in retarded plant growth and development. Heat stress reduces photosynthetic and chlorophyll content, membrane ion leakage, protein degradation, and lipid depletion. This is because an increase in ROS generation induces oxidative stress (Wahid, 2007; Karuppanapandian et al., 2011; Prasad et al., 2011). Haghighi et al. (2014) reported the effect of low concentrations SeNPs in reducing heat stress by stimulating the photosynthetic ability of plants, increasing hydration, and improving plant growth.

Anti-oxidative properties of the plant have also been improved at low SeNPs levels, while high concentrations of SeNPs induce oxidative stress (Haghighi et al., 2014). Plants induce the production of molecular chaperones and heat shock proteins during heat stress to resist oxidative stress (Hasanuzzaman et al., 2013; Hasanuzzaman et al., 2014).

Furthermore, carbon nanotubes, such as HSP90 have been used to upregulate genes involved in heat shock protein synthesis. A study by Zhao et al. (2012) showed that the exposure of maize to CeO_2NPs upregulates HSP70 and generates large amounts of hydrogen peroxide.

Effect of NPs on salinity stress

Salinity is an important abiotic stressor that deteriorates and limits the output of food crops. Owing to the susceptibility of most plants (i.e., lycophyte category) to salt stress, the majority of plant products are negatively affected, thereby reducing their economic value (Munns and Tester, 2008; Akinola and Babalola, 2020). Salinity stress hinders both physiological and biochemical processes associated with the sprouting of the plant.

Salinity causes one or more of the following: specific ionic toxicity, nutritional imbalance, and a reduced osmotic potential (Jalil and Ansari, 2019). In addition, some other critical physiological processes, such as lipid metabolism, protein synthesis, and photosynthesis, are often negatively affected (Parida and Das, 2005). The use of nano-based-fertilization

TABLE 2 Some recent reports of the effect of nanotechnology in alleviating plant stressors.

Nanoparticle	Characterization	Plant stress	Size of the nanoparticle	Test plant	Inference	References
CuNPs	SEM, XRD	Drought	30 nm–40 nm	Maize (*Zea mays* L.)	CuNPs increased carotenoid, chlorophyll, and anthocyanin levels in maize grown under drought stress. Also, reactive oxygen species (ROS) decreased as a result of the activities of scavenging enzymes	Van Nguyen et al. (2022)
MgNPs	SEM, XRD	Lead-induced	≈20 nm	*Daucus carota*	MgNPs help to detoxify ROS to mitigate Pb-induced stress and improve plant growth and nutrient uptake	Faiz et al. (2022)
Chitosan-Selenium NPs (Cs-SeNPs)	XRD, SEM, TEM	Salinity	≈50 nm	Bitter melon (*Momordica charantia*)	Cs-SeNPs alleviated the effect of salinity stress by reducing Na^+ aggregation, MDA and H_2O_2 oxidants and increased relative water content, K^+, proline concentration and antioxidant enzyme activity in plant	Sheikhalipour et al. (2021)
CeNPs	XRD, SEM	Salinity	10 nm	Rice (*Oryza sativa* L.)	CeNPs enhanced nitric oxide production by activating the transcription of *NIA2*-encoding nitrate reductase and controlling dephosphorylation of its protein which resulted in NO production and plant tolerance to salt	Zhou et al. (2021)
FeNPs	FTIR, XRD, SEM, TEM, EDS	Drought and Cadmium toxicity	18 nm–94 nm	Rice (*Oryza sativa* L.)	FeNPs decreased ROS and improved plant biomass, nutrient acquisition, photosynthesis efficiency, and other plant physiological traits. More also, Cd transporter genes (*OsLCT1*, *OsHMA2*, *OsHMA3*) were curtailed in FeNPs-treated rice plant	Ahmed et al. (2021)
SiNPs	XRD, SEM, TEM	Salinity	< 50 nm	Lentil (*Lens culinaris* Medik.)	SiNPs improved the physiological traits *viz.* root length, shoot length, seedling fresh and dry weight of lentil under salinity stress	Sabaghnia and Janmohammadi (2015)
ZnNPs	SEM, XRD	Drought	10 nm–30 nm	Soybean (*Glycine max*) seeds	ZnNPs were effective on seedling growth in water stress conditions	Sedghi et al. (2013)
AgNPs + 2, 4-dichlorophenoxyacetic acid	XRD, SEM	Oxidative	10 nm–40 nm	*Vigna radiata* L	The synergistic effect of AgNPs and 2, 4-dichlorophenoxyacetic acid inhibited senescence in plants under oxidative stress	Karuppanapandian et al. (2011)
TiNPs	SEM, XRD	Cold	7 nm–40 nm	*Cicer arietinum* L	TiNPs increased cold tolerance *via* an improved redox status of plant	Mohammadi et al. (2013)
SiNPs	SEM, UV-Vis, XRD	Heavy metal	10 nm–30 nm	*Pisum sativum* L	SiNPs protected plants against phytotoxicity induced by chromium and improved plant growth	Tripathi et al. (2015)
CeNPs	SEM, XRD	Heat shock and lipid peroxidation	10 nm ± 1 nm	*Zea mays* L	Improved plant growth under heat shock	Zhao et al. (2012)
TiNPs	SEM, XRD, TEM	Heavy metal	< 100 nm	*Glycine max*	TiNPs increased Cd uptake and minimize stress induced by Cd on soybean	Singh and Lee (2016)

(Continued on following page)

TABLE 2 (*Continued*) Some recent reports of the effect of nanotechnology in alleviating plant stressors.

Nanoparticle	Characterization	Plant stress	Size of the nanoparticle	Test plant	Inference	References
SiNPs	XRD, SEM, TEM	Salinity	20 nm–30 nm	Basil (*Ocimum basilicum*)	Significantly increased the morphological and physiological traits of plants under salt stress	Kalteh et al. (2018)
Single-walled carbon nanotubes (SWNTs)	ICP-MS, SEM	Drought	10 nm–20 nm	*Arabidopsis thaliana*	Plant nanotubes augmented photosynthetic and biochemical sensing	Giraldo et al. (2014)
TiNPs	SEM, TEM	Drought	20 nm–30 nm	Wheat	TiNPs increased the agronomic traits of plants under drought stress	Jaberzadeh et al. (2013)
TiNPs	SEM, XRD	Cold	7 nm–40 nm	*Cicer arietinum* L	TiNPs induced positive physiological effects on plant cells	Hasanpour et al. (2015)
SeNPs	XRD, SEM	High and low tempt	20 nm–30 nm	*Lycopersicum esculentum*	SeNPs helped to improve plant growth under high and low-temperature stress	Haghighi et al. (2014)
Hydroxyapatite (HAP) NPs	SEM, TEM	Heavy metal (Cd)	10 nm–40 nm	*Brassica chinensis* L. (bok choy)	HAPNP reduced Cd uptake and other effects of Cd-contaminated soil	Li and Huang (2014)
SiNPs	XRD, ICP-MS, SEM	Drought	10 nm–30 nm	Hawthorn (*Crataegus* sp.)	Increased plant biomass, xylem water potential, and malondialdehyde (MDA) content	Ashkavand et al. (2015)
SiNPs	TEM	Drought	10 nm–15 nm	Wheat grass (*Agropyron elongatum* L.)	SiO_2NPs significantly increased seed germination of tall wheat grass	Azimi et al. (2014)
TiNPs	TEM, SEM	Drought	≈21 nm	Onion (*Allium cepa*)	TiNPs enhanced seed germination and seedling growth. It also increased the activities of hydrolytic and antioxidant enzymes, amylase, protease, and SOD	Laware and Raskar (2014)
AgNPs	XRD, SEM	Salinity, cold, Heat and Drought	10 nm–30 nm	*A. thaliana*	AgNPs are a novel and eco-friendly method to control multiple abiotic stressors	Kohan-Baghkheirati and Geisler-Lee (2015)

Key (definition of abbreviations): SEM, scanning electron microscope, XRD—X-Ray Diffraction Crystallography, TEM, Transmission Electron Microscopy; FTIR, Fourier-Transform Infrared Spectroscopy; EDS, Energy Dispersive Spectroscopy, UV-Vis—Ultraviolet-Visible Infrared Spectrophotometry, ICP-MS, Inductively Coupled Plasma Mass Spectrometry; MDA, Malonaldehyde.

processes proffers solutions to relieve unwanted plant stresses and enhance the efficient use of plant resources. Less than 50% of applied chemical pesticides and fertilizers are used by the plant; the remainder often increases soil toxicity. This problem and many other growth-impeding factors may be effectively resolved using nanoscience (Martínez-Ballesta et al., 2016). For instance, the use of SiNPs and Si-fertilizer has a sustainable effect on the morphological and physiology of basil plants (*Ocimum basilicum*) under salinity stress. The results of this study suggested that the change in the physiological traits may be a result of tolerance induction in the basil plant, which helps to mitigate the effect of salt stress (Kalteh et al., 2018). Many other studies have shown that SiO_2NPs can relieve the effect of salinity stress. For example, Haghighi et al. (2014) and Sabaghnia and Janmohammadi (2015) showed the positive effects of SiNPs on *Lens culinaris* Medik. Under salinity stress, SiNPs was able to induce a significant increase in the growth of *Lens culinaris* Medik seedlings and the germination of seeds. Introducing SiNPs not only enhances early seedling growth and seed germination but also improves other growth features associated with the plant under salinity stress. In the same study by Haghighi et al. (2014) on tomatoes, SiO_2NPs decreased ionic toxicity of the stressor leading to a substantial increase in the shoot, root fresh and dry weight of tomato plants under salt stress. Gao et al. (2006) showed the effect of SiO_2NPs on maize plants after long exposure to salinity stress. Applying SiO_2NPs enhanced the sprouting of the plant (Savvas et al., 2009), as shown in Table 2. The mechanism of action of silica nanoparticles reduces the Na^+ ion concentration in the plant. As a result, limited Na^+ ion is available for absorption by plant tissues. Since salinity stress increases Na^+ ion uptake and osmotic potential, the process of contamination is reduced using SiO_2NPs because of this mechanism of action (Raven, 1983).

In addition, multi-walled carbon nanotubes (MCN) have been tested against salinity-stressed broccoli plants (Martínez-Ballesta et al. (2016). The MCN-treated plants exhibited increased assimilation of CO_2, aquaporin transduction, increased water uptake and modified the broccoli root plasma membrane which increased the sprouting of the plant.

Effect of NPs on chilling stress

Low temperatures can destroy plant cells because of ion leakage and permeability distortion of the plant cell membrane. This chilling stress leads to a reduction in plant growth and germination (Bhattacharya, 2022; Petruccelli et al., 2022) with tolerance to chilling varying between different plant species. The greater the damage to plant membranes, the more deleterious the effect of chilling stress on the plant (Rawat et al., 2020). In addition, photosynthesis and its biochemical components are greatly affected by chilling stress because low temperature damages the photosystems, inhibiting properties associated with light absorption, such as increasing Rubisco degradation, CO_2 assimilation, transpiration rate, and reducing the chlorophyll content (Jajoo and Mathur, 2021; Sherin et al., 2022). To ensure the relief of plants from chilling stress, NPs are used to enhance photosystem activities by inhibiting ROS production, increasing the activities of the chloroplast, and improving the production of Rubisco enzymes (Ayyaz et al., 2022; Chandel et al., 2022).

TiO_2NPs activate processes needed to enhance the synthesis of chlorophyll and the expression of the Rubisco binding protein gene, improve leaf pigment, antioxidant enzyme synthesis, and decrease the effect of chilling stress by reducing plant cell damage and ion leakage (Asadi and Cheniany, 2022; Sardar et al., 2022; Zare et al., 2022). Low-temperature stress upregulates the expression of *MeAPX2* and *ZnSOD*/*MeCu* genes, which increases glutathione reductase, dehydroascorbate reductase, and monodehydroascorbate activities that remove ROS. It also helps to reduce oxidative stress (Sonkar et al., 2021). The use of TiO_2NPs to reduce chilling stress has restructured plant biochemical physiognomies whenever plant cells are exposed to low-temperature environments (El-Gazzar et al., 2020; Elsheerya et al., 2020; Nasr et al., 2021).

Effect of NPs on drought stress

Soil drought is an abiotic stress limiting crop productivity in arid and semi-arid regions (Gamalero and Glick, 2022). Several studies have highlighted the effects of silicon NPs on drought-induced plant stress. For instance, SiNPs have been used to relieve the impact of drought stress on hawthorns (*Crataegus sp.*) (Ashkavand et al., 2015). The aforementioned study was conducted using different concentrations of SiNPs, depending on the severity of the stress. Biochemical and physiological responses differ in plant seedlings based on the positive effect of SiNPs on carbohydrate contents, proline, leaf pigments, membrane leakage, water content, malondialdehyde, and photosynthetic parameters (Ashkavand et al., 2015). A study was conducted to test the effect of SiNPs on two different sorghum (*Sorghum bicolor* (L.) Moench) cultivars with different drought tolerance susceptibility patterns, maintaining the photosynthetic rate and reducing the root-to-shoot ratio. This showed that SiNPs was able to augment plant water uptake efficacy (Hattori et al., 2005). Also, a low concentration of sodium silicate was used to mitigate the effect of drought stress on wheat (Pei et al., 2010). The silicon content of the compound was able to maintain the leaf potential in water absorption, improve the leaf chlorophyll content, and enhance shoot growth. Although the mechanism of action of this compound is yet to be determined, silicon compounds have been reported to be involved in the reduction of plant membrane lipid peroxidation.

In soybean, ZnONPs have been reported to boost the resilience of soybean plants to drought stress (Sedghi et al., 2013). This study revealed that the application of ZnONPs helped in the germination of soybean in a drought-stressed plant; an effect attributed to the role of Zn in the improvement of seed viability and sprouting of plant seeds in Zn deficient areas (Degenhardt and Gimmler, 2000).

Iron is an essential nutrient needed for plant growth and development; an iron-deficient plant shows physiological change, *viz*., chlorosis and reduced metabolism (Jalil and Ansari, 2019). Micronutrients can be used to relieve the effects of drought stress in some plants. Davar et al. (2014) showed the impact of exogenous FeNPs in the flowering and fruiting stages of a plant under drought stress. In addition, to reduce the adverse effects of drought stress, TiO_2NPs have been applied to the leaves of wheat to improve agronomic and physiological features, such as gluten, starch, photosynthetic activities, biomass, harvest index, final yield and plant weight (Jaberzadeh et al., 2013).

Plant microbes in agriculture to address future food scarcity

Some bacteria and fungi can colonize the internal tissues of their host plants without causing any detrimental effects (Adeleke and Babalola, 2021b). Various bacterial and fungal endophytes produce plant growth traits, such as siderophores, nitrogen fixation, phosphate solubilization, antibiotic production and induced systemic resistance to various environmental stresses (Santoyo et al., 2016; Adeleke et al., 2021).

Plant roots absorb water and minerals from the soil, then translocate them to other plant parts (Liu et al., 2021). In addition, the plant produces copious amounts of exudates such as amino acids, organic acids, and sugars into the soil which are utilized by soil microbes and contribute to the

TABLE 3 Various endophytic microbes inhabiting crop plants and their functions.

Endophyte	Plant(s)	Functions	References
Burkholderia seminalis strain 869T2	*Arabidopsis*, loose-leaf lettuce, romaine lettuce, red-leaf lettuce, and Chinese amaranth	Plant growth promotion, auxin production, siderophore synthesis, and phosphate solubilization	Hwang et al. (2021)
Cyanobacteria (*Nostoc punctiforme* PCC 73102)	Rice (*Oryza sativa*)	When these organisms are inoculated into the roots of rice, they produce heterocysts and nitrogenase activity that contributes to plant growth under a limited nitrogen supply	Álvarez et al. (2020)
Firmicutes	Tomato (*Solanum lycopersicum*)	These endophytes dominate different cultivars of tomato promoting resistance against *Ralstonia solanacearum*	Sahu et al. (2020)
Proteobacteria, Bacteroidetes, Firmicutes, Actinobacteria	Sugarcane (*Saccharum officinarum*)	These organisms were isolated from sugarcane leaves, sheaths, and roots. They contributed to plant growth promotion	Teheran-Sierra et al. (2021)
Klebsiella MK2R2, *Bacillus* B2L2, *Enterobacter* E1S2	Maize (*Zea mays*)	These endophytic organisms have the potential to improve the growth of maize and nitrogen fertilization	Mowafy et al. (2021)
Pseudomonas protegens MP12	Grapevine (*Vitis vinifera*)	This organism colonizes inner grapevine tissues, and contributes to antifungal ability, preventing mycelial growth of certain grapevine phytopathogens	Andreolli et al. (2021)
Rhizobium (*Bacillus siamensis*)	Chickpea plants (*Cicer arietinum* L.)	This rhizobium had various PGP features including nitrogen fixation, phosphate solubilization, ACC deaminase, IAA production, synthesis of hydroxamate-type siderophores	Gorai et al. (2021)

microbial biomass in the root environment (Lyu et al., 2021). Also, seeds produce low molecular weight organic exudates into the surrounding soil during germination. Several endophytes have been reported to be present in the endosphere (He et al., 2021).

Endophytic relationships with the host plants can be symbiotic or pathogenic. Often, essential and uncommon organic substances are secreted by endophytes that assist in providing various functions, not only for soil health but also as a solution to plant stress challenges. Endophytes can often protect plants from phytopathogens and abiotic stresses (Table 3).

The impact of abiotic stressors on plant growth and soil health can be major or minor depending on the prevailing environmental conditions (Sachdev et al., 2021). Abiotic stresses negatively affect crop production and microbial diversity (Chouhan et al., 2021). Various mechanisms employed by endophytic microorganisms induce systemic resistance (ISR) or abiotic stress tolerance in plants (Gupta et al., 2021). Therefore, there is a need to restructure modern agricultural systems to include recent developments in endosphere biology (Santoyo et al., 2021b). Some studies have explained the role of endophytic bacteria in agricultural systems under abiotic stresses in combating future food scarcity. For instance, *B. amyloliquefaciens* RWL-1 producing ABA can enhance rice yield in soil with a high salt concentration (Ganie et al., 2021). This bacterium produces essential amino acids and salicylic acid which assist rice growth in salinity/drought conditions (Thepbandit et al., 2021). The endophytic fungus, *Bipolaris sp*., produces gibberellins which contribute to the growth of *Glycine max* (Lubna et al., 2022). *Sphingomonas sp.* LK11 is an endophyte from leguminous plants that also synthesizes gibberellins which enhance tomato growth and the plant chlorophyll content (Adeleke and Babalola, 2021a).

Various reports revealed the presence of IAA-producing endophytic bacteria (Rashid et al., 2012; Panigrahi et al., 2020; Turbat et al., 2020). *Burkholderia kururiensis* is an endophyte that stimulates the expression of IAA genes, especially in the roots of transgenic rice, thereby contributing to rice growth (Zhou et al., 2020).

Some endophytes are halotolerant, which can be isolated from the weed *Psoralea corylifolia* to assess their PGP activity in wheat. The growth of wheat plants can be improved with the aid of an extract from the bacterial isolates during the production of IAA under saline-stress conditions (Amini Hajiabadi et al., 2021). The identification of various strains embedded in weeds revealed various genera including *Acinetobacter, Enterobacter, Marinobacterium, Pseudomonas, Rhizobium*, and *Sinorhizobium* (AlSharari et al., 2022). The hormone cytokinin is also produced by some endophytic bacteria, according to Eid et al. (2021). *Pseudomonas resinovorans* and *Paenibacillus polymyxa* isolated from *Gynura procumbens* are good examples of endophytic bacteria producing cytokinin (Eid et al., 2021). From a bacterial culture, the obtained extracts were tested *in vitro* and inoculated into the cotyledon of cucumber to observe their cytokinin activity.

A strain of *Sinorhizobium meliloti* engineered to overproduce cytokinin by transferring the *Agrobacterium tumefaciens ipt* gene into the bacterium, and a strain of *Pseudomonas spp*., that protected alfalfa plants from drought-stressed conditions (Oleńska et al., 2020), these two bacteria were inoculated together or separately, in the cultivation of sorghum (*Sorghum bicolor*). The results revealed that the two strains inoculated together reduced the requirement for chemical nitrogen fertilizer

TABLE 4 The biological activities of nanoparticle-synthesizing endophytic microbes against plant pathogens.

Endophytic organisms	Plant pathogens	Microbial activity	References
Silver (Ag) Nanoparticle			
Alternaria alternate	Bacillus cereus, Klebsiella pneumoniae, Pseudomonas aeruginosa, E.coli, Staphylococcus aureus, Proteus mirabilis	Antibacterial and antioxidant	Govindappa et al. (2022)
Micromonospora sp. SH121 (Mm-AgNPs)	Bacillus cereus, Enterococcus faecalis, Enterococcus hirae, Escherichia coli, Klebsiella pneumoniae, Proteus vulgaris, Pseudomonas putida, Staphylococcus epidermidis, Streptococcus pneumoniae, Aspergillus flavus	Antimicrobial, antibiofilm, and anticancer	Mazmancı et al. (2022)
Streptomyces species	Bacterial and fungal agents	Biosynthesis and Antibacterial	ALqahtani et al. (2022)
Phoma sp. (MN995524), Chaetomium globosum (MN995493), and Chaetomium sp. (MN995550)	Klebsiella pneumonia	Antibacterial activities	Sonbol et al. (2022)
Trichoderma atroviride	Pathogenic bacteria and fungi	Antibacterial, anticandidal, and antifungal effects	Abdel-Azeem et al. (2020)
Pseudomonas poae	Fusarium graminearum head blight pathogen	Antifungal	Ibrahim et al. (2020)
Rhizobium pusense (MS-1), Bacillus cereus MS-2, Bacillus flexus (MS-3), Methylophilus flavus (MS-4), Pseudomonas aeruginosa (MS-5)	Bacillus thuringiensis, Azotobacter chroococcum (CL13), Escherichia coli, Pseudomonas putida (ECL5), Bacillus licheniformis (R-1), Rhizobium sp. (CV1)	Antibacterial activity	Singh et al. (2022b)
Talaromyces purpureogenus	Listeria monocytogenes, Escherichia coli, Shigella dysenteriae, Salmonella typhi	Antibacterial activity	Sharma et al. (2022)
Serratia marcescens, Burkholderia cepacia	Aspergillus niger, A. fumigatus, Fusarium oxysporum, Pythium sp., Rosellinia sp	Antifungal activity	Mittal et al. (2021)
Terminalia arjuna	Escherichia coli MTCC1687, Pseudomonas aeruginosa ATCC9027, Staphylococcus aureus ATCC6538	Antibacterial activity	Singh et al. (2022a)
Penicillium cinnamopurpureum	Bacillus subtilis (MTCC-121), Pseudomonas aeruginosa (MCC-3097), Staphylococcus aureus (MCC-2043), Escherichia coli (MCC-3099)	Antibacterial activity	Dinesh et al. (2022)
Phoma glomerata, Phoma herbarium, Fusarium semitectum, Trichoderma, Candida albicans	Candida albicans, Pseudomonas aeruginosa, E. coli, Bipolaris sorokiniana, Magnaporthe grisea	Antibacterial, antifungal, and insecticidal activity	Shinde et al. (2022)
Gold (Au) Nanoparticle			
Phoma sp	Rhizoctonia solani AG1-IA, Xanthomonas oryzae	Antifungal and antibacterial activity	Soltani Nejad et al. (2022)
Pseudomonas aeruginosa	Vigna unguiculata	Plant growth enhancement/ promotion	Panichikkal and Krishnankutty, (2022)
Aspergillus terreus	Fusarium oxysporum, Rhizoctonia solani	Antimicrobial, antioxidant, and antifungal activity	Mishra et al. (2022)
Alternaria alternate, Fusarium species	Cervical carcinoma (HeLa), breast carcinoma (MCF-7), non-small cell lung carcinoma (H1975), hepatocellular carcinoma cell line (Hep G2)	Anticancer activity	Ravi et al. (2022)
Aspergillus sp., Alternaria sp	Escherichia coli, Staphylococcus aureus	Antibacterial, antifungal, and antitumor activities	Mostafa et al. (2022)
Lysinibacillus odyssey	Staphylococcus epidermidis Staphylococcus aureus, Streptococcus pyogenes, Enterococcus faecalis, Bacillus subtilis	Dose-dependent antioxidant and antibacterial activity	Cherian et al. (2022)
Zinc-oxide (ZnO) nanoparticles			
Aspergillus niger	Staphylococcus aureus	Antibacterial activity	Abdelkader et al. (2022)
Enterobacter hormaechei	Klebsiella pneumoniae (ATCC: 4617), Escherichia coli (ATCC: 15224), Pseudomonas aeruginosa (ATCC: 9721), Bacillus subtilis (ATCC: 6633), Staphylococcus epidermidis (ATCC: 14990) Aspergillus fumigatus, Aspergillus niger, Aspergillus flavus, Fusarium solani, Mucor mycosis	Antifungal, antibacterial, and antioxidant potential	Saqib et al. (2022)
Trichoderma viride	Staphylococcus aureus, Bacillus spp., Pseudomonas aeruginosa, Klebsiella spp., Acinetobacter baumannii, Candida albicans	Antimicrobial and antioxidant activities	Kaur et al. (2022)

to a low level and significantly improved the cultivation of sorghum. The procedure also enhanced the colonization effectiveness of both bacteria in the roots of rice plants (Abbaszadeh-Dahaji et al., 2020). In summary, endophytes can play a major role in modulating phytohormone levels in plants, thereby contributing to plant growth and managing various stress conditions.

Symbiotic nitrogen fixation reduces atmospheric nitrogen by the action of the leguminous plants in association with nitrogen-fixing bacteria, increasing the plant's nutritional value (Rana et al., 2020). Several years ago, the only known nitrogen-fixing bacteria in legume nodules were rhizobia. However, numerous non-rhizobial bacterial species have been found in legume root nodules. Hanaka et al. (2021) reported how an endophytic bacteria isolated from the soybean, *Bacillus mojavensis,* exhibited biocontrol activity against the soybean pathogenic fungus, *Rhizoctonia solani.* These endophytic microorganisms have antagonistic activity against soil-borne pathogens and possess the ability to enhance the growth of soybean plants. The *B. mojavensis* strain produced ammonia, HCN, and siderophores. It also contributed to chitinase activity and solubilization of phosphate (Hanaka et al., 2021). The inoculation of this endophyte onto soybean seeds can help control various pathogens.

The introduction of nanotechnology in agriculture is a developing sector in agriculture despite several applications, and the true possibilities are yet to be obtained. Nanotechnology constitutes certain substances with unusual features that are revealed either as a result of the quantum confinement effects or the production of certain reactive surfaces that are at a nanoscale (Umapathy et al., 2022). The nanoscale degree when compared with the macroscopic level, reveals the properties of the material that are special as a result of the reduced size, shape of nanomaterials, and greater surface area-to-weight ratio. Nanomaterials or nanoparticles (NPs) have beneficial properties, with high reactivity, modified bioactivity, and surface effects (Bruchiel-Spanier et al., 2022). NPs are produced by either a single element like silver (Au) or gold (Au) or by a mixture of elements, which are observed in those constituting oxides like titanium oxide (TiO_2), silicon oxide (SiO_2), and zinc oxide (ZnO) (Behl et al., 2022). Gold and silver NPs regarded as inorganic NPs, are relevant as a result of their application. Although, few studies have shown how the NPs are manufactured from endophytes (Fadiji et al., 2022a; Kaur et al., 2022; Saqib et al., 2022), thus suggesting possible means for continuous studies on endophytic nanoparticles.

Various approaches including biological, chemical, and physical approaches are made use of in the production of NP, yet, the process of biosynthesis is environmentally friendly, free of chemical derivatives that are hazardous to humans, animals, and the environment. These chemicals have been used recently to reduce the potential of applying chemicals in the biomedical and food processing industries. Several procedures involving intracellular and extracellular for the biological synthesis of nanomaterials coexist in nature. In this field, the study is still understudied (Qian et al., 2022). The production of environmentally friendly, and non-toxic biological materials for manufacturing NPs would result in supporting the production of natural materials with the aid of living organisms (Fadiji et al., 2022a).

NPs produced from metal-based are manufactured by microorganisms through extracellular and intracellular mechanisms (Franco et al., 2022). The process of electrostatic induction takes place in metallic ions between negative and positive charges intracellularly in the cell wall of the microorganisms, followed by the decrease of the metal ions to their metallic form. Cell disruption is a constitutional prerequisite to acquiring pure NPs (Fadiji et al., 2022a). The biomass extracts from the cell, or culture supernatant when added to the solution of metals produce NPs outside the cell of the microorganisms (extracellularly) (Jadoun et al., 2022). Reductases are produced and liberated into the culture medium by cofactors, with microbial cells that execute this procedure. Endophytic microbes have been suggested as biofactories for the synthesis of metal-based NPs with agricultural and therapeutic applications. These microbes are embedded in plants intercellularly, producing a symbiotic link (Roy et al., 2022). The advantage confers on the plant by the endophytes is to improve health status *via* various mechanisms, like the release of antimicrobial (antibacterial and antifungal) compounds and the secretion of growth-promoting metabolites (Shahid et al., 2022).

In plant tissues, endophytic microbes accommodating them can produce nanoparticles, which are advantageous to the host plant by promoting plant growth or reducing the prevalence of diseases (Koné et al., 2022). Endophytes can resist metals occurring in the environment to alleviate toxicity and stress in the host plant, as well as improve their beneficial association and adaption over other microbes inhabiting the ecosystem (Mathur and Ulanova, 2022). The potential of endophytes to take away metals can be applied to manufacture metal-based NPs *via* extracellular and intracellular processes (Table 4). Typical examples were obtained in the production of AgNPs, which have a spherical shape and a mean size of 22 nm–45 nm, which can be manufactured intracellularly employing the supernatant of Ag-resistant *Bacillus safensis* TEN12 (Ahmed et al., 2020). Zinc oxide (ZnO) NPs sized 2 nm–9 nm, were produced extracellularly by the zinc-tolerant endophyte *Curvularia geniculata* (Ahmed et al., 2020). Gürsoy et al. (2021) reported how gold nanoparticles (AuNPs) sized 20 nm–40 nm were produced intracellularly in the cell wall and cytoplasm of *Chlorella sorokiniana*. Cobalt oxide nanoparticles (CoONPs), which are spherical at 20 nm in diameter, were produced extracellularly by the *A. nidulans* that are CoO-tolerant (Ahmed et al., 2020). *Aspergillus nidulans* are endophytes, which reveal the potential of the CoO-tolerant produced spherical CoONPs with a diameter of 20 nm through an extracellular tract (Fadiji et al., 2022a). Endophytic microorganisms can produce some biological active materials with a broad gap of structural and biological potential, which can be employed to examine the health and promote plant growth and are significant in improving the sustainability of agriculture (Kumar and Nautiyal, 2022). Fungi and bacteria isolated from parts of plants can be cultured in the laboratory under the most desirable growth conditions to synthesize NPs with the needed characteristics for application in the agricultural sector (Elnahal et al., 2022).

Fate of NPs

The use of NPs for agroecosystem practices could be a very complicated matrix and information on the fate of nanomaterials in the soil is inadequate. After applying NPs to the soil, they are absorbed in the plant tissue directly. Such interaction could either increase or decrease the bioavailability and toxicity of NPs depending on the physicochemical properties of the soil. However, the potency of NPs is most dependent on the type of crop and the properties of the soil *viz*., microbial community, clay content, ionic strength, pH, salinity, organic matter, etc., (Reddy et al., 2016; Thiagarajan and Ramasubbu, 2021).

Effect of microbial community

Plant endophyte and the microbial community helps in the transformation of NPs. They help to recycle nutrients, effectively decomposition of organic compounds and conserve soil quality. The introduction of nanomaterials could affect microbial inhabitation which invariably reduces plant productivity (Jacoby et al., 2017; Chavan et al., 2020). The effect of NPs on the rhizosphere bacteria of butter crunch lettuce was reported by Kibbey and Strevett (2019). NPs and rhizosphere bacteria react together *via* electrostatic interactions that affect the surface properties of bacteria, which disallow easy attachment to the root surfaces of the plant. They also reported that fluctuations in soil mineral nutrients (P, Fe, Mn, etc.) were a result of spiked biosolid amendment of soil with NPs, which affects soil microbial load. Withal, NPs were also reported to have affected the sequestration of plant nutrients and other agroecosystem processes as reported by Bellani et al. (2020).

At times, NPs may also inhibit the colonization of plant growth promoters when combined with other nutrients. This deleterious effect was reported by Liu et al. (2020). Here, the negative effect associated with the combination of TiO_2NPs with $Cu_2\ (OH)_2\ CO_3$ was reported. The synergy between TiO_2NPs and $Cu_2\ (OH)_2\ CO_3$ boosted photocatalytic disinfection processes that disabled the effect of microorganisms such as *Fusarium graminearum* and *E. coli* within a short time of application (Liu et al., 2020).

Effect of clay content

Another important component that determines the fate of NPs is the clay content of the soil. The high the clay content of the soil, the decreased mobility of NPs because both the physical straining and electrostatic interactions would be increased. However, the soil retention capacity depends mainly on the clay to NPs ratio. The higher the ratio, the better the soil retention capacity (Shah et al., 2016). Metals are easily retained in the soil when there is an increase in the clay content. And as such reduces the uptake of metallic ions by the plant. This simply indicates the low toxicity of metallic NPs (Larue et al., 2018; Thiagarajan and Ramasubbu, 2021).

Effect of natural organic matter

NOM influences the stability and aggregation of NPs within the soil. NOM includes mobile and reactive organic fractions *viz*. hydrocarbons, amino acids, hydrophilic acids, fatty acids, fulvic, and humic acids. NOM is produced through the disintegration of animal and plant remains in the soil. Sludge-amended soil and NOM have been reported to cover 10.9% and 8.9% of soil, respectively. Meanwhile, the physicochemical properties of NPs and features of proximal soil are usually influenced after the adsorption of NOM (Bakshi et al., 2019). A recent study by Zhang et al. (2020) showed the stability of TiO_2NPs when introduced to a paddy field with high organic matter. In another study that demonstrated the effect of a high concentration of NOM on the bioaccumulation of NPs, the ability of NOM to retrain NPs could be attributed to the change in the surface area of soil as a result of an increase in the concentration of NOM. The interaction of NPs with NOM alters the binding property of the soil to improve the steric repulsion between nanomaterials by aggregating and retaining them in the soil. Asides, the reaction of NPs and NOM depends greatly on their particle sizes through hydrophobic interaction (Lee et al., 2011).

Conclusion

Globally, crop improvement and productivity are faced with diverse abiotic stress challenges. To avert this problem, the use of nanomaterials from endophytic microbes has the potential to mitigate the effects of abiotic stresses affecting plants by stimulating plant defense mechanisms. Beneficial endophytic microbes as bioinoculants can be effectively harnessed for various ecological purposes such as abiotic stress reduction, nutrient absorption, enhancing photosynthesis, increasing plant growth parameters, and obviating agrochemical use. Additionally, the nanomaterial synthesizing endophytic microbes promise to improve crop productivity sustainably.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Abbaszadeh-Dahaji, P., Masalehi, F., and Akhgar, A. (2020). Improved growth and nutrition of sorghum (*Sorghum bicolor*) plants in a low-fertility calcareous soil treated with plant growth–promoting rhizobacteria and Fe-edta. *J. Soil Sci. Plant Nutr.* 20, 31–42. doi:10.1007/s42729-019-00098-9

Abd-Alla, M. H., Nafady, N. A., Bashandy, S. R., and Hassan, A. A. (2019). Mitigation of effect of salt stress on the nodulation, nitrogen fixation and growth of chickpea (*Cicer arietinum* L.) by triple microbial inoculation. *Rhizosphere* 10, 100148. doi:10.1016/j.rhisph.2019.100148

Abdel-Azeem, A., Nada, A., O'donovan, A., Kumar Thakur, V., and Elkelish, A. (2020). Mycogenic silver nanoparticles from endophytic *Trichoderma atroviride* with antimicrobial activity. *J. Renew. Mat.* 8, 171–185. doi:10.32604/jrm.2020.08960

Abdel-Aziz, S. M., Prasad, R., Hamed, A. A., and Abdelraof, M. (2018). "Fungal nanoparticles: A novel tool for a green biotechnology?," in *Fungal nanobionics: Principles and applications* (Springer), 61–87.

Abdelkader, D. H., Negm, W. A., Elekhnawy, E., Eliwa, D., Aldosari, B. N., and Almurshedi, A. S. (2022). Zinc oxide nanoparticles as potential delivery carrier: Green synthesis by *Aspergillus niger* endophytic fungus, characterization, and *in vitro/in vivo* antibacterial activity. *Pharm. (Basel).* 15, 1057. doi:10.3390/ph15091057

Aboyewa, J. A., Sibuyi, N. R., Meyer, M., and Oguntibeju, O. O. (2021). Green synthesis of metallic nanoparticles using some selected medicinal plants from southern Africa and their biological applications. *Plants* 10, 1929. doi:10.3390/plants10091929

Acuña, J. J., Campos, M., De La Luz Mora, M., Jaisi, D. P., and Jorquera, M. A. (2019). ACCD-producing rhizobacteria from an Andean Altiplano native plant (*Parastrephia quadrangularis)* and their potential to alleviate salt stress in wheat seedlings. *Appl. Soil Ecol.* 136, 184–190. doi:10.1016/j.apsoil.2019.01.005

Adeleke, B. S., Ayilara, M. S., Akinola, S. A., and Babalola, O. O. (2022). Biocontrol mechanisms of endophytic fungi. *Egypt. J. Biol. Pest Control* 32, 46–17. doi:10.1186/s41938-022-00547-1

Adeleke, B. S., and Babalola, O. O. (2021a). Biotechnological overview of agriculturally important endophytic fungi. *Hortic. Environ. Biotechnol.* 62, 507–520. doi:10.1007/s13580-021-00334-1

Adeleke, B. S., Babalola, O. O., and Glick, B. R. (2021). Plant growth-promoting root-colonizing bacterial endophytes. *Rhizosphere* 20, 100433. doi:10.1016/j.rhisph.2021.100433

Adeleke, B. S., and Babalola, O. O. (2022). Meta-omics of endophytic microbes in agricultural biotechnology. *Biocatal. Agric. Biotechnol.* 42, 102332. doi:10.1016/j.bcab.2022.102332

Adeleke, B. S., and Babalola, O. O. (2021b). Pharmacological potential of fungal endophytes associated with medicinal plants: A review. *J. Fungi (Basel).* 7, 147. doi:10.3390/jof7020147

Agri, U., Chaudhary, P., Sharma, A., and Kukreti, B. (2022). Physiological response of maize plants and its rhizospheric microbiome under the influence of potential bioinoculants and nanochitosan. *Plant Soil* 474, 451–468. doi:10.1007/s11104-022-05351-2

Ahmad, F., Siddiqui, M. A., Babalola, O. O., and Wu, H.-F. (2012a). Biofunctionalization of nanoparticle assisted mass spectrometry as biosensors for rapid detection of plant associated bacteria. *Biosens. Bioelectron. X.* 35, 235–242. doi:10.1016/j.bios.2012.02.055

Ahmad, M., Zahir, Z. A., Asghar, H. N., and Arshad, M. J. a. O. M. (2012b). The combined application of rhizobial strains and plant growth promoting rhizobacteria improves growth and productivity of mung bean (*Vigna radiata* L.) under salt-stressed conditions. *Ann. Microbiol.* 62, 1321–1330. doi:10.1007/s13213-011-0380-9

Ahmad, M., Zahir, Z. A., Nazli, F., Akram, F., Arshad, M., and Khalid, M. J. B. J. O. M. (2013). Effectiveness of halo-tolerant, auxin producing *Pseudomonas* and *Rhizobium* strains to improve osmotic stress tolerance in mung bean (*Vigna radiata* L.). *Braz. J. Microbiol.* 44, 1341–1348. doi:10.1590/s1517-83822013000400045

Ahmad, P., Hashem, A., Abd-Allah, E. F., Alqarawi, A., John, R., Egamberdieva, D., et al. (2015). Role of *Trichoderma harzianum* in mitigating NaCl stress in Indian mustard (*Brassica juncea* L) through antioxidative defense system. *Front. Plant Sci.* 6, 868. doi:10.3389/fpls.2015.00868

Ahmadpour, K. S., Salari, S., and Ghasemi, N. A. P. (2021). Comparison of antifungal and cytotoxicity activities of titanium dioxide and zinc oxide nanoparticles with amphotericin B against different Candida species: *In vitro* evaluation. *J. Clin. Lab. Anal.* 35, 23577. doi:10.1002/jcla.23577

Ahmed, B., Cao, B., Mishra, B., Boyanov, M. I., Kemner, K. M., Fredrickson, J. K., et al. (2012). Immobilization of U (VI) from oxic groundwater by Hanford 300 Area sediments and effects of Columbia River water. *Water Res.* 46, 3989–3998. doi:10.1016/j.watres.2012.05.027

Ahmed, F., and Rodrigues, D. F. (2013). Investigation of acute effects of graphene oxide on wastewater microbial community: A case study. *J. Hazard. Mat.* 256, 33–39. doi:10.1016/j.jhazmat.2013.03.064

Ahmed, T., Noman, M., Manzoor, N., Shahid, M., Abdullah, M., Ali, L., et al. (2021). Nanoparticle-based amelioration of drought stress and cadmium toxicity in rice via triggering the stress responsive genetic mechanisms and nutrient acquisition. *Ecotoxicol. Environ. Saf.* 209, 111829. doi:10.1016/j.ecoenv.2020.111829

Ahmed, T., Shahid, M., Noman, M., Bilal Khan Niazi, M., Zubair, M., Almatroudi, A., et al. (2020). Bioprospecting a native silver-resistant *Bacillus safensis* strain for green synthesis and subsequent antibacterial and anticancer activities of silver nanoparticles. *J. Adv. Res.* 24, 475–483. doi:10.1016/j.jare.2020.05.011

Ajilogba, C. F., Babalola, O. O., and Nikoro, D. (2021). "Nanotechnology as vehicle for biocontrol of plant diseases in crop production," in *Food security and safety: Africa's Perspective*. Editor O. O. Babalola (Hardcover: eBook), 709–724. 978-3-030-50672-8978-3-030-50671-1.

Akanmu, A. O., Babalola, O. O., Venturi, V., Ayilara, M. S., Adeleke, B. S., Amoo, A. E., et al. (2021). Plant disease management: Leveraging on the plant-microbe-soil interface in the biorational use of organic amendments. *Front. Plant Sci.* 12, 700507. doi:10.3389/fpls.2021.700507

Akinola, S. A., Adeyemo, R. O., and Adebayo, I. A. (2022). "Overview and emergence of nanobiotechnology in plants," in *Diverse applications of nanotechnology in the biological sciences* (Apple Academic Press), 173–197.

Akinola, S. A., Ayangbenro, A. S., and Babalola, O. O. (2021c). Metagenomic insight into the community structure of maize-rhizosphere bacteria as predicted by different environmental factors and their functioning within plant proximity. *Microorganisms* 9, 1419. doi:10.3390/microorganisms9071419

Akinola, S. A., Ayangbenro, A. S., and Babalola, O. O. (2021a). The diverse functional genes of maize rhizosphere microbiota assessed using shotgun metagenomics. *J. Sci. Food Agric.* 101, 3193–3201. doi:10.1002/jsfa.10948

Akinola, S. A., Ayangbenro, A. S., and Babalola, O. O. (2021b). The immense functional attributes of maize rhizosphere microbiome: A shotgun sequencing approach. *Agriculture* 11, 118. doi:10.3390/agriculture11020118

Akinola, S. A., and Babalola, O. O. (2021). The fungal and archaeal community within plant rhizosphere: A review on their contribution to crop safety. *J. Plant Nutr.* 44, 600–618. doi:10.1080/01904167.2020.1845376

Akinola, S. A., and Babalola, O. O. (2020). The importance of adverse soil microbiomes in the light of omics: Implications for food safety. *Plant Soil Environ.* 66, 421–430. doi:10.17221/118/2020-pse

Ali, S., and Glick, B. R. (2019). "Plant–bacterial interactions in management of plant growth under abiotic stresses," in *New and future developments in microbial biotechnology and bioengineering* (Elsevier), 21–45.

Alqahtani, M. S., Hozzein, W. N., and Alharbi, S. A. (2022). Biosynthesis and antibacterial activity of silver nanoparticles using medicinal plants associated endophytic bacteria from in Riyadh Region Saudi Arabia. *Sch. Acad. J. Biosci.* 4, 68–76. doi:10.36347/sajb.2022.v10i04.001

Alsharari, S. S., Galal, F. H., and Seufi, A. M. (2022). Composition and diversity of the culturable endophytic community of six stress-tolerant dessert plants grown in stressful soil in a hot dry desert region. *J. Fungi (Basel).* 8, 241. doi:10.3390/jof8030241

Álvarez, C., Navarro, J. A., Molina-Heredia, F. P., and Mariscal, V. (2020). Endophytic colonization of rice (*Oryza sativa* L.) by the symbiotic strain *Nostoc punctiforme* PCC 73102. *Mol. Plant. Microbe. Interact.* 33, 1040–1045. doi:10.1094/mpmi-01-20-0015-sc

Alvarez, L. H., and Cervantes, F. J. (2012). Assessing the impact of alumina nanoparticles in an anaerobic consortium: Methanogenic and humus reducing activity. *Appl. Microbiol. Biotechnol.* 95, 1323–1331. doi:10.1007/s00253-011-3759-4

Amini Hajiabadi, A., Mosleh Arani, A., Ghasemi, S., Rad, M. H., Etesami, H., Shabazi Manshadi, S., et al. (2021). Mining the rhizosphere of halophytic rangeland plants for halotolerant bacteria to improve growth and yield of salinity-stressed wheat. *Plant Physiol. biochem.* 163, 139–153. doi:10.1016/j.plaphy.2021.03.059

Anam, G. B., Reddy, M. S., and Ahn, Y.-H. (2019). Characterization of *Trichoderma asperellum* RM-28 for its sodic/saline-alkali tolerance and plant growth promoting activities to alleviate toxicity of red mud. *Sci. Total Environ.* 662, 462–469. doi:10.1016/j.scitotenv.2019.01.279

Andreolli, M., Zapparoli, G., Lampis, S., Santi, C., Angelini, E., and Bertazzon, N. (2021). *In vivo* endophytic, rhizospheric and epiphytic colonization of *Vitis vinifera* by the plant-growth promoting and antifungal strain *Pseudomonas protegens* MP12. *Microorganisms* 9, 234. doi:10.3390/microorganisms9020234

Ansari, F. A., Ahmad, I., and Pichtel, J. (2019). Growth stimulation and alleviation of salinity stress to wheat by the biofilm forming *Bacillus pumilus* strain FAB10. *Appl. Soil Ecol.* 143, 45–54. doi:10.1016/j.apsoil.2019.05.023

Armada, E., Azcón, R., López-Castillo, O. M., Calvo-Polanco, M., and Ruiz-Lozano, J. M. (2015a). Autochthonous arbuscular mycorrhizal fungi and *Bacillus thuringiensis* from a degraded Mediterranean area can be used to improve physiological traits and performance of a plant of agronomic interest under drought conditions. *Plant Physiol. biochem.* 90, 64–74. doi:10.1016/j.plaphy.2015.03.004

Armada, E., Barea, J.-M., Castillo, P., Roldán, A., and Azcón, R. J. a. S. E. (2015b). Characterization and management of autochthonous bacterial strains from semiarid soils of Spain and their interactions with fermented agrowastes to improve drought tolerance in native shrub species. *Appl. Soil Ecol.* 96, 306–318. doi:10.1016/j.apsoil.2015.08.008

Asadi, A., and Cheniany, M. (2022). Enhancing effect of titanium dioxide nanoparticles on growth, phenolic metabolites production and antioxidant potential of *Ziziphora clinopodioides* Lam. *Russ. J. Plant Physiol.* 69, 74. doi:10.1134/s1021443722040021

Ashkavand, P., Tabari, M., Zarafshar, M., Tomaskova, I., and Struve, D. (2015). Effect of SiO2 nanoparticles on drought resistance in hawthorn seedlings. *For. Res. Pap.* 76, 350–359. doi:10.1515/frp-2015-0034

Ashraf, M., Hasnain, S., Berge, O., and Mahmood, T. (2004). Inoculating wheat seedlings with exopolysaccharide-producing bacteria restricts sodium uptake and stimulates plant growth under salt stress. *Biol. Fertil. Soils* 40, 157–162. doi:10.1007/s00374-004-0766-y

Audah, K. A. (2019). *Nanotechnology: Applications in energy, drug and food*. Springer, 249–265.Drug discovery: A biodiversity perspective.

Ayyaz, A., Fang, R., Ma, J., Hannan, F., Huang, Q., Athar, H., et al. (2022). Calcium nanoparticles (Ca-NPs) improve drought stress tolerance in Brassica napus by modulating the photosystem II, nutrient acquisition and antioxidant performance. *NanoImpact* 28, 100423. doi:10.1016/j.impact.2022.100423

Azimi, R., Borzelabad, M. J., Feizi, H., and Azimi, A. (2014). Interaction of SiO_2 nanoparticles with seed prechilling on germination and early seedling growth of tall wheatgrass (*Agropyron elongatum* L.). *Pol. J. Chem. Technol.* 16, 25–29. doi:10.2478/pjct-2014-0045

Babalola, O. O., Fasusi, O. A., Amoo, A. E., and Ayangbenro, A. S. (2021). Complete genome sequence of a plant growth-promoting rhizobacterium, *Bacillus* sp. strain OA1, isolated from soybeans. *Biocatal. Agric. Biotechnol.* 36, 102121. doi:10.1016/j.bcab.2021.102121

Baker, S., Kavitha, K. S., Yashavantha Rao, H. C., Rakshith, D., Harini, B. P., Kumar, K., et al. (2015a). Bacterial endo-symbiont inhabiting *Tridax procumbens* L. and their antimicrobial potential. *Chin. J. Biol.* 2015, 1–6. doi:10.1155/2015/309267

Baker, S., Kumar, K. M., Santosh, P., Rakshith, D., and Satish, S. (2015b). Extracellular synthesis of silver nanoparticles by novel *Pseudomonas veronii* AS41G inhabiting *Annona squamosa* L. and their bactericidal activity. *Spectrochimica Acta Part A Mol. Biomol. Spectrosc.* 136, 1434–1440. doi:10.1016/j.saa.2014.10.033

Bakshi, M., Liné, C., Bedolla, D. E., Stein, R. J., Kaegi, R., Sarret, G., et al. (2019). Assessing the impacts of sewage sludge amendment containing nano-TiO_2 on tomato plants: A life cycle study. *J. Hazard. Mat.* 369, 191–198. doi:10.1016/j.jhazmat.2019.02.036

Bal, H. B., Nayak, L., Das, S., and Adhya, T. K. (2013). Isolation of ACC deaminase producing PGPR from rice rhizosphere and evaluating their plant growth promoting activity under salt stress. *Plant Soil* 366, 93–105. doi:10.1007/s11104-012-1402-5

Baltruschat, H., Fodor, J., Harrach, B. D., Niemczyk, E., Barna, B., Gullner, G., et al. (2008). Salt tolerance of barley induced by the root endophyte *Piriformospora indica* is associated with a strong increase in antioxidants. *New Phytol.* 180, 501–510. doi:10.1111/j.1469-8137.2008.02583.x

Baral, B., and Izaguirre-Mayoral, M. L. (2017). "Purine-derived ureides under drought and salinity," in *Advances in agronomy* (Elsevier), 167–204.

Battin, T. J., Kammer, F. V., Weilhartner, A., Ottofuelling, S., and Hofmann, T. (2009). Nanostructured TiO_2: Transport behavior and effects on aquatic microbial communities under environmental conditions. *Environ. Sci. Technol.* 43, 8098–8104. doi:10.1021/es9017046

Behl, T., Kaur, I., Sehgal, A., Singh, S., Sharma, N., Bhatia, S., et al. (2022). The dichotomy of nanotechnology as the cutting edge of agriculture: Nano-farming as an asset versus nanotoxicity. *Chemosphere* 288, 132533. doi:10.1016/j.chemosphere.2021.132533

Belimov, A., Dodd, I., Safronova, V., Hontzeas, N., and Davies, W. (2007). *Pseudomonas brassicacearum* strain Am3 containing 1-aminocyclopropane-1-carboxylate deaminase can show both pathogenic and growth-promoting properties in its interaction with tomato. *J. Exp. Bot.* 58, 1485–1495. doi:10.1093/jxb/erm010

Bellani, L., Siracusa, G., Giorgetti, L., Di Gregorio, S., Castiglione, M. R., Spanò, C., et al. (2020). TiO2 nanoparticles in a biosolid-amended soil and their implication in soil nutrients, microorganisms and *Pisum sativum* nutrition. *Ecotoxicol. Environ. Saf.* 190, 110095. doi:10.1016/j.ecoenv.2019.110095

Bhattacharya, A. (2022). "Low temperature stress and plant-water relationship: A review," in *Physiological processes in plants under low temperature stress* (Singapore: Springer), 107–197.

Brotman, Y., Landau, U., Cuadros-Inostroza, Á., Takayuki, T., Fernie, A. R., Chet, I., et al. (2013). *Trichoderma*-plant root colonization: Escaping early plant defense responses and activation of the antioxidant machinery for saline stress tolerance. *PLoS Pathog.* 9, e1003221. doi:10.1371/journal.ppat.1003221

Bruchiel-Spanier, N., Betsis, S., Naim, G., and Mandler, D. (2022). Electrochemical and electrophoretic coatings of medical implants by nanomaterials. *J. Solid State Electrochem.* 26, 1871–1896. doi:10.1007/s10008-022-05235-6

Cao, B., Majors, P. D., Ahmed, B., Renslow, R. S., Silvia, C. P., Shi, L., et al. (2012). Biofilm shows spatially stratified metabolic responses to contaminant exposure. *Environ. Microbiol.* 14, 2901–2910. doi:10.1111/j.1462-2920.2012.02850.x

Chandel, S. S., Shree, B., Mondal, K., and Mali, S. (2022). "Mechanism of nanoparticles-mediated alleviating biotic and abiotic stresses in agricultural crops: Recent advances and future perspectives," in *The Role of nanoparticles in plant nutrition under soil pollution. Sustainable plant nutrition in a changing world*. Editors V. D. Rajput, K. K. Verma, N. Sharma, and T. Minkina (Cham: Springer), 117–139.

Chandra, D., Srivastava, R., Glick, B. R., and Sharma, A. K. J. P. (2018). Drought-tolerant Pseudomonas spp. improve the growth performance of finger millet (*Eleusine coracana* (L.) Gaertn.) under non-stressed and drought-stressed conditions. *Pedosphere* 28, 227–240. doi:10.1016/s1002-0160(18)60013-x

Chang, P., Gerhardt, K. E., Huang, X.-D., Yu, X.-M., Glick, B. R., Gerwing, P. D., et al. (2014). Plant growth-promoting bacteria facilitate the growth of barley and oats in salt-impacted soil: Implications for phytoremediation of saline soils. *Int. J. Phytoremediation* 16, 1133–1147. doi:10.1080/15226514.2013.821447

Changmei, L., Chaoying, Z., Junqiang, W., Guorong, W., and Mingxuan, T. (2002). Research of the effect of nanometer materials on germination and growth enhancement of *Glycine max* and its mechanism. *Soybean Sci.* 21, 168–171.

Chaudhary, A., Chaudhary, P., Upadhyay, A., Kumar, A., and Singh, A. (2021a). Effect of *Gypsum* on plant growth promoting rhizobacteria. *Environ. Ecol.* 39, 1248–1256.

Chaudhary, P., Chaudhary, A., Bhatt, P., Kumar, G., Khatoon, H., Rani, A., et al. (2022). Assessment of soil health indicators under the influence of nanocompounds and *Bacillus* spp. in field condition. *Front. Environ. Sci.* 9, 769871. doi:10.3389/fenvs.2021.769871

Chaudhary, P., Chaudhary, A., Khati, P., and Kumar, G. (2021b). Nanotechnology and its role in improvement of crop production for sustainable agriculture. *Krishi Sci.* 2, 22–24.

Chaudhary, P., Khati, P., Chaudhary, A., Gangola, S., Kumar, R., and Sharma, A. (2021c). Bioinoculation using indigenous *Bacillus* spp. improves growth and yield of *Zea mays* under the influence of nanozeolite. *3 Biotech.* 11, 11. doi:10.1007/s13205-020-02561-2

Chavan, S., and Nadanathangam, V. (2019). Effects of nanoparticles on plant growth-promoting bacteria in Indian agricultural soil. *Agron. (Basel).* 9, 140. doi:10.3390/agronomy9030140

Chavan, S., Sarangdhar, V., and Nadanathangam, V. (2020). Toxicological effects of TiO_2 nanoparticles on plant growth promoting soil bacteria. *Emerg. Contam.* 6, 87–92. doi:10.1016/j.emcon.2020.01.003

Cherian, T., Maity, D., Rajendra Kumar, R. T., Balasubramani, G., Ragavendran, C., Yalla, S., et al. (2022). Green chemistry based gold nanoparticles synthesis using the marine bacterium *Lysinibacillus odysseyi* PBCW2 and their multitudinous activities. *Nanomaterials* 12, 2940. doi:10.3390/nano12172940

Chibuike, G. U., and Obiora, S. C. (2014). Heavy metal polluted soils: Effect on plants and bioremediation methods. *Appl. Environ. Soil Sci.* 2014, 1–12. doi:10.1155/2014/752708

Chouhan, G. K., Verma, J. P., Jaiswal, D. K., Mukherjee, A., Singh, S., De Araujo Pereira, A. P., et al. (2021). Phytomicrobiome for promoting sustainable agriculture and food security: Opportunities, challenges, and solutions. *Microbiol. Res.* 248, 126763. doi:10.1016/j.micres.2021.126763

Damodaran, T., Sharma, D., Mishra, V., Jha, S., Kannan, R., Sah, V., et al. (2013). Isolation of salt tolerant endophyticand rhizospheric bacteria by natural selection and screening for promising plant growth promoting rhizobacteria [PGPR] and growth vigour in tomato under sodic soil. *Afr. J. Microbiol. Res.* 7, 5082–5089.

Das, P., Williams, C. J., Fulthorpe, R. R., Hoque, M. E., Metcalfe, C. D., and Xenopoulos, M. A. (2012). Changes in bacterial community structure after exposure to silver nanoparticles in natural waters. *Environ. Sci. Technol.* 46, 9120–9128. doi:10.1021/es3019918

Daudi, A., Cheng, Z., O'brien, J. A., Mammarella, N., Khan, S., Ausubel, F. M., et al. (2012). The apoplastic oxidative burst peroxidase in *Arabidopsis* is a major component of pattern-triggered immunity. *Plant Cell* 24, 275–287. doi:10.1105/tpc.111.093039

Davar, Z. F., Roozbahani, A., and Hosnamidi, A. (2014). Evaluation the effect of water stress and foliar application of Fe nanoparticles on yield, yield components and oil percentage of safflower (*Carthamus tinctorious* L.) *Int. J. Adv. Biol. Biomed. Res.* 2, 1150–1159.

Degenhardt, B., and Gimmler, H. (2000). Cell wall adaptations to multiple environmental stresses in maize roots. *J. Exp. Bot.* 51, 595–603. doi:10.1093/jexbot/51.344.595

Devi, L. S., and Joshi, S. (2015). Ultrastructures of silver nanoparticles biosynthesized using endophytic fungi. *J. Microsc. Ultrastruct.* 3, 29–37. doi:10.1016/j.jmau.2014.10.004

Dimkpa, C. O., Mclean, J. E., Britt, D. W., and Anderson, A. J. (2012). CuO and ZnO nanoparticles differently affect the secretion of fluorescent siderophores in the beneficial root colonizer, *Pseudomonas chlororaphis* O6. *Nanotoxicology* 6, 635–642. doi:10.3109/17435390.2011.598246

Dinesh, B., Monisha, N., Shalini, H. R., Prathap, G. K., Poyya, J., Shantaram, M., et al. (2022). Antibacterial activity of silver nanoparticles synthesized using endophytic fungus - *Penicillium cinnamopurpureum*. *Spectrosc. Lett.* 55, 20–34. doi:10.1080/00387010.2021.2010764

Ding, Y., Peng, N., Du, Y., Ji, L., and Cao, B. (2014). Disruption of putrescine biosynthesis in *Shewanella oneidensis* enhances biofilm cohesiveness and performance in Cr (VI) immobilization. *Appl. Environ. Microbiol.* 80, 1498–1506. doi:10.1128/aem.03461-13

Dutta, G., and Sugumaran, A. (2021). Bioengineered zinc oxide nanoparticles: Chemical, green, biological fabrication methods and its potential biomedical applications. *J. Drug Deliv. Sci. Technol.* 66, 102853. doi:10.1016/j.jddst.2021.102853

Egamberdieva, D. J. (2009). Alleviation of salt stress by plant growth regulators and IAA producing bacteria in wheat. *Acta Physiol. Plant.* 31, 861–864. doi:10.1007/s11738-009-0297-0

Eid, A. M., Fouda, A., Abdel-Rahman, M. A., Salem, S. S., Elsaied, A., Oelmüller, R., et al. (2021). Harnessing bacterial endophytes for promotion of plant growth and biotechnological applications: An overview. *Plants (Basel).* 10, 935. doi:10.3390/plants10050935

Eida, A. A., Alzubaidy, H. S., De Zélicourt, A., Synek, L., Alsharif, W., Lafi, F. F., et al. (2019). Phylogenetically diverse endophytic bacteria from desert plants induce transcriptional changes of tissue-specific ion transporters and salinity stress in *Arabidopsis thaliana*. *Plant Sci.* 280, 228–240. doi:10.1016/j.plantsci.2018.12.002

El-Gazzar, N., Almaary, K., Ismail, A., and Polizzi, G. (2020). Influence of *Funneliformismosseae* enhanced with titanium dioxide nanoparticles (TiO_2NPs) on *Phaseolus vulgaris* L. under salinity stress. *PLoS One* 15, e0243491. doi:10.1371/journal.pone.0243491

Elemike, E. E., Uzoh, I. M., Onwudiwe, D. C., and Babalola, O. O. (2019). The role of nanotechnology in the fortification of plant nutrients and improvement of crop production. *Appl. Sci. (Basel).* 9, 499. doi:10.3390/app9030499

Elnahal, A. S. M., El-Saadony, M. T., Saad, A. M., Desoky, E.-S. M., El-Tahan, A. M., Rady, M. M., et al. (2022). The use of microbial inoculants for biological control, plant growth promotion, and sustainable agriculture: A review. *Eur. J. Plant Pathol.* 162, 759–792. doi:10.1007/s10658-021-02393-7

Elsheerya, N. I., Sunoja, V. S. J., Wena, Y., Zhua, J. J., Muralidharana, G., and Cao, K. F. (2020). Foliar application of nanoparticles mitigates the chilling effect on photosynthesis and photoprotection in sugarcane. *Plant Physiol. biochem.* 149, 50–60. doi:10.1016/j.plaphy.2020.01.035

Emamverdian, A., Ding, Y., Mokhberdoran, F., and Xie, Y. (2015). Heavy metal stress and some mechanisms of plant defense response. *Sci. World J.* 2015, 1–18. doi:10.1155/2015/756120

Fabrega, J., Zhang, R., Renshaw, J. C., Liu, W.-T., and Lead, J. R. (2011). Impact of silver nanoparticles on natural marine biofilm bacteria. *Chemosphere* 85, 961–966. doi:10.1016/j.chemosphere.2011.06.066

Fadiji, A. E., Mortimer, P. E., Xu, J., Ebenso, E. E., and Babalola, O. O. (2022a). Biosynthesis of nanoparticles using endophytes: A novel approach for enhancing plant growth and sustainable agriculture. *Sustainability* 14, 10839. doi:10.3390/su141710839

Fadiji, A. E., Onwudiwe, D. C., Mthiyane, D. M. N. B., and Oluranti, O. (2022b). Harnessing the known and unknown impact of nanotechnology on enhancing food security and reducing postharvest losses: Constraints and future prospects. *Agron. (Basel).* 12, 1657. doi:10.3390/agronomy12071657

Faiz, S., Yasin, N. A., Khan, W. U., Shah, A. A., Akram, W., Ahmad, A., et al. (2022). Role of magnesium oxide nanoparticles in the mitigation of lead-induced stress in daucus carota: Modulation in polyamines and antioxidant enzymes. *Int. J. Phytoremediation* 24, 364–372. doi:10.1080/15226514.2021.1949263

Fan, P., Chen, D., He, Y., Zhou, Q., Tian, Y., and Gao, L. J. I. J. O. P. (2016). Alleviating salt stress in tomato seedlings using Arthrobacter and Bacillus megaterium isolated from the rhizosphere of wild plants grown on saline–alkaline lands. *Int. J. Phytoremediation* 18, 1113–1121. doi:10.1080/15226514.2016.1183583

FAO (2009). *Food Agriculture Organization of the United Nations. High level expert forum—how to feed the world in 2050.* Italy: Office of the Director, Agricultural Development Economics Division Rome.

Fasusi, O. A., Amoo, A. E., and Babalola, O. O. (2021). Characterization of plant growth-promoting rhizobacterial isolates associated with food plants in South Africa. *Antonie Leeuwenhoek* 114, 1683–1708. doi:10.1007/s10482-021-01633-4

Flemming, H., and Wingender, J. (2010). The biofilm matrix. *Nat. Rev. Microbiol.* 8, 623–633. doi:10.1038/nrmicro2415

Franco, D., Calabrese, G., Guglielmino, S. P. P., and Conoci, S. (2022). Metal-based nanoparticles: Antibacterial mechanisms and biomedical application. *Microorganisms* 10, 1778. doi:10.3390/microorganisms10091778

Franken, P. (2012). The plant strengthening root endophyte *Piriformospora indica*: Potential application and the biology behind. *Appl. Microbiol. Biotechnol.* 96, 1455–1464. doi:10.1007/s00253-012-4506-1

Frenk, S., Ben-Moshe, T., Dror, I., Berkowitz, B., and Minz, D. (2013). Effect of metal oxide nanoparticles on microbial community structure and function in two different soil types. *PloS One* 8, e84441. doi:10.1371/journal.pone.0084441

Fu, P. P., Xia, Q., Hwang, H.-M., Ray, P. C., and Yu, H. (2014). Mechanisms of nanotoxicity: Generation of reactive oxygen species. *J. Food Drug Anal.* 22, 64–75. doi:10.1016/j.jfda.2014.01.005

Gamalero, E., and Glick, B. R. (2022). Recent advances in bacterial amelioration of plant drought and salt stress. *Biology* 11, 437. doi:10.3390/biology11030437

Gangadoo, S., Xu, C., Cozzolino, D., Latham, K., Della Gaspera, E., Chapman, J., et al. (2022). Probing nanoscale interactions of antimicrobial zinc oxide quantum dots on bacterial and fungal cell surfaces. *Adv. Mat. Interfaces* 9, 2101484. doi:10.1002/admi.202101484

Ganie, S. A., Bhat, J. A., and Devoto, A. (2021). The influence of endophytes on rice fitness under environmental stresses. *Plant Mol. Biol.* 109, 447–467. doi:10.1007/s11103-021-01219-8

Gao, X., Zou, C., Wang, L., and Zhang, F. (2006). Silicon decreases transpiration rate and conductance from stomata of maize plants. *J. Plant Nutr.* 29, 1637–1647. doi:10.1080/01904160600851494

Gepstein, S., and Glick, B. R. (2013). Strategies to ameliorate abiotic stress-induced plant senescence. *Plant Mol. Biol.* 82, 623–633. doi:10.1007/s11103-013-0038-z

Giraldo, J. P., Landry, M. P., Faltermeier, S. M., Mcnicholas, T. P., Iverson, N. M., Boghossian, A. A., et al. (2014). Plant nanobionics approach to augment photosynthesis and biochemical sensing. *Nat. Mat.* 13, 400–408. doi:10.1038/nmat3890

Glick, B. R. (2004). Bacterial ACC deaminase and the alleviation of plant stress. *Adv. Appl. Microbiol.* 56, 291–312. doi:10.1016/S0065-2164(04)56009-4

Glick, B. R. (2020). *Beneficial plant-bacterial interactions*. 2nd Edition. Heidelberg: Springer, 383.

Glick, B. R., and Gamalero, E. (2021). Recent developments in the study of plant microbiomes. *Microorganisms* 9, 1533. doi:10.3390/microorganisms9071533

Gopalakrishnan, S., Sathya, A., Vijayabharathi, R., Varshney, R. K., Gowda, C., and Krishnamurthy, L. (2015). Plant growth promoting rhizobia: Challenges and opportunities. *3 Biotech.* 5, 355–377. doi:10.1007/s13205-014-0241-x

Gorai, P. S., Ghosh, R., Mandal, S., Ghosh, S., Chatterjee, S., Gond, S. K., et al. (2021). *Bacillus siamensis* CNE6- a multifaceted plant growth promoting endophyte of *Cicer arietinum* L. having broad spectrum antifungal activities and host colonizing potential. *Microbiol. Res.* 252, 126859. doi:10.1016/j.micres.2021.126859

Govindappa, M., Manasa, D., Vinaykiya, V., Dutta, S., Pawar, R., and Raghavendra, V. B. (2022). Screening of antibacterial and antioxidant activity of biogenically synthesized silver nanoparticles from *alternaria alternata*, endophytic fungus of *Dendrophthoe falcata*-a Parasitic Plant. *Bionanoscience* 12, 128–141. doi:10.1007/s12668-021-00932-4

Gunjan, B., and Zaidi, M. (2014). Impact of gold nanoparticles on physiological and biochemical characteristics of *Brassica juncea*. *J. Plant Biochem. Physiol.* 2, 1000133.

Gupta, S., Schillaci, M., Walker, R., Smith, P. M. C., Watt, M., and Roessner, U. (2021). Alleviation of salinity stress in plants by endophytic plant-fungal symbiosis: Current knowledge, perspectives and future directions. *Plant Soil* 461, 219–244. doi:10.1007/s11104-020-04618-w

Gürsoy, N., Yilmaz Öztürk, B., and Dağ, İ. (2021). Synthesis of intracellular and extracellular gold nanoparticles with a green machine and its antifungal activity. *Turk. J. Biol.* 45, 196–213. doi:10.3906/biy-2010-64

Haghighi, M., Abolghasemi, R., and Da Silva, J. a. T. (2014). Low and high temperature stress affect the growth characteristics of tomato in hydroponic culture with Se and nano-Se amendment. *Sci. Hortic.* 178, 231–240. doi:10.1016/j.scienta.2014.09.006

Halliwell, B., and Gutteridge, J. M. (2015). *Free radicals in biology and medicine*. USA: Oxford University Press.

Hanaka, A., Ozimek, E., Reszczyńska, E., Jaroszuk-Ściseł, J., and Stolarz, M. (2021). Plant tolerance to drought stress in the presence of supporting bacteria and fungi: An efficient strategy in horticulture. *Horticulturae* 7, 390. doi:10.3390/horticulturae7100390

Hasanpour, H., Maali-Amir, R., and Zeinali, H. (2015). Effect of TiO_2 nanoparticles on metabolic limitations to photosynthesis under cold in chickpea. *Russ. J. Plant Physiol.* 62, 779–787. doi:10.1134/s1021443715060096

Hasanuzzaman, M., Bhuyan, M., Anee, T. I., Parvin, K., Nahar, K., Mahmud, J. A., et al. (2019). Regulation of ascorbate-glutathione pathway in mitigating oxidative damage in plants under abiotic stress. *Antioxidants* 8, 384. doi:10.3390/antiox8090384

Hasanuzzaman, M., Nahar, K., and Fujita, M. (2013). "Extreme temperature responses, oxidative stress and antioxidant defense in plants," in *Abiotic stress-plant responses and applications in agriculture*. Editors K. Vahdat and C. Leslie (Rijeka: InTech), 169–205. doi:10.5772/54833

Hasanuzzaman, M., Nahar, K., and Fujita, M. (2014). "Silicon and selenium: Two vital trace elements that confer abiotic stress tolerance to plants," in *Emerging technologies and management of crop stress tolerance* (Elsevier), 377–422.

Hattori, T., Inanaga, S., Araki, H., An, P., Morita, S., Luxová, M., et al. (2005). Application of silicon enhanced drought tolerance in *Sorghum bicolor*. *Physiol. Plant.* 123, 459–466. doi:10.1111/j.1399-3054.2005.00481.x

Hayat, R., Ali, S., Amara, U., Khalid, R., and Ahmed, I. (2010). Soil beneficial bacteria and their role in plant growth promotion: A review. *Ann. Microbiol.* 60, 579–598. doi:10.1007/s13213-010-0117-1

He, C., Zeng, Q., Chen, Y., Chen, C., Wang, W., Hou, J., et al. (2021). Colonization by dark septate endophytes improves the growth and rhizosphere soil microbiome of licorice plants under different water treatments. *Appl. Soil Ecol.* 166, 103993. doi:10.1016/j.apsoil.2021.103993

He, L., Liu, Y., Mustapha, A., and Lin, M. (2011). Antifungal activity of zinc oxide nanoparticles against *Botrytis cinerea* and *Penicillium expansum*. *Microbiol. Res.* 166, 207–215. doi:10.1016/j.micres.2010.03.003

Hmaeid, N., Wali, M., Mahmoud, O. M.-B., Pueyo, J. J., Ghnaya, T., and Abdelly, C. (2019). Efficient rhizobacteria promote growth and alleviate NaCl-induced stress in the plant species *Sulla carnosa*. *Appl. Soil Ecol.* 133, 104–113. doi:10.1016/j.apsoil.2018.09.011

Hulikere, M. M., and Joshi, C. G. (2019). Characterization, antioxidant and antimicrobial activity of silver nanoparticles synthesized using marine endophytic fungus-*Cladosporium cladosporioides*. *Process Biochem.* 82, 199–204. doi:10.1016/j.procbio.2019.04.011

Hwang, H. H., Chien, P. R., Huang, F. C., Hung, S. H., Kuo, C. H., Deng, W. L., et al. (2021). A plant endophytic bacterium, *Burkholderia seminalis* strain 869T2, promotes plant growth in *Arabidopsis*, Pak Choi, Chinese Amaranth, Lettuces, and other vegetables. *Microorganisms* 9, 1703. doi:10.3390/microorganisms9081703

Ibrahim, E., Zhang, M., Zhang, Y., Hossain, A., Qiu, W., Chen, Y., et al. (2020). Green-synthesization of silver nanoparticles using endophytic bacteria isolated from garlic and its antifungal activity against Wheat *Fusarium* head blight pathogen *Fusarium graminearum*. *Nanomaterials* 10, 219. doi:10.3390/nano10020219

Igiehon, N. O., Babalola, O. O., Cheseto, X., and Torto, B. (2021). Effects of rhizobia and arbuscular mycorrhizal fungi on yield, size distribution and fatty acid of soybean seeds grown under drought stress. *Microbiol. Res.* 242, 126640. doi:10.1016/j.micres.2020.126640

Igiehon, O. N., and Babalola, O. O. (2021). Rhizobium and mycorrhizal fungal species improved soybean yield under drought stress conditions. *Curr. Microbiol.* 78, 1615–1627. doi:10.1007/s00284-021-02432-w

Imade, E. E., Ajiboye, T. O., Fadiji, A. E., Onwudiwe, D. C., and Babalola, O. O. (2022). Green synthesis of zinc oxide nanoparticles using plantain peel extracts and the evaluation of their antibacterial activity. *Sci. Afr.* 16, e01152. doi:10.1016/j.sciaf.2022.e01152

Iravani, S., Korbekandi, H., Mirmohammadi, S. V., and Zolfaghari, B. (2014). Synthesis of silver nanoparticles: Chemical, physical and biological methods. *Res. Pharm. Sci.* 9, 385–406.

Ishida, K., Cipriano, T. F., Rocha, G. M., Weissmüller, G., Gomes, F., Miranda, K., et al. (2013). Silver nanoparticle production by the fungus *Fusarium oxysporum*: Nanoparticle characterisation and analysis of antifungal activity against pathogenic yeasts. *Mem. Inst. Oswaldo Cruz* 109, 220–228. doi:10.1590/0074-0276130269

Jaberzadeh, A., Moaveni, P., Moghadam, H. R. T., and Zahedi, H. (2013). Influence of bulk and nanoparticles titanium foliar application on some agronomic traits, seed gluten and starch contents of wheat subjected to water deficit stress. *Not. Bot. Horti Agrobot. Cluj. Napoca.* 41, 201–207. doi:10.15835/nbha4119093

Jacoby, R., Peukert, M., Succurro, A., Koprivova, A., and Kopriva, S. (2017). The role of soil microorganisms in plant mineral nutrition—Current knowledge and future directions. *Front. Plant Sci.* 8, 1617. doi:10.3389/fpls.2017.01617

Jadoun, S., Chauhan, N. P. S., Zarrintaj, P., Barani, M., Varma, R. S., Chinnam, S., et al. (2022). Synthesis of nanoparticles using microorganisms and their applications: A review. *Environ. Chem. Lett.* 20, 3153–3197. doi:10.1007/s10311-022-01444-7

Jajoo, A., and Mathur, S. (2021). Role of arbuscular mycorrhizal fungi as an underground saviuor for protecting plants from abiotic stresses. *Physiol. Mol. Biol. Plants* 27, 2589–2603. doi:10.1007/s12298-021-01091-2

Jalil, S. U., and Ansari, M. I. (2019). Nanoparticles and abiotic stress tolerance in plants: Synthesis, action, and signaling mechanisms. *Plant Signal. Mol.* 2019, 549–561.

Jha, Y., and Subramanian, R. B. (2014). PGPR regulate caspase-like activity, programmed cell death, and antioxidant enzyme activity in paddy under salinity. *Physiol. Mol. Biol. Plants* 20, 201–207. doi:10.1007/s12298-014-0224-8

Jin, L., Son, Y., Deforest, J. L., Kang, Y. J., Kim, W., and Chung, H. (2014). Single-walled carbon nanotubes alter soil microbial community composition. *Sci. Total Environ.* 466, 533–538. doi:10.1016/j.scitotenv.2013.07.035

Kalteh, M., Alipour, Z. T., Ashraf, S., Marashi Aliabadi, M., and Falah Nosratabadi, A. (2018). Effect of silica nanoparticles on basil (*Ocimum basilicum*) under salinity stress. *J. Chem. Health Risks.* 4, 49–55.

Kang, S., Herzberg, M., Rodrigues, D. F., and Elimelech, M. (2008). Antibacterial effects of carbon nanotubes: Size does matter. *Langmuir* 24, 6409–6413. doi:10.1021/la800951v

Karuppanapandian, T., Wang, H. W., Prabakaran, N., Jeyalakshmi, K., Kwon, M., Manoharan, K., et al. (2011). 2, 4-dichlorophenoxyacetic acid-induced leaf senescence in mung bean (*Vigna radiata* L. *Wilczek*) and senescence inhibition by co-treatment with silver nanoparticles. *Plant Physiol. biochem.* 49, 168–177. doi:10.1016/j.plaphy.2010.11.007

Kaur, T., Bala, M., Kumar, G., and Vyas, A. (2022). Biosynthesis of zinc oxide nanoparticles via endophyte *Trichoderma viride* and evaluation of their antimicrobial and antioxidant properties. *Arch. Microbiol.* 204, 620. doi:10.1007/s00203-022-03218-9

Kaushal, M., and Wani, S. P. (2016). Plant-growth-promoting rhizobacteria: Drought stress alleviators to ameliorate crop production in drylands. *Ann. Microbiol.* 66, 35–42. doi:10.1007/s13213-015-1112-3

Khalid, M., Bilal, M., Hassani, D., Iqbal, H., Wang, H., and Huang, D. J. B. S. (2017). Mitigation of salt stress in white clover (*Trifolium repens*) by *Azospirillum brasilense* and its inoculation effect. *Bot. Stud.* 58, 5. doi:10.1186/s40529-016-0160-8

Khan, A., Zhao, X. Q., Javed, M. T., Khan, K. S., Bano, A., Shen, R. F., et al. (2016). *Bacillus pumilus* enhances tolerance in rice (*Oryza sativa* L.) to combined stresses of NaCl and high boron due to limited uptake of Na+. *Environ. Exp. Bot.* 124, 120–129. doi:10.1016/j.envexpbot.2015.12.011

Khati, P., Pankaj, P., Nisha, B., Kumar, R., and Sharma, A. (2018). Effect of nanozeolite and plant growth promoting rhizobacteria on maize. *3 Biotech.* 8, 141. doi:10.1007/s13205-018-1142-1

Khatoon, U. T., Rao, G. N., Mohan, M. K., Ramanaviciene, A., and Ramanavicius, A. (2018). Comparative study of antifungal activity of silver and gold nanoparticles synthesized by facile chemical approach. *J. Environ. Chem. Eng.* 6, 5837–5844. doi:10.1016/j.jece.2018.08.009

Kibbey, T. C., and Strevett, K. A. (2019). The effect of nanoparticles on soil and rhizosphere bacteria and plant growth in lettuce seedlings. *Chemosphere* 221, 703–707. doi:10.1016/j.chemosphere.2019.01.091

Kim, K.-J., Sung, W. S., Suh, B. K., Moon, S.-K., Choi, J.-S., Kim, J. G., et al. (2009). Antifungal activity and mode of action of silver nano-particles on *Candida albicans*. *Biometals* 22, 235–242. doi:10.1007/s10534-008-9159-2

Kohan-Baghkheirati, E., and Geisler-Lee, J. (2015). Gene expression, protein function and pathways of *Arabidopsis thaliana* responding to silver nanoparticles in comparison to silver ions, cold, salt, drought, and heat. *Nanomaterials* 5, 436–467. doi:10.3390/nano5020436

Komaresofla, B. R., Alikhani, H. A., Etesami, H., and Khoshkholgh-Sima, N. A. (2019). Improved growth and salinity tolerance of the halophyte *Salicornia* sp. by co–inoculation with endophytic and rhizosphere bacteria. *Appl. Soil Ecol.* 138, 160–170. doi:10.1016/j.apsoil.2019.02.022

Koné, Y., Alves, E., Silveira, P. R., Ferreira, A. N., De Medeiros, F. H. V., and Cruz-Magalhães, V. (2022). Control of blast disease caused by *Pyricularia oryzae* with *Epicoccum nigrum* and microscopic studies of their interaction with rice plants under greenhouse conditions. *Biol. Control* 167, 104840. doi:10.1016/j.biocontrol.2022.104840

Kumar, A., Patel, J. S., Meena, V. S., and Srivastava, R. (2019). Recent advances of PGPR based approaches for stress tolerance in plants for sustainable agriculture. *Biocatal. Agric. Biotechnol.* 20, 101271. doi:10.1016/j.bcab.2019.101271

Kumar, R., Sahoo, S., Joanni, E., Singh, R. K., Tan, W. K., Kar, K. K., et al. (2021). Recent progress on carbon-based composite materials for microwave electromagnetic interference shielding. *Carbon* 177, 304–331. doi:10.1016/j.carbon.2021.02.091

Kumar, V., and Nautiyal, C. S. (2022). Plant abiotic and biotic stress alleviation: From an endophytic microbial perspective. *Curr. Microbiol.* 79, 311. doi:10.1007/s00284-022-03012-2

Kumari, S., Sharma, A., Chaudhary, P., and Khati, P. (2020). Management of plant vigor and soil health using two agriusable nanocompounds and plant growth promotory rhizobacteria in Fenugreek. *3 Biotech.* 10, 461. doi:10.1007/s13205-020-02448-2

Kushwaha, P., Kashyap, P. L., Bhardwaj, A. K., Kuppusamy, P., Srivastava, A. K., and Tiwari, R. K. (2020). Bacterial endophyte mediated plant tolerance to salinity: Growth responses and mechanisms of action. *World J. Microbiol. Biotechnol.* 36, 26. doi:10.1007/s11274-020-2804-9

Larue, C., Baratange, C., Vantelon, D., Khodja, H., Surblé, S., Elger, A., et al. (2018). Influence of soil type on TiO_2 nanoparticle fate in an agro-ecosystem. *Sci. Total Environ.* 630, 609–617. doi:10.1016/j.scitotenv.2018.02.264

Laware, S., and Raskar, S. (2014). Effect of titanium dioxide nanoparticles on hydrolytic and antioxidant enzymes during seed germination in onion. *Int. J. Curr. Microbiol. App. Sci.* 3, 749–760.

Lee, S., Kim, K., Shon, H., Kim, S. D., and Cho, J. (2011). Biotoxicity of nanoparticles: Effect of natural organic matter. *J. Nanopart. Res.* 13, 3051–3061. doi:10.1007/s11051-010-0204-z

Lee, Y., Krishnamoorthy, R., Selvakumar, G., Kim, K., and Sa, T. (2015). Alleviation of salt stress in maize plant by co-inoculation of arbuscular mycorrhizal fungi and *Methylobacterium oryzae* CBMB20. *J. Korean Soc. Appl. Biol. Chem.* 58, 533–540. doi:10.1007/s13765-015-0072-4

Li, D., Cui, F., Zhao, Z., Liu, D., Xu, Y., Li, H., et al. (2014). The impact of titanium dioxide nanoparticles on biological nitrogen removal from wastewater and bacterial community shifts in activated sludge. *Biodegradation* 25, 167–177. doi:10.1007/s10532-013-9648-z

Li, J., Zhang, P., Ye, J., Zhang, G., and Cai, Y. (2019). Simultaneous *in-situ* remediation and fertilization of Cd-contaminated weak-alkaline farmland for wheat production. *J. Environ. Manage.* 250, 109528. doi:10.1016/j.jenvman.2019.109528

Li, Z., and Huang, J. (2014). Effects of nanoparticle hydroxyapatite on growth and antioxidant system in pakchoi (*Brassica chinensis* L.) from cadmium-contaminated soil. *J. Nanomater.* 2014, 470962.

Liang, Z., Das, A., and Hu, Z. (2010). Bacterial response to a shock load of nanosilver in an activated sludge treatment system. *Water Res.* 44, 5432–5438. doi:10.1016/j.watres.2010.06.060

Liu, B., Mu, L., Zhang, J., Han, X., and Shi, H. (2020). $TiO_2/Cu_2\ (OH)_2\ CO_3$ nanocomposite as efficient antimicrobials for inactivation of crop pathogens in agriculture. *Mater. Sci. Eng. C* 107, 110344. doi:10.1016/j.msec.2019.110344

Liu, H. Q., Lu, X. B., Li, Z. H., Tian, C. Y., and Song, J. (2021). The role of root-associated microbes in growth stimulation of plants under saline conditions. *Land Degrad. Dev.* 32, 3471–3486. doi:10.1002/ldr.3955

Liu, X., Jin, X., Cao, B., and Tang, C. Y. (2014). Bactericidal activity of silver nanoparticles in environmentally relevant freshwater matrices: Influences of organic matter and chelating agent. *J. Environ. Chem. Eng.* 2, 525–531. doi:10.1016/j.jece.2013.10.008

Lowry, G. V., Gregory, K. B., Apte, S. C., and Lead, J. R. (2012). Transformations of nanomaterials in the environment. *Environ. Sci. Technol.* 7, 6893–6899.

LubnaKhan, M. A., Asaf, S., Jan, R., Waqas, M., Kim, K.-M., et al. (2022). Endophytic fungus *Bipolaris* sp. CSL-1 induces salt tolerance in *Glycine max*. L via modulating its endogenous hormones, antioxidative system and gene expression. *J. Plant Interact.* 17, 319–332. doi:10.1080/17429145.2022.2036836

Lyu, D., Msimbira, L. A., Nazari, M., Antar, M., Pagé, A., Shah, A., et al. (2021). The coevolution of plants and microbes underpins sustainable agriculture. *Microorganisms* 9, 1036. doi:10.3390/microorganisms9051036

Mahmood, A., Amaya, R., Turgay, O. C., Yaprak, A. E., Taniguchi, T., and Kataoka, R. (2019). High salt tolerant plant growth promoting rhizobacteria from the common ice-plant *Mesembryanthemum crystallinum* L. *Rhizosphere* 9, 10–17. doi:10.1016/j.rhisph.2018.10.004

Mahmood, S., Daur, I., Al-Solaimani, S. G., Ahmad, S., Madkour, M. H., Yasir, M., et al. (2016). Plant growth promoting rhizobacteria and silicon synergistically enhance salinity tolerance of mung bean. *Front. Plant Sci.* 7, 876. doi:10.3389/fpls.2016.00876

Mallmann, E. J. J., Cunha, F. A., Castro, B. N., Maciel, A. M., Menezes, E. A., and Fechine, P. B. A. (2015). Antifungal activity of silver nanoparticles obtained by green synthesis. *Rev. Inst. Med. Trop. S. Paulo* 57, 165–167. doi:10.1590/s0036-46652015000200011

Martínez-Ballesta, M., Zapata, L., Chalbi, N., and Carvajal, M. (2016). Multiwalled carbon nanotubes enter broccoli cells enhancing growth and water uptake of plants exposed to salinity. *J. Nanobiotechnol.* 14, 42–14. doi:10.1186/s12951-016-0199-4

Masoumizadeh, M., Madani, M., Fatahian, S., and Shakib, P. (2022). Effect of silver nanoparticles (AgNPs) on *Candida albicans, Candida dubliniensis* and *Candida guilliermondii*. *Curr. Drug Ther.* 17, 50–55. doi:10.2174/1574885517666220221093456

Masrahi, A., Vandevoort, A. R., and Arai, Y. (2014). Effects of silver nanoparticle on soil-nitrification processes. *Arch. Environ. Contam. Toxicol.* 66, 504–513. doi:10.1007/s00244-013-9994-1

Massad, T. J., Dyer, L. A., and Vega C, G. (2012). Costs of defense and a test of the carbon-nutrient balance and growth-differentiation balance hypotheses for two co-occurring classes of plant defense. *PLoS One* 7, e47554. doi:10.1371/journal.pone.0047554

Mathur, V., and Ulanova, D. (2022). Microbial metabolites beneficial to plant hosts across ecosystems. *Microb. Ecol.* doi:10.1007/s00248-022-02073-x

Mazmancı, B., Könen Adıgüzel, S., Sadak, Y. S., Yetkin, D., Ay, H., and Adıgüzel, A. O. (2022). Antimicrobial, antibiofilm, and anticancer potential of silver nanoparticles synthesized using pigment-producing *Micromonospora* sp. SH121. *Prep. Biochem. Biotechnol.*, 1–13. doi:10.1080/10826068.2022.2101001

Mcquillan, J. (2010). Bacterial nanoparticle interactions. PhD thesis. Exeter: University of Exeter, 211.

Mcquillan, J. S., and Shaw, A. M. (2014). Differential gene regulation in the Ag nanoparticle and Ag+-induced silver stress response in *Escherichia coli:* A full transcriptomic profile. *Nanotoxicology* 8, 177–184. doi:10.3109/17435390.2013.870243

Meena, K. K., Kumar, M., Kalyuzhnaya, M. G., Yandigeri, M. S., Singh, D. P., Saxena, A. K., et al. (2012). Epiphytic pink-pigmented methylotrophic bacteria enhance germination and seedling growth of wheat (*Triticum aestivum*) by producing phytohormone. *Ant. Van Leeuwenhoek* 101, 777–786. doi:10.1007/s10482-011-9692-9

Meena, K. K., Sorty, A. M., Bitla, U. M., Choudhary, K., Gupta, P., Pareek, A., et al. (2017). Abiotic stress responses and microbe-mediated mitigation in plants: The omics strategies. *Front. Plant Sci.* 8, 172. doi:10.3389/fpls.2017.00172

Mickelbart, M. V., Hasegawa, P. M., and Bailey-Serres, J. (2015). Genetic mechanisms of abiotic stress tolerance that translate to crop yield stability. *Nat. Rev. Genet.* 16, 237–251. doi:10.1038/nrg3901

Mishra, R. C., Kalra, R., Dilawari, R., Goel, M., and Barrow, C. J. (2022). Bio-synthesis of *Aspergillus terreus* mediated gold nanoparticle: Antimicrobial, antioxidant, antifungal and *in vitro* cytotoxicity studies. *Materials* 15, 3877. doi:10.3390/ma15113877

Mittal, D., Kumar, A., Balasubramaniam, B., Thakur, R., Singh Siwal, S., Saini, V., et al. (2021). Synthesis of Biogenic silver nanoparticles using plant growth-promoting bacteria: Potential use as biocontrol agent against phytopathogens. *Biomat. Polym. Horiz.* 1, 22–31. doi:10.37819/bph.001.01.0130

Mohammadi, R., Maali-Amiri, R., and Abbasi, A. (2013). Effect of TiO_2 nanoparticles on chickpea response to cold stress. *Biol. Trace Elem. Res.* 152, 403–410. doi:10.1007/s12011-013-9631-x

Mohanty, A., Wu, Y., and Cao, B. (2014). Impacts of engineered nanomaterials on microbial community structure and function in natural and engineered ecosystems. *Appl. Microbiol. Biotechnol.* 98, 8457–8468. doi:10.1007/s00253-014-6000-4

Moreira, H., Pereira, S. I., Marques, A. P., Rangel, A. O., Castro, P. M. J. E. S., and Research, P. (2016). Mine land valorization through energy maize production enhanced by the application of plant growth-promoting rhizobacteria and arbuscular mycorrhizal fungi. *Environ. Sci. Pollut. Res.* 23, 6940–6950. doi:10.1007/s11356-015-5914-4

Moreno-Galván, A. E., Cortés-Patiño, S., Romero-Perdomo, F., Uribe-Vélez, D., Bashan, Y., and Bonilla, R. R. (2020). Proline accumulation and glutathione reductase activity induced by drought-tolerant rhizobacteria as potential mechanisms to alleviate drought stress in Guinea grass. *Appl. Soil Ecol.* 147, 103367. doi:10.1016/j.apsoil.2019.103367

Mostafa, E. M., Abdelgawad, M. A., Musa, A., Alotaibi, N. H., Elkomy, M. H., Ghoneim, M. M., et al. (2022). Chitosan silver and gold nanoparticle formation using endophytic fungi as powerful antimicrobial and anti-biofilm potentialities. *Antibiotics* 11, 668. doi:10.3390/antibiotics11050668

Mowafy, A. M., Fawzy, M. M., Gebreil, A., and Elsayed, A. (2021). Endophytic *Bacillus, Enterobacter,* and *Klebsiella* enhance the growth and yield of maize. *Acta Agric. Scand. Sect. B —. Soil & Plant Sci.* 71, 237–246. doi:10.1080/09064710.2021.1880621

Mueller, C. F., Laude, K., Mcnally, J. S., and Harrison, D. G. (2005). Redox mechanisms in blood vessels. *Arterioscler. Thromb. Vasc. Biol.* 25, 274–278. doi:10.1161/01.atv.0000149143.04821.eb

Mukhtar, S., Mirza, B. S., Mehnaz, S., Mirza, M. S., Mclean, J., and Malik, K. A. (2018). Impact of soil salinity on the microbial structure of halophyte rhizosphere microbiome. *World J. Microbiol. Biotechnol.* 34, 136. doi:10.1007/s11274-018-2509-5

Munns, R., and Tester, M. (2008). Mechanisms of salinity tolerance. *Annu. Rev. Plant Biol.* 59, 651–681. doi:10.1146/annurev.arplant.59.032607.092911

Nadeem, S. M., Zahir, Z. A., Naveed, M., and Nawaz, S. J. a. O. M. (2013). Mitigation of salinity-induced negative impact on the growth and yield of wheat by plant growth-promoting rhizobacteria in naturally saline conditions. *Ann. Microbiol.* 63, 225–232. doi:10.1007/s13213-012-0465-0

Nagy, A., Harrison, A., Sabbani, S., Munson, R. S., Jr, Dutta, P. K., and Waldman, W. J. (2011). Silver nanoparticles embedded in zeolite membranes: Release of silver ions and mechanism of antibacterial action. *Int. J. Nanomedicine* 6, 1833–1852. doi:10.2147/ijn.s24019

Nasr, F., Pateiro, M., Rabiei, V., Razavi, F., Formaneck, S., Gohari, G., et al. (2021). Chitosan-phenylalanine nanoparticles (Cs-Phe Nps) extend the postharvest life of Persimmon (*Diospyros kaki*) fruits under chilling stress. *Coatings* 11, 819. doi:10.3390/coatings11070819

Nasrollahi, A., Pourshamsian, K., and Mansourkiaee, P. (2011). Antifungal activity of silver nanoparticles on some of fungi. *Int. J. Nano Dimens.* 1, 233–239.

Nautiyal, C. S., Srivastava, S., Chauhan, P. S., Seem, K., Mishra, A., and Sopory, S. K. (2013). Plant growth-promoting bacteria *Bacillus amyloliquefaciens* NBRISN13 modulates gene expression profile of leaf and rhizosphere community in rice during salt stress. *Plant Physiol. biochem.* 66, 1–9. doi:10.1016/j.plaphy.2013.01.020

Naveed, M., Hussain, M. B., Zahir, Z. A., Mitter, B., and Sessitsch, A. (2014a). Drought stress amelioration in wheat through inoculation with *Burkholderia phytofirmans* strain PsJN. *Plant Growth Regul.* 73, 121–131. doi:10.1007/s10725-013-9874-8

Naveed, M., Mitter, B., Reichenauer, T. G., Wieczorek, K., and Sessitsch, A. (2014b). Increased drought stress resilience of maize through endophytic colonization by *Burkholderia phytofirmans* PsJN and *Enterobacter* sp. FD17. *Environ. Exp. Bot.* 97, 30–39. doi:10.1016/j.envexpbot.2013.09.014

Ndeddy Aka, R. J., and Babalola, O. O. (2016). Effect of bacterial inoculation of strains of *Pseudomonas aeruginosa, Alcaligenes feacalis* and *Bacillus subtilis* on germination, growth and heavy metal (Cd, Cr, and Ni) uptake of *Brassica juncea. Int. J. Phytoremediation* 18, 200–209. doi:10.1080/15226514.2015.1073671

Neethu, S., Midhun, S. J., Sunil, M., Soumya, S., Radhakrishnan, E., and Jyothis, M. (2018). Efficient visible light induced synthesis of silver nanoparticles by *Penicillium polonicum* ARA 10 isolated from *Chetomorpha antennina* and its antibacterial efficacy against *Salmonella enterica serovar Typhimurium*. *J. Photochem. Photobiol. B Biol.* 180, 175–185. doi:10.1016/j.jphotobiol.2018.02.005

Noukelag, S. K., Mewa-Ngongang, M., Ngqoloda, S., Kotsedi, L., Razanamahandry, L. C., Ntwampe, S. K. O., et al. (2022). *Influence of synthesis method on structural, morphological, magnetic, and antimicrobial properties of Fe-Ag nanoparticles*. *J. Inorg. Organomet. Polym. Mat.* doi:10.1007/s10904-022-02493-9

Nyberg, L., Turco, R. F., and Nies, L. (2008). Assessing the impact of nanomaterials on anaerobic microbial communities. *Environ. Sci. Technol.* 42, 1938–1943. doi:10.1021/es072018g

Oh, M.-M., Trick, H. N., and Rajashekar, C. (2009). Secondary metabolism and antioxidants are involved in environmental adaptation and stress tolerance in lettuce. *J. Plant Physiol.* 166, 180–191. doi:10.1016/j.jplph.2008.04.015

Ojuederie, O. B., Olanrewaju, O. S., and Babalola, O. O. (2019). Plant growth promoting rhizobacterial mitigation of drought stress in crop plants: Implications for sustainable agriculture. *Agron. (Basel).* 9, 712. doi:10.3390/agronomy9110712

Oleńska, E., Małek, W., Wójcik, M., Swiecicka, I., Thijs, S., and Vangronsveld, J. (2020). Beneficial features of plant growth-promoting rhizobacteria for improving plant growth and health in challenging conditions: A methodical review. *Sci. Total Environ.* 743, 140682. doi:10.1016/j.scitotenv.2020.140682

Omar, M., Osman, M., Kasim, W., and El-Daim, A. (2009). “Improvement of salt tolerance mechanisms of barley cultivated under salt stress using Azospirillum brasilense,” in *Salinity and water stress* (Springer), 133–147.

Omomowo, O. I., and Babalola, O. O. (2019). Bacterial and fungal endophytes: Tiny giants with immense beneficial potential for plant growth and sustainable agricultural productivity. *Microorganisms* 7, 481. doi:10.3390/microorganisms7110481

Ortiz, N., Armada, E., Duque, E., Roldán, A., and Azcón, R. (2015). Contribution of arbuscular mycorrhizal fungi and/or bacteria to enhancing plant drought tolerance under natural soil conditions: Effectiveness of autochthonous or allochthonous strains. *J. Plant Physiol.* 174, 87–96. doi:10.1016/j.jplph.2014.08.019

Ovais, M., Khalil, A. T., Islam, N. U., Ahmad, I., Ayaz, M., Saravanan, M., et al. (2018). Role of plant phytochemicals and microbial enzymes in biosynthesis of metallic nanoparticles. *Appl. Microbiol. Biotechnol.* 102, 6799–6814. doi:10.1007/s00253-018-9146-7

Palaniyandi, S., Damodharan, K., Yang, S., and Suh, J. (2014). *Streptomyces* sp. strain PGPA39 alleviates salt stress and promotes growth of 'Micro Tom'tomato plants. *J. Appl. Microbiol.* 117, 766–773. doi:10.1111/jam.12563

Pandey, G. (2018). Challenges and future prospects of agri-nanotechnology for sustainable agriculture in India. *Environ. Technol. Innov.* 11, 299–307. doi:10.1016/j.eti.2018.06.012

Pandey, V., Ansari, M. W., Tula, S., Yadav, S., Sahoo, R. K., Shukla, N., et al. (2016). Dose-dependent response of *Trichoderma harzianum* in improving drought tolerance in rice genotypes. *Planta* 243, 1251–1264. doi:10.1007/s00425-016-2482-x

Panichikkal, J., and Krishnankutty, R. E. (2022). Chitosan and gold nanoparticles supplementation for augmentation of indole-3-acetic acid production by rhizospheric *Pseudomonas aeruginosa* and plant growth enhancement. *Curr. Microbiol.* 79, 185. doi:10.1007/s00284-022-02850-4

Panigrahi, S., Mohanty, S., and Rath, C. C. (2020). Characterization of endophytic bacteria *Enterobacter cloacae* MG00145 isolated from *Ocimum sanctum* with indole acetic acid (IAA) production and plant growth promoting capabilities against selected crops. *S. Afr. J. Bot.* 134, 17–26. doi:10.1016/j.sajb.2019.09.017

Parida, A., and Das, A. (2005). Salt tolerance and salinity effects on plants: A review. *Ecotoxicol. Environ. Saf.* 60, 324–349. doi:10.1016/j.ecoenv.2004.06.010

Park, H.-J., Kim, J. Y., Kim, J., Lee, J.-H., Hahn, J.-S., Gu, M. B., et al. (2009). Silver-ion-mediated reactive oxygen species generation affecting bactericidal activity. *Water Res.* 43, 1027–1032. doi:10.1016/j.watres.2008.12.002

Pasala, R. K., Khan, M. I. R., Minhas, P. S., Sultana, R., Per, T., Deokate, P., et al. (2016). Can plant bioregulators minimize the crop productivity losses caused by drought, heat stress and salinity? An integrated review. *J. Appl. Bot. Food.* 89, 113–125.

Pawlett, M., Ritz, K., Dorey, R. A., Rocks, S., Ramsden, J., and Harris, J. A. (2013). The impact of zero-valent iron nanoparticles upon soil microbial communities is context dependent. *Environ. Sci. Pollut. Res.* 20, 1041–1049. doi:10.1007/s11356-012-1196-2

Pei, Z., Ming, D., Liu, D., Wan, G., Geng, X., Gong, H., et al. (2010). Silicon improves the tolerance to water-deficit stress induced by polyethylene glycol in wheat (*Triticum aestivum* L.) seedlings. *J. Plant Growth Regul.* 29, 106–115. doi:10.1007/s00344-009-9120-9

Pelletier, D. A., Suresh, A. K., Holton, G. A., Mckeown, C. K., Wang, W., Gu, B., et al. (2010). Effects of engineered cerium oxide nanoparticles on bacterial growth and viability. *Appl. Environ. Microbiol.* 76, 7981–7989. doi:10.1128/aem.00650-10

Petruccelli, R., Bartolini, G., Ganino, T., Zelasco, S., Lombardo, L., Perri, E., et al. (2022). Cold stress, freezing adaptation, varietal susceptibility of *Olea europaea* L.: A review. *Plants (Basel).* 11, 1367. doi:10.3390/plants11101367

Pinedo, I., Ledger, T., Greve, M., and Poupin, M. J. (2015). *Burkholderia phytofirmans* PsJN induces long-term metabolic and transcriptional changes involved in *Arabidopsis thaliana* salt tolerance. *Front. Plant Sci.* 6, 466. doi:10.3389/fpls.2015.00466

Prasad, P., Pisipati, S., Momčilović, I., and Ristic, Z. (2011). Independent and combined effects of high temperature and drought stress during grain filling on plant yield and chloroplast EF-Tu expression in spring wheat. *J. Agron. Crop Sci.* 197, 430–441. doi:10.1111/j.1439-037x.2011.00477.x

Premachandra, D., Hudek, L., Enez, A., Ballard, R., Barnett, S., Franco, C. M., et al. (2020). Assessment of the capacity of beneficial bacterial inoculants to enhance canola (*Brassica napus* L.) growth under low water activity. *Agron. (Basel).* 10, 1449. doi:10.3390/agronomy10091449

Prucek, R., Tuček, J., Kilianová, M., Panáček, A., Kvítek, L., Filip, J., et al. (2011). The targeted antibacterial and antifungal properties of magnetic nanocomposite of iron oxide and silver nanoparticles. *Biomaterials* 32, 4704–4713. doi:10.1016/j.biomaterials.2011.03.039

Qian, D., Liu, H., Hu, F., Song, S., and Chen, Y. (2022). Extracellular electron transfer-dependent Cr(VI)/sulfate reduction mediated by iron sulfide nanoparticles. *J. Biosci. Bioeng.* 134, 153–161. doi:10.1016/j.jbiosc.2022.05.005

Qian, Y., Yu, H., He, D., Yang, H., Wang, W., Wan, X., et al. (2013). Biosynthesis of silver nanoparticles by the endophytic fungus *Epicoccum nigrum* and their activity against pathogenic fungi. *Bioprocess Biosyst. Eng.* 36, 1613–1619. doi:10.1007/s00449-013-0937-z

Radzig, M., Nadtochenko, V., Koksharova, O., Kiwi, J., Lipasova, V., and Khmel, I. (2013). Antibacterial effects of silver nanoparticles on gram-negative bacteria: Influence on the growth and biofilms formation, mechanisms of action. *Colloids Surfaces B Biointerfaces* 102, 300–306. doi:10.1016/j.colsurfb.2012.07.039

Rahi, D. K., and Parmar, A. S. (2014). Mycosynthesis of silver nanoparticles by an endophytic *Penicillium* species of *Aloe vera* root, evaluation of their antibacterial and antibiotic enhancing activity. *Int. J. Nanomater. Biostructures.* 6, 160–166.

Rahman, S., Rahman, L., Khalil, A. T., Ali, N., Zia, D., Ali, M., et al. (2019). Endophyte-mediated synthesis of silver nanoparticles and their biological applications. *Appl. Microbiol. Biotechnol.* 103, 2551–2569. doi:10.1007/s00253-019-09661-x

Ramadoss, D., Lakkineni, V. K., Bose, P., Ali, S., and Annapurna, K. J. S. (2013). Mitigation of salt stress in wheat seedlings by halotolerant bacteria isolated from saline habitats. *SpringerPlus* 2, 6. doi:10.1186/2193-1801-2-6

Ramalingmam, P., Muthukrishnan, S., and Thangaraj, P. (2015). Biosynthesis of silver nanoparticles using an endophytic fungus, *Curvularia lunata* and its antimicrobial potential. *J. Nanosci. Nanoeng.* 1, 241–247.

Rana, K. L., Kour, D., Kaur, T., Devi, R., Yadav, A. N., Yadav, N., et al. (2020). Endophytic microbes: Biodiversity, plant growth-promoting mechanisms and potential applications for agricultural sustainability. *Antonie Leeuwenhoek* 113, 1075–1107. doi:10.1007/s10482-020-01429-y

Rani, A., Souche, Y. S., and Goel, R. (2009). Comparative assessment of *in situ* bioremediation potential of cadmium resistant acidophilic *Pseudomonas putida* 62BN and alkalophilic *Pseudomonas monteilli* 97AN strains on soybean. *Int. Biodeterior. Biodegrad.* 63, 62–66. doi:10.1016/j.ibiod.2008.07.002

Rashid, S., Charles, T. C., and Glick, B. R. (2012). Isolation and characterization of new plant growth-promoting bacterial endophytes. *Appl. Soil Ecol.* 61, 217–224. doi:10.1016/j.apsoil.2011.09.011

Raven, J. A. (1983). The transport and function of silicon in plants. *Biol. Rev.* 58, 179–207. doi:10.1111/j.1469-185x.1983.tb00385.x

Ravi, P., Somu, P., Acharya, D., Gomez, L. A., Thathapudi, J. J., Ramachandra, Y. L., et al. (2022). Isolation and phytochemical screening of endophytic fungi isolated from medicinal plant *Mappia foetida* and evaluation of its *in vitro* cytotoxicity in cancer. *Appl. Biochem. Biotechnol.* 194, 4570–4586. doi:10.1007/s12010-022-03929-1

Rawat, N., Sneh, L., and Singla-Pareek, A. P. (2020). Membrane dynamics during individual and combined abiotic stresses in plants and tools to study the same. *Physiol. Plant.* 171, 653–676.

Reddy, P. V. L., Hernandez-Viezcas, J., Peralta-Videa, J., and Gardea-Torresdey, J. (2016). Lessons learned: Are engineered nanomaterials toxic to terrestrial plants? *Sci. Total Environ.* 568, 470–479. doi:10.1016/j.scitotenv.2016.06.042

Rehman, H., Ali, W., Khan, N. Z., Aasim, M., Khan, T., and Khan, A. L. (2022). *Delphinium uncinatum* mediated biosynthesis of zinc oxide nanoparticles and *in-vitro* evaluation of their antioxidant, cytotoxic, antimicrobial, anti-diabetic, anti-inflammatory, and anti-aging activities. *Saudi J. Biol. Sci.* 30, 103485. doi:10.1016/j.sjbs.2022.103485

Rojas-Tapias, D., Moreno-Galván, A., Pardo-Díaz, S., Obando, M., Rivera, D., and Bonilla, R. (2012). Effect of inoculation with plant growth-promoting bacteria (PGPB) on amelioration of saline stress in maize (*Zea mays*). *Appl. Soil Ecol.* 61, 264–272. doi:10.1016/j.apsoil.2012.01.006

Rouet, M., Mathieu, Y., Barbier-Brygoo, H., and Laurière, C. (2006). Characterization of active oxygen-producing proteins in response to hypo-osmolarity in tobacco and *arabidopsis* cell suspensions: Identification of a cell wall peroxidase. *J. Exp. Bot.* 57, 1323–1332. doi:10.1093/jxb/erj107

Roy, A., Pandit, C., Gacem, A., Alqahtani, M. S., Bilal, M., Islam, S., et al. (2022). Biologically derived gold nanoparticles and their applications. *Bioinorg. Chem. Appl.* 2022, 1–13. doi:10.1155/2022/8184217

Sabaghnia, N., and Janmohammadi, M. (2015). "Effect of nano-silicon particles application on salinity tolerance in early growth of some lentil genotypes," in *Annales universitatis mariae curie-sklodowska, sectio C–biologia*, 39.

Sachdev, S., Ansari, S. A., Ansari, M. I., Fujita, M., and Hasanuzzaman, M. (2021). Abiotic stress and reactive oxygen species: Generation, signaling, and defense mechanisms. *Antioxidants* 10, 277. doi:10.3390/antiox10020277

Sadeghi, A., Karimi, E., Dahaji, P. A., Javid, M. G., Dalvand, Y., and Askari, H. (2018). Plant growth promoting activity of an auxin and siderophore producing isolate of *Streptomyces* under saline soil conditions. *World J. Microbiol. Biotechnol.* 34, 16. doi:10.1007/s11274-017-2393-4

Sadek, M. E., Shabana, Y. M., Sayed-Ahmed, K., and Abou-Tabl, A. H. (2022). Antifungal activities of sulfur and copper nanoparticles against cucumber postharvest diseases caused by *Botrytis cinerea* and *Sclerotinia sclerotiorum*. *J. Fungi (Basel).* 8, 412. doi:10.3390/jof8040412

Sahu, P. K., Thomas, P., Singh, S., and Gupta, A. (2020). Taxonomic and functional diversity of cultivable endophytes with respect to the fitness of cultivars against *Ralstonia solanacearum*. *J. Plant Dis. Prot. (2006).* 127, 667–676. doi:10.1007/s41348-020-00320-2

Saluja, B., Sharma, V. J. S., and Journal, S. (2014). Cadmium resistance mechanism in acidophilic and alkalophilic bacterial isolates and their application in bioremediation of metal-contaminated soil. *Soil Sediment Contam. Int. J.* 23, 1–17. doi:10.1080/15320383.2013.772094

Santhoshkumar, J., Sowmya, B., Kumar, S. V., and Rajeshkumar, S. (2019). Toxicology evaluation and antidermatophytic activity of silver nanoparticles synthesized using leaf extract of *Passiflora caerulea*. *S. Afr. J. Chem. Eng.* 29, 17–23. doi:10.1016/j.sajce.2019.04.001

Santoyo, G., Gamalero, E., and Glick, B. R. (2021a). Mycorrhizal-bacterial amelioration of plant abiotic and biotic stress. *Front. Sustain. Food Syst.* 5, 672881. doi:10.3389/fsufs.2021.672881

Santoyo, G., Guzmán-Guzmán, P., Parra-Cota, F. I., Santos-Villalobos, S. D. L., Orozco-Mosqueda, M. D. C., and Glick, B. R. (2021b). Plant growth stimulation by microbial consortia. *Agron. (Basel).* 11, 219. doi:10.3390/agronomy11020219

Santoyo, G., Moreno-Hagelsieb, G., Del Carmen Orozco-Mosqueda, M., and Glick, B. R. (2016). Plant growth-promoting bacterial endophytes. *Microbiol. Res.* 183, 92–99. doi:10.1016/j.micres.2015.11.008

Saqib, S., Nazeer, A., Ali, M., Zaman, W., Younas, M., Shahzad, A., et al. (2022). Catalytic potential of endophytes facilitates synthesis of biometallic zinc oxide nanoparticles for agricultural application. *BioMetals* 35, 967–985. doi:10.1007/s10534-022-00417-1

Sardar, R., Ahmed, S., and Yasin, N. A. (2022). Titanium dioxide nanoparticles mitigate cadmium toxicity in Coriandrum sativum L. through modulating antioxidant system, stress markers and reducing cadmium uptake. *Environ. Pollut.* 292, 118373. doi:10.1016/j.envpol.2021.118373

Savvas, D., Giotis, D., Chatzieustratiou, E., Bakea, M., and Patakioutas, G. (2009). Silicon supply in soilless cultivations of zucchini alleviates stress induced by salinity and powdery mildew infections. *Environ. Exp. Bot.* 65, 11–17. doi:10.1016/j.envexpbot.2008.07.004

Saxena, R., Tomar, R. S., and Kumar, M. (2016). Exploring nanobiotechnology to mitigate abiotic stress in crop plants. *J. Pharm. Sci. Res.* 8, 974.

Sedghi, M., Hadi, M., and Toluie, S. G. (2013). Effect of nano zinc oxide on the germination parameters of soybean seeds under drought stress. *Ser. Biol.* 16, 73.

Sen, S., and Chandrasekhar, C. (2014). Effect of PGPR on growth promotion of rice (*Oryza sativa* L.) under salt stress. *Asian J. Plant Sci. Res.* 4, 62–67.

Shabnam, N., Pardha-Saradhi, P., and Sharmila, P. (2014). Phenolics impart Au^{3+}-stress tolerance to cowpea by generating nanoparticles. *PLoS One* 9, e85242. doi:10.1371/journal.pone.0085242

Shah, V., Luxton, T. P., Walker, V. K., Brumfield, T., Yost, J., Shah, S., et al. (2016). Fate and impact of zero-valent copper nanoparticles on geographically-distinct soils. *Sci. Total Environ.* 573, 661–670. doi:10.1016/j.scitotenv.2016.08.114

Shahid, M., Zeyad, M. T., Syed, A., Singh, U. B., Mohamed, A., Bahkali, A. H., et al. (2022). Stress-tolerant endophytic isolate *Priestia aryabhattai* BPR-9 modulates physio-biochemical mechanisms in wheat (*Triticum aestivum* L.) for enhanced salt tolerance. *Int. J. Environ. Res. Public Health* 19, 10883. doi:10.3390/ijerph191710883

Sharma, A., Sagar, A., Rana, J., and Rani, R. (2022). Green synthesis of silver nanoparticles and its antibacterial activity using fungus *Talaromyces purpureogenus* isolated from *Taxus baccata* Linn. *Micro Nano Syst. Lett.* 10, 2–12. doi:10.1186/s40486-022-00144-9

Sharma, A., Shankhdhar, D., and Shankhdhar, S. (2013). Enhancing grain iron content of rice by the application of plant growth promoting rhizobacteria. *Plant Soil Environ.* 59, 89–94. doi:10.17221/683/2012-pse

Sharma, P., Jha, A. B., Dubey, R. S., and Pessarakli, M. (2012). Reactive oxygen species, oxidative damage, and antioxidative defense mechanism in plants under stressful conditions. *J. Bot.* 2012, 1–26. doi:10.1155/2012/217037

Sheikhalipour, M., Esmaielpour, B., Behnamian, M., Gohari, G., Giglou, M. T., Vachova, P., et al. (2021). Chitosan–selenium nanoparticle (Cs–Se NP) foliar spray alleviates salt stress in bitter melon. *Nanomaterials* 11, 684. doi:10.3390/nano11030684

Sherin, G., Raj-Aswathi, K. P., and Puthur, J. T. (2022). Photosynthetic functions in plants subjected to stresses are positively influenced by priming. *Plant Stress* 4, 100079. doi:10.1016/j.stress.2022.100079

Shilev, S., Sancho, E. D., and Benlloch-González, M. J. (2012). Rhizospheric bacteria alleviate salt-produced stress in sunflower. *J. Environ. Manage.* 95, S37–S41. doi:10.1016/j.jenvman.2010.07.019

Shinde, B. H., Inamdar, S. N., Nalawade, S. A., and Chaudhari, S. B. (2022). A systematic review on antifungal and insecticidal applications of biosynthesized metal nanoparticles. *Mater. Today Proc.* doi:10.1016/j.matpr.2022.09.548

Shirinbayan, S., Khosravi, H., and Malakouti, M. J. (2019). Alleviation of drought stress in maize (*Zea mays*) by inoculation with *Azotobacter* strains isolated from semi-arid regions. *Appl. Soil Ecol.* 133, 138–145. doi:10.1016/j.apsoil.2018.09.015

Shukla, P. S., Agarwal, P. K., and Jha, B. J. J. O. P. G. R. (2012). Improved salinity tolerance of *Arachis hypogaea* (L.) by the interaction of halotolerant plant-growth-promoting rhizobacteria. *J. Plant Growth Regul.* 31, 195–206. doi:10.1007/s00344-011-9231-y

Silambarasan, S., Logeswari, P., Valentine, A., and Cornejo, P. (2019). Role of *Curtobacterium herbarum* strain CAH5 on aluminum bioaccumulation and enhancement of *Lactuca sativa* growth under aluminum and drought stresses. *Ecotoxicol. Environ. Saf.* 183, 109573. doi:10.1016/j.ecoenv.2019.109573

Silambarasan, S., and Vangnai, A. S. (2017). Plant-growth promoting *Candida* sp. AVGB4 with capability of 4-nitroaniline biodegradation under drought stress. *Ecotoxicol. Environ. Saf.* 139, 472–480. doi:10.1016/j.ecoenv.2017.02.018

Simontacchi, M., Galatro, A., Ramos-Artuso, F., and Santa-María, G. E. (2015). Plant survival in a changing environment: The role of nitric oxide in plant responses to abiotic stress. *Front. Plant Sci.* 6, 977. doi:10.3389/fpls.2015.00977

Singh, D. P., Prabha, R., Yandigeri, M. S., and Arora, D. K. (2011). Cyanobacteria-mediated phenylpropanoids and phytohormones in rice (*Oryza sativa*) enhance plant growth and stress tolerance. *Ant. Van Leeuwenhoek* 100, 557–568. doi:10.1007/s10482-011-9611-0

Singh, D., Rathod, V., Ninganagouda, S., Herimath, J., and Kulkarni, P. (2013). Biosynthesis of silver nanoparticle by endophytic fungi *Pencillium* sp. isolated from *Curcuma longa* (turmeric) and its antibacterial activity against pathogenic gram negative bacteria. *J. Pharm. Res.* 7, 448–453. doi:10.1016/j.jopr.2013.06.003

Singh, J., and Lee, B.-K. (2016). Influence of nano-TiO_2 particles on the bioaccumulation of Cd in soybean plants (*Glycine max*): A possible mechanism for the removal of Cd from the contaminated soil. *J. Environ. Manage.* 170, 88–96. doi:10.1016/j.jenvman.2016.01.015

Singh, J., Perumal, V., Singh, U., Tripathi, D. K., and Sharma, S. (2022a). Green synthesis of silver nanoparticles from bark extract of *terminalia arjuna* and their application as next generation antibacterial agents. *Curr. Nanosci.* 18, 743–757. doi:10.2174/1573413718666220221102909

Singh, J., Vishwakarma, K., Ramawat, N., Rai, P., Singh, V. K., Mishra, R. K., et al. (2019). Nanomaterials and microbes' interactions: A contemporary overview. *3 Biotech.* 9, 68–14. doi:10.1007/s13205-019-1576-0

Singh, M., Qureshi, K. A., Jaremko, M., Rajput, M., Singh, S. K., KaushalendraPandey, K. D., et al. (2022b). Bioprospects of endophytic bacteria in plant growth promotion and ag-nanoparticle biosynthesis. *Plants (Basel).* 11, 1787. doi:10.3390/plants11141787

Soliman, A. M., Abdel-Latif, W., Shehata, I. H., Fouda, A., Abdo, A. M., and Ahmed, Y. M. (2021). Green approach to overcome the resistance pattern of *Candida* spp. using biosynthesized silver nanoparticles fabricated by *Penicillium chrysogenum* F9. *Biol. Trace Elem. Res.* 199, 800–811. doi:10.1007/s12011-020-02188-7

Soltani Nejad, M., Samandari Najafabadi, N., Aghighi, S., Pakina, E., and Zargar, M. (2022). Evaluation of *Phoma* sp. biomass as an endophytic fungus for synthesis of extracellular gold nanoparticles with antibacterial and antifungal properties. *Molecules* 27, 1181. doi:10.3390/molecules27041181

Sonawane, H., Shelke, D., Chambhare, M., Dixit, N., Math, S., Sen, S., et al. (2022). Fungi-derived agriculturally important nanoparticles and their application in crop stress management–Prospects and environmental risks. *Environ. Res.* 212, 113543. doi:10.1016/j.envres.2022.113543

Sonbol, H., Mohammed, A., and Korany, S. M. (2022). Soil fungi as biomediator in silver nanoparticles formation and antimicrobial efficacy. *Int. J. Nanomedicine* 17, 2843–2863. doi:10.2147/ijn.s356724

Sonkar, S., Pandey, B., Rathore, S. S., Sharma, L., and Singh, A. K. (2021). "Applications of nanobiotechnology in overcoming temperature stress," in *Nanobiotechnology*. Editors J. M. Al-Khayri, M. I. Ansari, and A. K. Singh (Cham: Springer), 417–435.

Sorty, A. M., Meena, K. K., Choudhary, K., Bitla, U. M., Minhas, P., and Krishnani, K. (2016). Effect of plant growth promoting bacteria associated with halophytic weed (*Psoralea corylifolia* L) on germination and seedling growth of wheat under saline conditions. *Appl. Biochem. Biotechnol.* 180, 872–882. doi:10.1007/s12010-016-2139-z

Suarez, C., Cardinale, M., Ratering, S., Steffens, D., Jung, S., Montoya, A. M. Z., et al. (2015). Plant growth-promoting effects of *Hartmannibacter diazotrophicus* on summer barley (*Hordeum vulgare* L.) under salt stress. *Appl. Soil Ecol.* 95, 23–30. doi:10.1016/j.apsoil.2015.04.017

Sun, C., Johnson, J. M., Cai, D., Sherameti, I., Oelmüller, R., and Lou, B. (2010). *Piriformospora indica* confers drought tolerance in Chinese cabbage leaves by stimulating antioxidant enzymes, the expression of drought-related genes and the plastid-localized CAS protein. *J. Plant Physiol.* 167, 1009–1017. doi:10.1016/j.jplph.2010.02.013

Sunkar, S., and Nachiyar, C. V. (2012a). Biogenesis of antibacterial silver nanoparticles using the endophytic bacterium *Bacillus cereus* isolated from *Garcinia xanthochymus*. *Asian pac. J. Trop. Biomed.* 2, 953–959. doi:10.1016/s2221-1691(13)60006-4

Sunkar, S., and Nachiyar, C. V. (2012b). Microbial synthesis and characterization of silver nanoparticles using the endophytic bacterium *Bacillus cereus*: A novel source in the benign synthesis. *Glob. J. Med. Res.* 12, 43–50.

Teheran-Sierra, L. G., Funnicelli, M. I. G., De Carvalho, L. a. L., Ferro, M. I. T., Soares, M. A., and Pinheiro, D. G. (2021). Bacterial communities associated with sugarcane under different agricultural management exhibit a diversity of plant growth-promoting traits and evidence of synergistic effect. *Microbiol. Res.* 247, 126729. doi:10.1016/j.micres.2021.126729

Thepbandit, W., Papathoti, N. K., Daddam, J. R., Thumanu, K., Siriwong, S., Thanh, T. L., et al. (2021). Identification of salicylic acid mechanism against leaf blight disease in *Oryza sativa* by SR-FTIR microspectroscopic and docking studies. *Pathogens* 10, 652. doi:10.3390/pathogens10060652

Thiagarajan, V., and Ramasubbu, S. (2021). Fate and behaviour of TiO_2 nanoparticles in the Soil: Their impact on staple food crops. *Water Air Soil Pollut.* 232, 274–318. doi:10.1007/s11270-021-05219-8

Thomas, T. T, D., and Puthur, J. T. (2017). UV radiation priming: A means of amplifying the inherent potential for abiotic stress tolerance in crop plants. *Environ. Exp. Bot.* 138, 57–66. doi:10.1016/j.envexpbot.2017.03.003

Tittabutr, P., Piromyou, P., Longtonglang, A., Noisa-Ngiam, R., Boonkerd, N., and Teaumroong, N. (2013). Alleviation of the effect of environmental stresses using co-inoculation of mungbean by *Bradyrhizobium* and rhizobacteria containing stress-induced ACC deaminase enzyme. *Soil Sci. Plant Nutr.* 59, 559–571. doi:10.1080/00380768.2013.804391

Tiwari, S., Lata, C., Chauhan, P. S., and Nautiyal, C. S. (2016). *Pseudomonas putida* attunes morphophysiological, biochemical and molecular responses in *Cicer arietinum* L. during drought stress and recovery. *Plant Physiol. biochem.* 99, 108–117. doi:10.1016/j.plaphy.2015.11.001

Tripathi, D. K., Singh, V. P., Prasad, S. M., Chauhan, D. K., and Dubey, N. K. (2015). Silicon nanoparticles (SiNp) alleviate chromium (VI) phytotoxicity in *Pisum sativum* (L.) seedlings. *Plant Physiol. biochem.* 96, 189–198. doi:10.1016/j.plaphy.2015.07.026

Turbat, A., Rakk, D., Vigneshwari, A., Kocsubé, S., Thu, H., Szepesi, Á., et al. (2020). Characterization of the plant growth-promoting activities of endophytic fungi isolated from *Sophora flavescens*. *Microorganisms* 8, 683. doi:10.3390/microorganisms8050683

Tuteja, N., and Mahajan, S. (2007). Calcium signaling network in plants: An overview. *Plant Signal. Behav.* 2, 79–85. doi:10.4161/psb.2.2.4176

Tuteja, N., and Sopory, S. K. (2008). Chemical signaling under abiotic stress environment in plants. *Plant Signal. Behav.* 3, 525–536. doi:10.4161/psb.3.8.6186

Umapathy, V. R., Natarajan, P. M., Sumathijones, C., Swamikannu, B., Johnson, W. M. S., Alagarsamy, V., et al. (2022). Current trends and future perspectives on dental nanomaterials – an overview of nanotechnology strategies in dentistry. *J. King Saud Univ. - Sci.* 34, 102231. doi:10.1016/j.jksus.2022.102231

Upadhyay, S., Singh, J., and Singh, D. P. (2011). Exopolysaccharide-producing plant growth-promoting rhizobacteria under salinity condition. *Pedosphere* 21, 214–222. doi:10.1016/s1002-0160(11)60120-3

Van Nguyen, D., Nguyen, H. M., Le, N. T., Nguyen, K. H., Nguyen, H. T., Le, H. M., et al. (2022). Copper nanoparticle application enhances plant growth and grain yield in maize under drought stress conditions. *J. Plant Growth Regul.* 41, 364–375. doi:10.1007/s00344-021-10301-w

Varshney, R. K., Bansal, K. C., Aggarwal, P. K., Datta, S. K., and Craufurd, P. Q. (2011). Agricultural biotechnology for crop improvement in a variable climate: Hope or hype? *Trends Plant Sci.* 16, 363–371. doi:10.1016/j.tplants.2011.03.004

Vimal, S. R., Patel, V. K., and Singh, J. S. (2019). Plant growth promoting *Curtobacterium albidum* strain SRV4: An agriculturally important microbe to alleviate salinity stress in paddy plants. *Ecol. Indic.* 105, 553–562. doi:10.1016/j.ecolind.2018.05.014

Vurukonda, S. S. K. P., Vardharajula, S., Shrivastava, M., and Skz, A. J. R. (2016). Multifunctional *Pseudomonas putida* strain FBKV2 from arid rhizosphere soil and its growth promotional effects on maize under drought stress. *Rhizosphere* 1, 4–13. doi:10.1016/j.rhisph.2016.07.005

Wahid, A. (2007). Physiological implications of metabolite biosynthesis for net assimilation and heat-stress tolerance of sugarcane (*Saccharum officinarum*) sprouts. *J. Plant Res.* 120, 219–228. doi:10.1007/s10265-006-0040-5

Wang, C. Y., Makvandi, P., Zare, E. N., Tay, F. R., and Niu, L. N. (2020). Advances in antimicrobial organic and inorganic nanocompounds in biomedicine. *Adv. Ther. (Weinh).* 3, 2000024. doi:10.1002/adtp.202000024

Worms, I. A., Boltzman, J., Garcia, M., and Slaveykova, V. I. (2012). Cell-wall-dependent effect of carboxyl-CdSe/ZnS quantum dots on lead and copper availability to green microalgae. *Environ. Pollut.* 167, 27–33. doi:10.1016/j.envpol.2012.03.030

Wu, H., Yin, J.-J., Wamer, W. G., Zeng, M., and Lo, Y. M. (2014). Reactive oxygen species-related activities of nano-iron metal and nano-iron oxides. *J. Food Drug Anal.* 22, 86–94. doi:10.1016/j.jfda.2014.01.007

Wu, Z., Yue, H., Lu, J., and Li, C. J. (2012). Characterization of rhizobacterial strain Rs-2 with ACC deaminase activity and its performance in promoting cotton growth under salinity stress. *World J. Microbiol. Biotechnol.* 28, 2383–2393. doi:10.1007/s11274-012-1047-9

Xu, H., Lu, Y., and Tong, S. (2018). Effects of arbuscular mycorrhizal fungi on photosynthesis and chlorophyll fluorescence of maize seedlings under salt stress. *Emir. J. Food Agric.* 30, 199–204. doi:10.9755/ejfa.2018.v30.i3.1642

Yadav, A. N. (2017). Agriculturally important microbiomes: Biodiversity and multifarious PGP attributes for amelioration of diverse abiotic stresses in crops for sustainable agriculture. *Biomed. J. Sci. Tech. Res.* 1, 861–864. doi:10.26717/bjstr.2017.01.000321

Yang, Y., Chen, Q., Wall, J. D., and Hu, Z. (2012a). Potential nanosilver impact on anaerobic digestion at moderate silver concentrations. *Water Res.* 46, 1176–1184. doi:10.1016/j.watres.2011.12.024

Yang, Y., Mathieu, J. M., Chattopadhyay, S., Miller, J. T., Wu, T., Shibata, T., et al. (2012b). Defense mechanisms of *Pseudomonas aeruginosa* PAO1 against quantum dots and their released heavy metals. *ACS Nano* 6, 6091–6098. doi:10.1021/nn3011619

Yashavantha Rao, H. C., Nagendra-Prasad, M. N., Prasad, A., Harini, B. P., Azmath, P., Rakshith, D., et al. (2016). Biomimetic synthesis of silver nanoparticles using endosymbiotic bacterium inhabiting *Euphorbia hirta* L. and their bactericidal potential. *Scientifica* 2016, 9020239. doi:10.1155/2016/9020239

Yolcu, S., Ozdemir, F., Güler, A., and Bor, M. (2016). Histone acetylation influences the transcriptional activation of POX in *Beta vulgaris* L. and *Beta maritima* L. under salt stress. *Plant Physiol. biochem.* 100, 37–46. doi:10.1016/j.plaphy.2015.12.019

Younesi, O., and Moradi, A. J. A. (2014). Effects of plant growth-promoting rhizobacterium (PGPR) and arbuscular mycorrhizal fungus (AMF) on antioxidant enzyme activities in salt-stressed bean (*Phaseolus vulgaris* L.) *Agriculture* 60, 10–21. doi:10.2478/agri-2014-0002

Zare, A. S., Ganjeali, A., Kakhki, M. R. V., Cheniany, M., and Mashreghi, M. (2022). Plant elicitation and TiO2 nanoparticles application as an effective strategy for improving the growth, biochemical properties, and essential oil of peppermint. *Physiol. Mol. Biol. Plants* 28, 1391–1406.

Zhang, J., Wang, P., Tian, H., Jiang, H., Wang, Y., and Yan, C. J. S. (2018). Identification of interior salt-tolerant bacteria from ice plant *Mesembryanthemum crystallinum* and evaluation of their promoting effects. *Symbiosis* 76, 243–252. doi:10.1007/s13199-018-0551-6

Zhang, R., Tu, C., Zhang, H., and Luo, Y. (2020). Stability and transport of titanium dioxide nanoparticles in three variable-charge soils. *J. Soils Sediments* 20, 1395–1403. doi:10.1007/s11368-019-02509-x

Zhao, L., Peng, B., Hernandez-Viezcas, J. A., Rico, C., Sun, Y., Peralta-Videa, J. R., et al. (2012). Stress response and tolerance of Zea mays to CeO2 nanoparticles: Cross talk among H2O2, heat shock protein, and lipid peroxidation. *ACS Nano* 6, 9615–9622. doi:10.1021/nn302975u

Zhou, H., Wu, H., Zhang, F., Su, Y., Guan, W., Xie, Y., et al. (2021). Molecular basis of cerium oxide nanoparticle enhancement of rice salt tolerance and yield. *Environ. Sci. Nano* 8, 3294–3311. doi:10.1039/d1en00390a

Zhou, J., Li, P., Meng, D., Gu, Y., Zheng, Z., Yin, H., et al. (2020). Isolation, characterization and inoculation of Cd tolerant rice endophytes and their impacts on rice under Cd contaminated environment. *Environ. Pollut.* 260, 113990. doi:10.1016/j.envpol.2020.113990

Zulfiqar, F., Navarro, M., Ashraf, M., Akram, N. A., and Munné-Bosch, S. (2019). Nanofertilizer use for sustainable agriculture: Advantages and limitations. *Plant Sci.* 289, 110270. doi:10.1016/j.plantsci.2019.110270