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PHYSIOLOGICAL RESPONSES OF CROP PLANTS TO METAL AND CARBON NANOPARTICLES

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Abstract: The fast development of nanotechnology (NT) and the application of metal and carbon nanoparticles (NPs) to plants, disturbs their metabolic processes and influences positively or harmfully the morphophysiological responses. Numerous types of NPs employed as plant growth regulators, nanopesticides and nanofertilizers, have shown promising evidence so far for increasing crop yields, and managing salt and water stress at the field. Some metal-based NPs are considered a biosafe material for organisms. Earlier studies have demonstrated the potential of some NPs for seed germination stimulation and plant growth, as well as disease suppression and plant protection by virtue of their antimicrobial activity. In this article both positive and negative effects of metallic and carbon NPs on plant growth and metabolism are documented. Uptake, translocation, and accumulation of NPs by plants depend upon the distinct features of the NPs as well as on the physiology of the host plant. This review contributes to the current understanding of the outcome of NPs in cultivated plants, their absorption, translocation, physiological responses, and mitigation impacts to various adverse conditions on plant growth. The results presented here correspond to the evaluation of NPs in more than 30 crops, belonging to 19 plant families.
Keywords: Agronanotechnolgy, nanomaterials, nanoparticles.

INTRODUCTION

It is well known that different types of NPs are being used to improve agriculture systems; they can offer certain advantages, but there is a lack of knowledge regarding the complete toxicological effects of NPs on other biological systems such as fungi, insects, and animals. Therefore, is very important to apprise both, promotion and inhibition of physiological effects by plants. It is difficult to know the effect that certain NPs can cause when they are interacting with a living system (Paramo et al., 2020). First, the physicochemical characteristics of the NPs are the main cause of the generated effects; the morphology, surface charge, concentration, and size distribution, are properties that if they are modified individually can cause different results in the same system. Therefore, in this review, we focus on almost all types of NPs that researchers are investigated on crop plants, including carbon nanotubes, graphene, and metal-based NPs from cerium, copper, iron, titanium, selenium, silicon, silver and zinc. The results presented here describe the evaluation of NPs in more than 38 crops, belonging to 23 families (Table 1).

ZINC OXIDE NANOPARTICLES

Metallic nanoparticles like ZnO have fascinated scientists for over a century and are now heavily utilized in biomedical sciences, engineering and agriproducts. They are a focus of interest because of their huge potential in nanoagriculture and because ZnONPs exhibit attractive antibacterial properties due to increased specific surface area as the reduced particle size leading to enhanced particle surface reactivity (Pillai et al., 2020). Zinc molecules in soil are present in soluble form and roots also exudate organic acid, i.e. mucilage on the root surface, which helps in the dissolution of Zn. Mucilage is a hydrated polysaccharide, pectic compound around roots which enhances Zn aggregation on the root surface. This increases the Zn concentration in the nearby root and Zn ions start moving towards the concentration gradient through ion pores in roots (Kumar et al., 2021). After adsorption, ZnONPs increases the permeability of the cell wall by making "holes" in the wall and move through plasmodesmata showing symplastic movement. During soil-to-root uptake,

Nanoparticle	Agricultural crop	Family	Reference
ZnO	Habanero pepper (*Capsicum chinense*	Solanaceae	García-López et al., 2019
	Wheat (*Triticum aewstivum*)	Graminaceae	Anderson et al., 2017
	Pepper (*Capsicum annumm*)	Solanaceae	García-López et al., 2018
	Tomato (*Solanum lycopersicum*)	Solanaceae	Pejam et al., 2021
	Fenugreek (*Trigonella foenum*)	Fabaceae	Noohpisheh et al., 2021
	Eggplant (*Solanum melongena*)	Solanaceae	Semida et al., 2021
	Soybean (*Glycine max*)	Leguminoseae	Nair and Chung, 2014; Yusefi et al., 2020
CuO	Rice (*Oryza sativa*)	Graminaceae	Da Costa et al., 2016
	Wheat (*Triticum aestivum*)	Graminaceae	Anderson et al., 2017
	Rice (*Oryza sativa*)	Graminaceae	Peng et al., 2017
	Barley (*Hordeum sativum*)	Graminaceae	Burachevskaya et al., 2021
	Turnip (*Brassica rapa*)	Brassicaceae	Chung et al., 2019
FeO	Tobacco (*Nicotiana benthamiana*)	Solanaceae	Cai et al., 2020
	Pummelo (*Citrus maxima*)	Rutaceae	Hu et al., 2017
	Wheat (*Triticum aestivum*)	Graminaceae	Hussain et al., 2019
	Moldavian Balm (*Dracocephalum moldavica*)	Lamiaceae	Moradbeygi et al., 2020
	Mulberry (*Morus alba*)	Moraceae	Haydar et al., 2021
	Rice (*Oryza sativa*)	Graminaceae	Afzal et al., 2021
	Fenugreek (*Trigonella foenum-graecum*)	Fabaceae	Sadak, 2019
Ag	Onion (*Allium cepa*)	Liliaceae	Heikal et al., 2020
	Lettuce (*Lactuca sativa*)	Asteraceae	Hasan et al., 2021
	Garlic (*Allium sativum*)	Amaryllidaceae	Darwesh and Elshahawy, 2021
	Sugar beet (*Beta vulgaris*)	Amaranthaceae	Ghazy et al., 2021
CeO_2	Soybean (*Glycine max*)	Leguminoseae	Rossi et al., 2017
	Grapevine (*Vitis vinifera*)	Vitaceae	Gohari et al., 2021
	Cotton (*Gossypium hirsutum*)	Malvaceae	An et al., 2020
	Wheat (*Triticum aestivum*)	Graminaceae	Abbas et al., 2020
TiO_2	Broad bean (*Vicia faba*)	Fabaceae	Abdel-Latef et al., 2018
	Moldavian balm (*Dracocephalum moldavica*)	Lamiaceae	Gohari et al., 2020
	Sunflower (*Heliantus annuus*)	Asteraceae	Kolenčík et al, 2020
	Wheat (*Triticum aestivum*)	Graminaceae	Satti et al., 2021
Se	Strawberry (*Fragaria ananassa*)	Rosaceae	Zahedi et al., 2019
	Tomato (*Solanum lycopersicum*) and eggplant (*Solanum melongena*)	Solanaceae	Gudkov et al., 2020
	Wheat (*Triticum aestivum*)	Graminaceae	Ikram et al., 2020

SiO_2	Saffron (*Crocus sativus*)	Iridaceae	Khalaki et al., 2020
	Tomato (*Solanum lycopersicum*)	Solanaceae	Udalova et al., 2020
	Beans (*Phaseolus vulgaris*)	Leguminoseae	El-Saadony et al., 2021
	Coriander (*Coriandrum sativum*)	Apiaceae	Fatemi et al., 2021
	Banana (*Musa acuminata*)	Musaceae	Mahmou et al., 2020
CNTs	Tomato (*Solanum lycopersicum*)	Solanaceae	Khodakovskaya et. al., 2009; Villagarcía et al., 2012
	Radish (*Raphanus sativus*);	Brasicaceae	Haghighi and da Silva, 2014
	Onion (*Allium cepa*); Turnip (*Brassica rapa*) and Cucumber (*Cucumis sativus*)	Liliaceae and Cucurbitaceae	
	Cabagge (*Brassica oleracea* and Carrot (*Daucus carota*)	Brassicaceae and Apiaceae	Cañas et al., 2008
MWCNTs	Mustard (*Brassica napus*), Sunflower (*Helianthus annus*), Marihuana (*Cannabis sativa*)	Brassicaceae, Asteraceae, Cannabaceae	Oloumi et al., 2018
	Okra (*Hibiscus escolentus*)	Malvaceae	Darvishzadeh and Hosseini, 2020
	Thale cress (*Arabidopsis thaliana*)	Brassicaceae	Ke et al., 2021
	Hopbush (*Dodonaea viscosa*)	Sapindaceae	Yousefi et al., 2017
	Maize (*Zea mays*)		Hou et al., 2021
SWCNTs	Pea (*Pisum sativum*)	Fabaceae	Velikova et al., 2021
	Soybean (*Glycine max*)	Leguminoseae	Sun et al., 2020
	Rice (*Oryza sativa*)	Graminaceae	Zhang et al. 2017
GO	Wheat (*Triticum aestivum*) and Tomato (*Solanum lycopersicum*)	Graminaceae and Solanaceae	Cao et al., 2021
	Carnation (*Dianthus caryophyllus*)	Caryophyllaceae	Di Zhang et al., 2021
	Lettuce (*Lactuca sativa*)	Asteraceae	Gao et al. 2020
	Wheat (*Triticum aestivum*)	Graminaceae	Chen et al., 2018

Table 1. Types of metallic and carbon-based nanoparticles (NPs) evaluated on crop plants belonging to different families.

ZnONPs aggregate in the rhizosphere, enter into the root cells either apoplastically or symplastically and reaches the vascular bundle from where it is transported promoting their effects (Figure 1).

The physiological responses of habanero pepper plants to foliar applications of zinc sulfate and zinc nano-fertilizer were evaluated in greenhouse trials (García-López et al., 2019). The plants were treated with foliar applications of Zn at concentrations of 1000 and 2000 mg L^{-1} in the form of ZnONPs and zinc sulfate ($ZnSO_4$). ZnONPs at a concentration of 1000 mg L^{-1} positively affected plant height, stem diameter, and chlorophyll content, and increased fruit yield and biomass compared to control and $ZnSO_4$ treatments. ZnONPs at 2000 mg L^{-1} negatively affected plant growth but significantly increased fruit quality, capsaicin content by 19.3%, dihydrocapsaicin by 10.9%, and Scoville Heat Units by 16.4%. In addition, at 2000 ZnO NPs mg L^{-1} also increased content of total phenols and total flavonoids (soluble + bound) in fruits (14.50% and 26.9%, respectively). These results indicate that the application of ZnONPs could be employed in habanero pepper production to improve the yield, quality, and nutraceutical properties of fruits.

ZnONPs have a potential application as a bacteriostatic agent and can be used to control the spread and infection of a variety of pathogens. Kumar et al. (2021) reported that ZnONPs promote seed germination, plant growth and improve crop yield and quality (Figure 2). When wheat seeds were primed with ZnONPs, the germinated plants showed increased plant growth, photosynthesis, and biomass. Noohpisheh et al. (2021) evaluated the interaction effects of ZnONPs and salinity stress on two cultivars of *Trigonella foenum-graecum*. At a high concentration of salinity, polyphenol oxidase, peroxidase, lipoxygenase, and phenylalanine ammonia lyase significantly increased in both cultivars. In addition, an increase in salinity concentration increased Na concentration, while it decreased K and Ca concentrations in the shoot and root in both cultivars.

Zinc oxide NPs influence on seeds germination, seedling growth, as well as on total phenols content, total flavonoids, and condensed tannins of pepper, were determined by (García-López et al., 2018). They report that seed vigor germination increased 123.50%, 129.40%, and 94.17% by treatments with ZnONPs at 100, 200, and 500 ppm, respectively. The morphological parameters revealed that ZnONPs treatments did not significantly affect shoot development, but they had a significant impact ($p \leq 0.01$) on radicle length. Suspensions at 100, 200, and 500 ppm of ZnONPs inhibited seedling radicle growth and promoted the accumulation of phenolic compounds, with a phytotoxic effect in this organ. These outcomes suggested that ZnONPs influence seed vigor and seedling development and promoted the accumulation of desirable phenolic compounds in the radicle.

Among various metals, zinc plays a vital role in biochemical, physiological, and anatomical responses of tomato plants, but below the threshold level. Pejam et al. (2021), show that ZnONPs mediated an increase in activity of nitrate reductase and proline content in leaves of tomato plants. Treatments applied increased soluble phenols and phenylalanine ammonia-lyase activity. The study provided evidence on how ZnONPs may remodel the chromatin ultrastructure and transcription program, and confer stress tolerance in crops.

In the study reported by Semida et al. (2021), two field-based trials were conducted during 2018 and 2019 to examine the influence of three ZnONPs concentrations (0, 50, and 100 ppm) in eggplants, grown under full irrigation and drought stress (60% of ET).

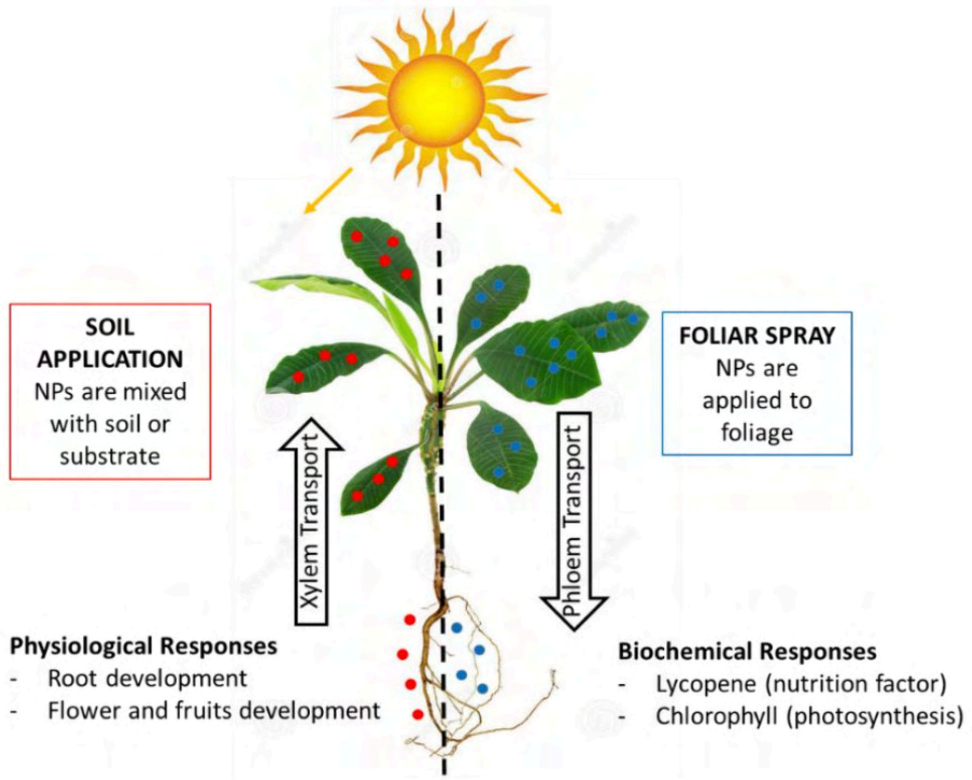

Figure 1. Sites of entry for ZnONPs when they are applied as a spray to the foliage, or when added to the soil or substrate, and penetrate through the root system following the symplastic and apoplastic pathways stimulating diverse physiological and biochemical processes.

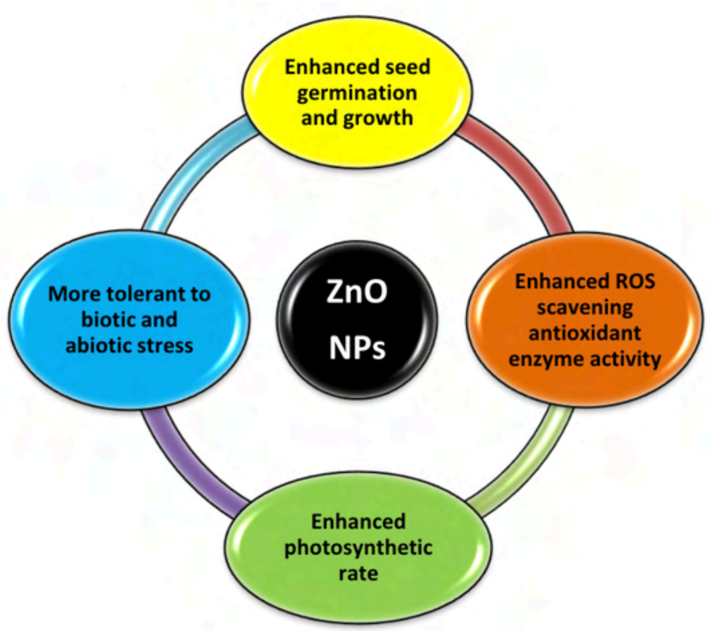

Figure 2. A schematic illustration displaying the effects of ZnONPs on plant growth, development and tolerance against abiotic and biotic stresses (Adapted from: Kumar et al., 2021).

Adition of ZnONPs to water-stressed eggplant resulted in increased relative water content and membrane stability index, associated with improved stem and leaf anatomical structures and enhanced photosynthetic efficiency. Under drought stress, supplementation of 50 and 100 ppm ZnONPs improved growth characteristics and increased fruit yield by 12.2% and 22.6%, respectively, compared with fully irrigated plants and nonapplied ZnO.

COPPER OXIDE NANOPARTICLES

The transformation of CuO and CuONPs in the soil and their accumulation by barley was assessed by Burachevskaya et al. (2021). They performed a comparative study on the effects of macro and nanosized copper oxide (CuO) on plants. The application of nanosized CuO had a greater toxic effect than the macro-sized CuO on the plants. A dose of 300 mg kg^{-1} of macro and nanosized CuO did not significantly affect the development and productivity of barley. The effect of high doses of macro- and nanosized CuO (2000 and 10,000 mg kg^{-1}) had a negative impact on the growth of barley. The application of nanosized CuO had a greater toxic effect than the macro-sized CuO on the plants.

The potential phytotoxicity of CuONPs on seed yield, focusing on particle size- and concentration-dependent responses of multiple antioxidant defense biomarkers in soybean during its lifecycle, were evaluated by Yusefi et al. (2020). They report that concentration-response curves for seed yield for all types of Cu compounds were linear (R2 > 0.65). Their findings indicate differential nano-specific toxicity compared to ionic Cu_2^+ toxicity in soybean. These results may guide researchers on how best to tailor NPs with specific particle characteristics rendering them more or less toxic, and better inform risk assessment of CuONPs in soil-grown food crops.

Chung et al. (2019) evaluated the role of CuONPs on plant growth, photosynthetic capacity, and bioactive compounds, as well as their transcriptional level changes in turnip seedlings. Chlorophyll, carotenoid, and sugar content decreased, while proline and anthocyanins were significantly enhanced in the CuONPs-treated seedlings compared with the controls. ROS, malondialdehyde, and hydrogen peroxide production were also enhanced in the seedlings exposed to CuONPs, which could have caused DNA damage. The glucosinolate and phenolic compound content were significantly increased in CuONPs treated seedlings compared to the control. Hence, the authors suggest that the use of CuONPs could stimulate the toxic effects and enhance phytochemicals (i.e., glucosinolates and phenolic compounds) in *B. rapa*.

Data suggests that agricultural soils are gradually becoming a primary sink for metal-based NPs. Peng et al. (2015) reports that CuONPs applied to soil had an acute negative effect on rice plants growth, compared to bulk particles, which dramatically reduced the fresh weight of grains to 6.51% of controls. Cooper and ZnONPs are fertilizers, as they provide bioavailable essential metals; and as pesticides, because of dose-dependent toxicity. It was documented that these NPs modify very important processes in the rhizosphere, which are involved in plant health. In this respect Anderson et al. (2017) point out that studies at the cellular, biochemical, and transcriptome levels show that CuO and ZnONPs changed the root morphology of wheat seedlings; they also, have an impact on metabolites acting as signals in the communication between the plant and the rhizobacteria cells.

The small size of CuNPs facilitates their easy absorption by the plants. CuNPs can be promisingly used in food packaging to avoid the growth of food spoilage microorganisms. CuO is also used as a fungicidal agent in the protection of tea, banana, cocoa, citrus, coffee, and other important plant species from major fungal diseases, for instance, blight, downy or powdery mildew, and rust, etc. Rai et al. (2018). The physiological and biochemical behavior of rice treated with CuONPs was studied by Da Costa and Sharma (2016). Germination rate, root, shoot length and biomass decreased, while uptake of Cu in the roots and shoots of rice plants increased at high concentrations of CuONPs. The accumulation of CuONPs was observed in the chloroplasts, and was accompanied by a lower number of thylakoids per granum. Photosynthetic and transpiration rate, stomatal conductance, maximal quantum yield of PSII, and photosynthetic pigments declined, with a complete loss of PSII photochemical quenching at 1,000 mg L^{-1}. Therefore, this work clearly demonstrated the toxic effect of Cu accumulation in roots and shoots that resulted in the loss of photosynthesis.

IRON OXIDE NANOPARTICLES

In order to assess the bio-effectiveness of Fe_2O_3NPs and EDTA functionalized FeNPs as a nano-micronutrient fertilizer to replace traditional Fe-fertilizer, Haydar et al. (2021) set up an experiment. Fe_2O_3NPs and their EDTA functionalized form were applied in two different dosages (10 and 50 mg kg^{-1} soil) by both soil application and foliar spray on mulberry plants. Fe_2O_3NPs application at a rate of 10 mg kg^{-1} in soil significantly improved morphological traits like sprouting percentage, number of leaves (52.73% improved over control), plant biomass (37.20% and 90.24% increase of shoot and root biomass over control, respectively), root attributes (34% increment for root length) and also shortened the first leaf appearance period. The same treatment showed an improvement of 42% and 15% over control in the case of chlorophyll and sugar content, respectively. These results showed that treated NPs could replace traditional Fe-fertilizer in the cultivation and propagation of mulberry crop.

The key objective of the experiment implemented by Afzal et al. (2021), was to compare the effect of biosynthesized FeONPs (27 ± 2 nm) applied at a concentrations range of 10, 50, 100, and 500 mg L^{-1} by foliar and root exposure methods on physiological and biochemical parameters, as well as on uptake, translocation, and deposit of NPs in rice plant parts. The results showed that there is a critical concentration of NPs up to which the rice crop growth is promoted with no enhancement beyond that. Foliar treatment was found to be more effective than the root treatment.

The uptake and physiological effects of Fe_2O_3NPs, and plant resistance response against tobacco mosaic virus (TMV) after foliar spraying were studied by Cai et al. (2020). They demonstrated that Fe_2O_3NPs entered leaf cells of tobacco and were transported and accumulated throughout the whole plant and increased plant dry and fresh weights, activated plant antioxidants, and upregulated salicylic acid (SA) synthesis and the expression of SA-responsive PR genes, thereby enhancing plant resistance against TMV. Conversely, the viral infection was not inhibited in transgenic plants treated by Fe_2O_3NPs, suggesting the involvement of SA induced by Fe_2O_3NPs on plant resistance.

The outcome of FeONPs, as a salinity stress modifier, was investigated on plant growth and antioxidant systems in moldavian balm plants. The results showed that the salinity causes a decrease in leaf area, length, and fresh and dry weight of the shoot and root. However, foliar application of FeONPs in the concentration of 60 ppm increased all aforementioned traits (Moradbeygi et al., 2020). Spraying the FeONPs, significantly increased leaf area in the plants under salt stress conditions. Total phenolic, flavonoid, and anthocyanin content, as well as the activity of guaiacol peroxidase, ascorbate peroxidase, catalase, and glutathione reductase enzymes, were enhanced in the shoot and root of the plants treated with 100 mM of NaCl solution. The results revealed that using FeONPs improves the antioxidant defense of plants under salinity stress.

An experiment was conducted in historically Cd-contaminated soil using five levels of FeNPs (0, 5, 10, 15, and 20 ppm) by soil and foliar application methods to wheat plants (Hussain et al. 2019). The results showed that the application of FeNPs mitigated the Cd toxicity on wheat growth and yield parameters. The exogenous application of FeNPs enhanced morphological parameters, photosynthetic pigments, and dry biomass of shoots, roots, spike husks, and grains. The activities of super oxide dismutase and peroxidase increased, whereas electrolit leakage reduced from wheat leaves over control. Therefore, the application of FeNPs on wheat in Cd-contaminated soils could be employed to improve growth, yield, and Fe biofortification as well as reduction in Cd concentrations in plants. One very important application of FeO in crop plants is for its antimicrobial activity, however, some reports suggest that the potential of these Fe_2O_3NPs to generate microbial toxicity is due to a series of interactions, including membrane depolarization with consequent impairment of cell integrity, production of ROS with lipid peroxidation and DNA damage, and release of metal ions that affect cellular homeostasis and proteins (Arias et al., 2018).

The study reported by Hu et al. (2017) compared and evaluated the physiological and molecular changes of pummelo plants as affected by different levels of γ-Fe_2O_3NPs and Fe_3^+. It was found that γ-Fe_2O_3NPs could enter plant roots but no translocation from roots to shoots was observed. 20 mg/L γ-Fe_2O_3NPs had no impact on plant growth. 50 mg/L γ-Fe_2O_3NPs significantly enhanced chlorophyll content by 23.2% and root activity by 23.8% as compared with control. However, 100 mg/L γ-Fe_2O_3NPs notably increased MDA formation, decreased chlorophyll content, and root activity. Physiological results showed that γ-Fe_2O_3NPs at proper concentrations had the potential to be an effective iron nanofertilizer for plant growth.

SILVER NANOPARTICLES

Silver nanoparticles (AgNPs) have been implicated to enhance seed germination, plant growth, improvement of photosynthetic quantum efficiency and as antimicrobial agents to manage plant diseases. AgNPs are capable of penetrating bacterial cell membranes and act as a catalyst to inactivate enzymes, which are required for their metabolism, to disrupt bacterial membranes, and by affecting DNA replication (Keshari et al., 2020). But also AgNPs had been reported as phytotoxic to lettuce plants (Hasan et al., 2021) and cucumber (Zhang et al., 2021).

Silver NPs have become one of the most commonly used nanomaterials in consumer products, and for several decades, silver (Ag^+) has been studied as an antimicrobial agent against various harmful microorganisms. Agricultural scientists are searching for eco-friendly and less capital-intensive approaches to control plant diseases. AgNPs has many applications in plant protections because it has long been known to have strong biocidal effects on fungi, virus and bacterias (Figure 3).

In the bioassay of Hasan et al. (2021) lettuce seedlings were exposed hydroponically to different concentrations of silver (Ag^+) ions and AgNPs to evaluate their impact on plants physiology. Seedlings taking Ag+ ions showed an increment of 18% in total phenolic content and 12% in total flavonoid content, whereas, under AgNPs,

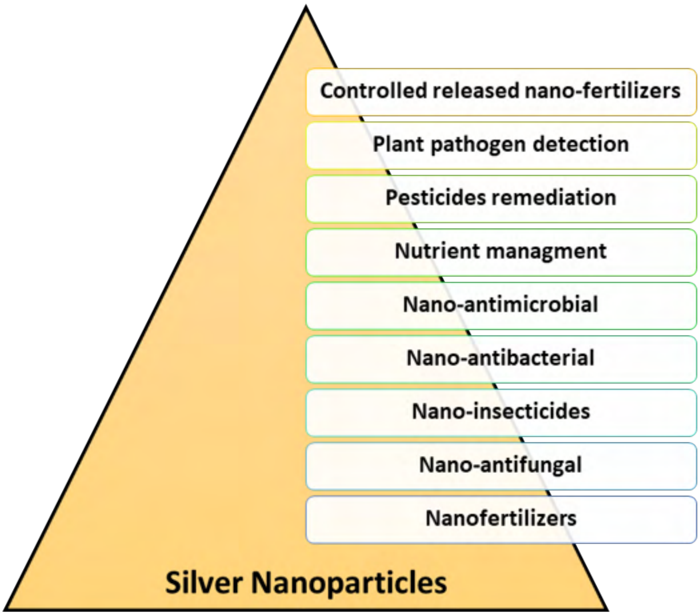

Figure 3. Silver nanoparticles application offers many possibilities in modern agricultural plants production and protection (Adapted form: Gupta et al., 2018).

7% free radical scavenging activity, 12% total phenolic contents, and 10% total reducing power were increased. A rise in 31% shoot length, 25% chlorophyll, 11% carbohydrate, and 16% protein content of the lettuce plants was observed in response to AgNPs, while $AgNO_3$ reduced growth by 40%. Further, biomolecules other than antioxidant enzymes showed higher phytotoxicity for Ag^+ ions, followed by AgNPs with the concentration of 25, 50, and 100 mg L^{-1} compared to the control. Thus, moderate concentrations of AgNPs have a stimulatory effect on seedling growth, while higher concentrations induced inhibitory effects due to the release of Ag^+ ions.

The white rot disease, caused by the fungus *Stromatinia cepivora*, causes a major problem in the production of onion and garlic crops. Darwesh and Elshahawy, (2021) evaluated AgNPs at various concentrations (40, 80, 120, 160, and 200 mg L^{-1}), showing a great antifungal activity against growth, mycelial biomass, and sclerotial germination of *S. cepivora*. With increasing AgNPs concentration, the antifungal activity was increased and the application of 200 mg L^{-1}produced maximum antifungal activity. The authors concluded that the application of AgNPs provides an improvement in the growth and yield of bulbs for both onion and garlic plants grown under field conditions. Therefore, AgNPs can be used as nanofungicide against white rot disease and as nanofertilizers for onion and garlic crops.

Reviewing the impact of AgNPs and two biological treatments to control soft rot disease in sugar beet, Ghazy et al. (2021) reported the *in vitro* and *in vivo* experiments, aimed to assess the effect of NPs and biological treatments to control this disease in beet plants. The treatments comprised three AgNPs concentrations (50, 75, and 100 ppm), three *Spirulina platensis* extract concentrations (50, 75, and 100%), and the fungus *Bacillus subtilis* (1×10^9 CFU mL). Under *in vitro* conditions, the zones of inhibition recorded

4.33 cm for 100 ppm AgNPs, 0.43 cm for 100% algal extract, and 0.2 cm for bacterial treatments. Also, the disease incidence % of bacterial soft rot was significantly decreased in all treatments in pot and field experiments. These results were reflected on sugar quality where AgNPs 100 ppm treatment, recorded the highest significant value (20.5%) followed by *S. platensis* 75% (19%). Therefore, this study showed the potential benefits of using AgNPs and two biological treatments to control soft rot disease in *B. vulgaris* plants.

The experiment carried out by Heikal et al. (2020) with onion, the roots were exposed to several AgNPs concentrations (0, 5, 10, 20, 40 and 80 mg L^{-1}) for different time intervals 2, 4 and 6 h. Cytotoxicity measured recorded maximum cell death of onion root tips after 20 mg L^{-1} treatment. The uptake, translocation, and accumulation of AgNPs in plants, also aggravates some phytotoxic effects of AgNPs on plants at the morphological, physiological, cellular, and molecular levels. According to Yan and Chen (2019), the phytotoxicity mechanisms by which AgNPs exert their toxicity follows after AgNPs are taken up by primary and lateral roots, then translocated to aboveground parts (stem, leaf, flower, etc.), where they can reduce biomass, decrease leaf area, affect pollen viability, and inhibit seed germination. At the cellular level, AgNPs enter into various organelles, leading to the production of excess ROS, thereby causing cytotoxicity and genotoxicity, such as membrane damage, chlorophyll degradation, vacuole shrinkage, DNA damage, and chromosomal aberrations.

The information presented by Sadak (2019) regarding to the role of AgNPs, was studied on growth, biochemical aspects, and yield of fenugreek plants. Foliar application of AgNPs with 20, 40, and 60 mg L^{-1}, improved growth parameters of the plants (e.g., shoot length, number of leaves/plant, and shoot dry weight) and increased some biochemical aspects such as photosynthetic pigment (chlorophyll a, chlorophyll b, and carotenoids) and IAA contents, thus enhanced the yield quantity (number of pods/plant, number of seeds/pod, weight of seeds/plant, and seed index) and quality (carbohydrate%, protein%, phenolics, flavonoids, and tannins contents), as well as increasing antioxidant activity of the yielded seeds.

CERIUM OXIDE NANOPARTICLES

Cerium oxide NPs have many applications in several fields of modern science (Figure 4) and have gained a lot of attention as a potential future candidate for ending various kinds of problems by exhibiting redox activity, free radical scavenging property, biofilm inhibition, etc. Synthesis of CeO_2NPs can be performed very easily by utilizing biological methods. Hence, these NPs are less toxic and compatible with the living tissues, which helps them to find their path as an anticancer, anti-inflammatory and antibacterial agents (Singh et al., 2020).

The interaction between CeO_2NPs (25, 50 and 100 mg L^{-1}) and salinity (25 and 75 mM NaCl) was evaluated by Gohari et al. (2021) in grapevine plants. Treatments with CeO_2NPs alleviated the adverse impacts of salt stress (75 mM NaCl) and significantly improving relevant agronomic traits of grapevine. CeO_2NPs considerably ameliorated chlorophyll damage under high levels of salinity. Furthermore, the presence of CeO_2NPs attenuated salinity-induced damages in grapevine as indicated by lower levels of proline, malondialdehyde and electrolyte leakage; however, H_2O_2 content was not improved by the presence of CeO_2NPs under salt stress. The presence of CeO_2NPs did not lead to significant alterations in Na, K and P content of salt-stressed plants. These findings suggest that CeO_2NPs could be

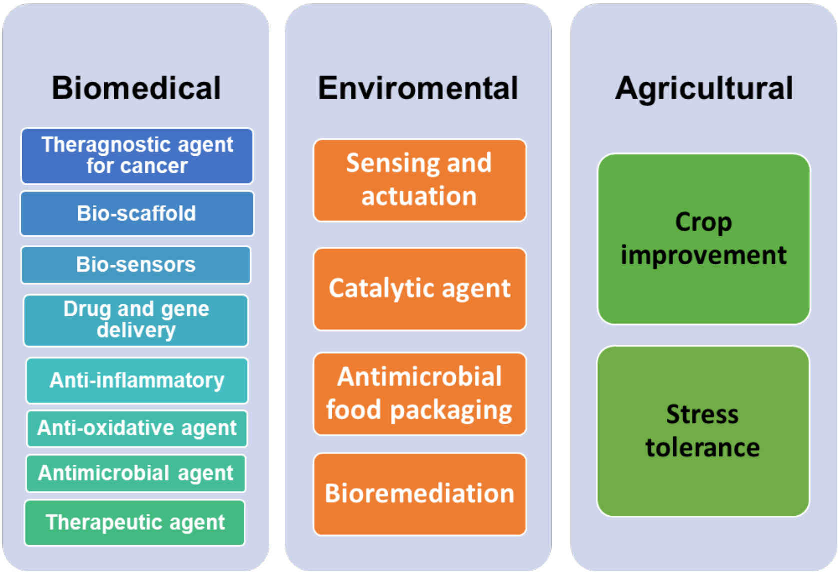

Figure 4. Potential applications of cerium oxide nanoparticles in the biomedical, environmental, and agricultural areas (Adapted from Singh et al., 2020).

employed as promising salt-stress alleviating agents.

An et al. (2020) investigated how priming seeds with antioxidant poly(acrylic acid)-coated CeO_2NPs impacts cotton seedling morphological, physiological, biochemical, and transcriptomic traits under salinity stress. Seed priming significantly ($P < 0.05$) increased seedling root length (56%), fresh weight (41%), and dry weight (38%), modified root anatomical structure, and increased root vitality (114%) under salt stress compared with the control. CeO_2NPs seed priming led to a decrease in ROS accumulation in seedling roots (46%) and alleviated root morphological and physiological changes induced by salinity stress. Roots from exposed seeds exhibited similar Na content, significantly decreased K (6%), greater Ca (22%) and Mg content (60%) compared to controls. These results provide potential unifying molecular mechanisms of nanoparticle-seed priming enhancement of plant salinity tolerance.

Abbas et al. (2020) investigated the biochar role in CeO_2NPs bioaccumulation and subsequent translocation in wheat plants as well as the impact on growth, photosynthesis, and gas exchange. Results indicated that CeO_2NPs up to 500 mg L^{-1} level promoted the plant growth by triggering photosynthesis, transpiration, and stomatal conductance. Higher NPs concentration (2000 mg CeO_2NPs L^{-1}) negatively affected plant growth and photosynthesis-related processes. Conversely, biochar amendment with CeO_2NPs considerably reduced (~9 folds) the plants accumulated contents of Ce even at 2000 mg L^{-1} exposure level of CeO_2NPs.

The mutual effects of CeO_2NPs and cadmium (Cd_2^+) on their uptake and accumulation by soybean seedlings in a hydroponic system was set up by Rossi et al. (2018). Soybean seedlings were exposed to four treatments (1.0 mg L^{-1} Cd_2^+, 1.0 mg L^{-1} Cd_2^+ + 100 mg L^{-1} CeO_2NPs, 100 mg L^{-1} CeO_2NPs and 0 mg L^{-1} Cd and CeO_2NPs as the control). Significant interactions between co-existing CeO_2NPs and Cd were found concerning their accumulation in plant tissues. The co-presence of Cd and CeO_2NPs led to higher excretion of plant root exudates, which might have altered the chemical environment in the plant rhizosphere and enhanced CeO_2NPs dissolution, leading to different plant accumulation of both chemicals. Therfore, the CeO_2NPs have an enormous use in biomedical, environmental, and agriculture applications.

TITANIUM OXIDE NANOPARTICLES

Titanium oxide (TiO_2) is one of the most widely used nanomaterial in the consumer products, agriculture, and energy sectors. Their large demand and widespread applications will inevitably cause damage to organisms and ecosystems. The toxic effects of TiO_2NPs occur on multiple taxa of microorganisms, algae, plants, invertebrates and vertebrates. The mechanism of TiO_2NP toxicity to organisms can be outlined in three aspects (Hou et al., 2019). ROS produced by the effect of TiO_2NPs can destroy cell membrane constituents directly, damage the integrity of the membrane, and even cross the bacterial membrane. In the last decade, several publications have shown fragments of information about the interaction, detection, uptake, and translocation of TiO_2NPs in plants (Tan et al., 2018).

A study carried out by (Satti et al., 2021) involving various concentrations (20, 40, 60, and 80 mg L^{-1}) of TiO_2NPs, were applied exogenously on wheat plants infected with the fungus *Bipolaris sorokiniana* responsible to cause spot blotch disease. The measurement of disease incidence and percent disease index showed the time-dependent response and 40 mg L^{-1} was reported a stable concentration of TiO_2NPs to reduce the disease severity. In wheat plants under biotic stress and 40 mg L^{-1} concentration, TiO_2NPs were found to be effective to elicit modifications to reduce biotic stress. This study highlights the significant role of biosynthesized TiO_2NPs in controlling fungal diseases and thus ultimately improving the quality and yield of wheat plants.

The article reported by (Irshad et al., 2021) describes the types of plants (shrubs, herbs, and trees), microorganisms (bacteria, fungi, and algae), biological derivatives (proteins, peptides, and starches) employed for the biosynthesis of TiO_2NPs. These NPs can be effectively used for the treatment of polluted water and positively affect the plant physiology, especially under abiotic stresses, but the response varied with types, size, shapes, doses, duration of exposure, metal species in concordance with other factors. TiO_2NPs has many pro-oxidant and antioxidant functions in the modulation of ROS signaling (Figure 5), but TiO_2NPs also affect plant nitrogen status by modulating inorganic-to-organic nitrogen conversion rate.

Considering TiO_2NPs role in plant growth and especially in plant tolerance against abiotic stress, a greenhouse experiment was carried out by Gohari et al. (2020) to evaluate TiO_2NPs effects (0, 50, 100, and 200 mg L^{-1}) on agronomic traits of Moldavian balm plants grown under different salinity levels (0, 50 and 100 mM NaCl). Results demonstrated that all agronomic traits were negatively affected under all salinity levels, but the application of 100 mg L^{-1} TiO_2NPs mitigated these negative effects. TiO_2NPs application on Moldavian balm grown under salt stress conditions improved all agronomic traits and increased antioxidant enzyme activity compared with plants grown under salinity without TiO_2NPs treatment. Also, the application of TiO_2NPs significantly lowered H_2O_2 concentration on plants tissue.

In the trial described by Kolenčík et al (2020) the effects of two nano-fertilizers on common sunflower production was compared under field conditions. The benefits arising from the foliar application

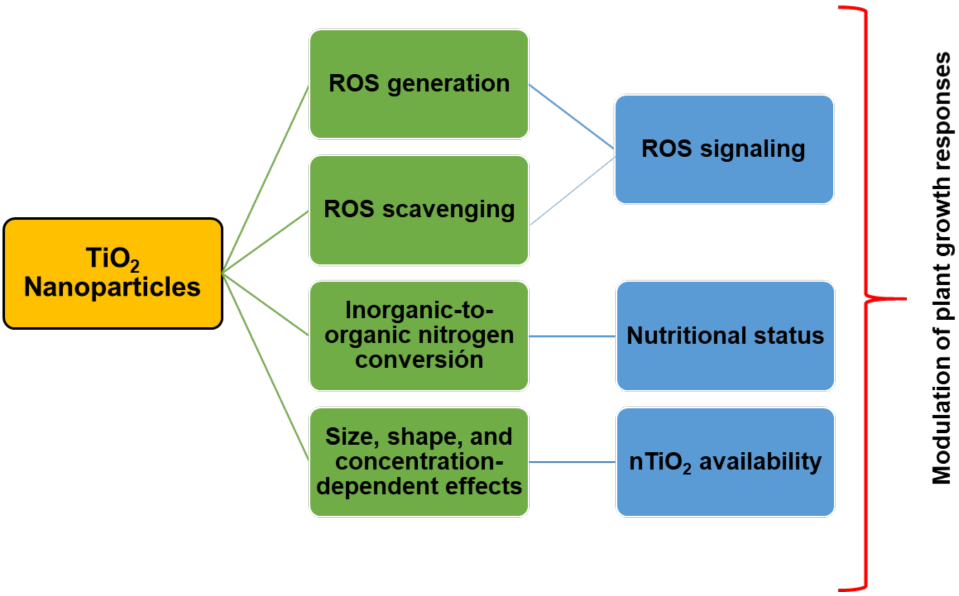

Figure 5. Titanium dioxide NPs have both pro-oxidant and antioxidant functions in the modulation of reactive oxygen species signaling. TiO_2NPs also affect plant nitrogen status by modulating inorganic-to-organic nitrogen conversion rate (Adapted from Abdel-Latef et al., 2018).

of micronutrient-based ZnO fertilizer were compared with those from the TiO_2 plant-growth enhancer. Both the ZnO and TiO_2 were delivered by foliar application in nano-size at a concentration of 2.6 $mg{\cdot}L^{-1}$. There were significant differences between these two experimental treatments in the leaf surface trichomes diversity, ratio, width, and length at the flower-bud development stage. Somewhat surprisingly, their results established that the ZnONPs treatment induced generally better sunflower physiological responses, while the TiO_2NPs primarily affected quantitative and nutritional parameters such as oil content and changed sunflower physiology to early maturation.

The results from Abdel-Latef et al. (2018), indicate that the 0·01% TiO_2NPs supplementation significantly increased the activities of enzymatic antioxidants and levels of soluble sugars, amino acids, and proline in salt-affected broad bean plants versus plants subjected to salinity alone. Thus, the increased antioxidant enzyme activities contributed to the observed reduction in H_2O_2 and malondialdehyde contents, while enhanced levels of proline and other metabolites contributed to osmoprotection, collectively resulting in significant plant growth improvement under salinity.

SELENIUM NANOPARTICLES

Selenium (Se) acts as an anti-oxidative agent at low concentrations and adequate doses; however, at high concentrations, it behaves like a pro-oxidant (Ikram et al., 2021). In addition, selenium at low concentrations can play a outstanding role in maintaining the structure and fluidity of the plastid membrane and chloroplast. Furthermore, Se can also play a significant role in the improvement of photosynthesis, delay senescence, and increase plant yield at low concentrations (Gudkov et al., 2020). Selenium is an essential trace element that is necessary for the normal functioning of plants, which protects them from the detrimental effects of climatic stresses (Feng and Wei, 2012). Selenium is considered a finite and non-renewable resource on Earth. While there is no evidence of Se need for higher plants, several reports show that when Se is added at low concentrations, exerts beneficial effects on plant growth (El-Ramady et al., 2016).

The beneficial role of SeNPs in mitigating the adverse effects of soil-salinity on the growth and yield of strawberry plants was evaluated by Zahedi et al. (2019). The foliar spray of SeNPs (10 and 20 mg L^{-1}) improved the growth and yield parameters of strawberry plants grown on non-saline and different saline soils (0, 25, 50, and 75 mM NaCl), which was attributed to their ability to protect photosynthetic pigments. Foliar application of SeNPs improved salinity tolerance in strawberries by reducing stress-induced lipid peroxidation and H_2O_2 content. Additionally, SeNPs treated strawberry plants showed accumulation of IAA and ABA, which are involved in regulating different morphological, physiological, and molecular responses of plants to salinity. These results demonstrate the definite roles of SeNPs in the management of soil salinity-induced adverse effects on not only strawberry plants but also other crops.

In the experiment reported by Gudkov et al. (2020), SeNPs suspended in water were introduced into the soil to evaluate their effect on tomato and eggplant. The soil SeNPs concentrations were about 1, 5, 10, and 25 μg kg^{-1}. An experiment was carried out in a climate chamber in two series: (1) growing plants in soil imitating the standard organogenesis environment conditions such as illumination of 16 h per day, a temperature of 22 °C, soil humidity of 25% and (2) growing plants in soil under changing environmental conditions. The highest plant growth rate was in SeNPs concentrations of 5 and 10 μg kg^{-1}. The eggplant growth on the soil with the SeNPs addition at a concentration of 10 μg kg^{-1} of leaf surface area was twice, compared to the eggplants growth in untreated soil. The same was for tomato plants. The leaf surface area of the cucumber plants grown using SeNPs was 50% higher compared to the control.

Selenium NPs were biosynthesized and evaluate their effect via foliar applications to improve the growth of wheat plants under controlled irrigation and drought stress (Ikram et al., 2020). Various concentrations of SeNPs (10, 20, 30, and 40 mg/L) were applied exogenously to drought-tolerant (V1) and drought-susceptible (V2) wheat varieties. A remarkable increase in plant height, shoot length, shoot fresh weight, shoot dry weight, root length, root fresh weight, root dry weight, leaf area, leaf number, and leaf length has been observed when 30 mg/L concentration of SeNPs was used. However, the plant morphological parameters decreased gradually at higher concentrations (40 mg/L) in both wheat varieties. Therefore, 30 mg/L concentration of SeNPs was found most preferable to enhance the growth of wheat varieties under normal and water-deficient conditions.

Selenium may act as a quasi-essential micronutrient through altering different physiological and biochemical traits (Figure 6). Thus, plants vary greatly in their physiological responses to Se.

SILICON NANOPARTICLES

Silicon (Si) the second-most abundant element found in the earth's crust, is a metalloid considered beneficial to plants (Siddiqui et al., 2018). Silicon is absorbed in the form of mono-silicic acid by plants and is transported across the plant via different transporter governed by genes such as *LSi1*, *LSi2*, and *LSi6* (Rao and Susmitha, 2017). Silicon is also regarded as a quasi-essential element for

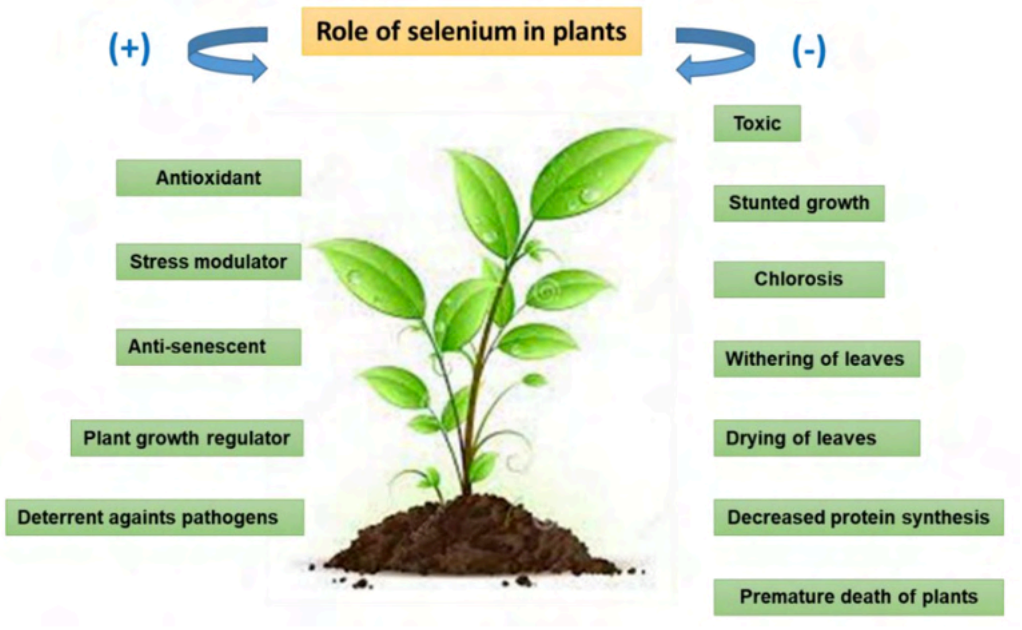

Figure 6. Selenium is an essential nutrient for animals, humans, and microorganisms. The positive and negative effects effect of selenium nanoparticles could be as a plant growth promoter, antioxidant, phytotoxic, and stress modulator (Adapted by Kaur et al., 2014).

plants and regulates a range of physiological processes including germination, vegetative growth, photosynthesis, and stress tolerance, however, it has been reported that induce cytotoxicity and apoptosis in human breast cancer and liver (Alkhudhayri et al., 2020).

Mahmou et al. (2020) appraised the water deficit stress remediating effects of SiO_2NPs on micro propagated banana either under *in vitro* conditions in the laboratory or *ex vitro* in the greenhouse. *In vitro* water deficit was induced with polyethylene glycol (PEG-8000). The addition of *in vitro* SiO_2NPs enhanced shoot growth and chlorophyll content. Malondialdehyde content and electrolyte leakage were reduced in 3% PEG-stressed plants followed by the addition of 150 mg L^{-1} SiO_2NPs (38.73 mmole and 4.93%) compared with the control plants (51.67 mmole and 5.76%). The overall results revealed that SiO_2NPs application can improve chlorophyll content, induce K^+ uptake, modulate Na^+ levels and decrease cell wall damage in the treated plants comparing to the untreated plants under abiotic stress.

A two-year field trial was conducted by El-Saadony et al. (2021) to compare the protective effects of biological SiNPs (2.5 and 5.0 mmol/L) and potassium silicate (10 mmol/L) as a foliar spray on the antioxidant defense system, physio-biochemical components, and the contaminants contents of bean plants grown on saline soil contaminated with heavy metals. Their findings showed that all treatments of Bio-SiNPs and potassium silicate improved plant growth and production, chlorophylls, carotenoids, transpiration and net photosynthetic rate, stomatal conductance, membrane stability index, relative water content, free proline, total soluble sugars, N, P, K, Ca_2^+, K^+/Na^+, and the activities of peroxidase, catalase, ascorbic peroxidase and superoxide oxide dismutase.

Foliar treatment of tomato plants with

colloidal solutions of SiNPs at concentrations of 0.5 and 1.0 μg/mL applied by Udalova et al. (2020) revealed an increase in the content of photosynthetic pigments and a number of biogenic elements (P, Mg, K, S, and Fe) in tomato leaves, indicating an improvement in the physiological state of the plants. The stimulating effect of SiNPs on the development and growth of plants and the inhibiting effect on the susceptibility of plants by root-knot nematodes and the morpho-physiological parameters of the parasite was manifest.

Lead (Pb) is among the most abundant toxic trace elements which causes direct and indirect negative effects on humans, animals, and plants. Therefore, Fatemi et al. (2021), explored the effects of SiNPs on coriander plants. Treatments applied included four levels of Pb (0, 500, 1000, and 1500 mg kg^{-1} of soil), and two levels of SiNPs (0 and 1.5 mM) in all combinations. The foliar-applied 1.5 mM SiNPs alleviated the adverse impacts of Pb on coriander plants which were due to the minimization of Pb concentration in plants and improvements in the plant defense system. SiNPs minimized accumulation of malondialdehyde in plant tissues and adjusted the activities of catalase, peroxidase, and super oxide dismutase in plants under Pb stress. The authors concluded that SiNPs foliar application, might be a suitable approach in reducing the Pb concentrations in plants.

The aim of the study reported by (Asemeh, 2020) was to examine the effect of salinity stress on saffron plants and the role of foliar application of silicon and SiNPs in alleviating the impact of salinity. Saffron plants were treated by different levels of salinity (0, 75 and 150 mM), silicon and SiO_2NPs (0.5 and 1 mM). The results showed that salinity reduced length of shoots and roots, fresh and dry weight of the aerial and underground organs, K^+ content, K^+/Na^+ ratio. Also, salinity incrased the cell death, amout of proline, glycine betain and Na^+ and Cl^- content in the treated plants. Foliar application of silicon and SiO_2NPs improved growth factors, K^+ content and K^+/Na^+ ratio. It was concluded that Si and SiO_2NPs, especially SiO_2NPs, had the ability to reduce the toxicity created under salinity stress in saffron and could play an important role in increasing the resistance to salinity stress.

CARBON NANOTUBES

The study reported by Jordan et al. (2020) focused on the effects of carbon nanotubes (CNTs) on tomato plants phenotype with growth, time to flowering, fruiting time, and physiology, through amino acid and phytohormone content, in tomato after exposure to multiple types of CNTs. CNTs did not affect plant growth or height later in the life cycle. No significant differences in ABA and citrulline content were observed between the treated and control plants. In the study of Sun et al. (2020), the toxicities of CNTs and three heavy metals, copper, cadmium, and zinc on the microalgae *Scenedesmus obliquus* were determined individually. Results showed that CNTs at the concentration of 5 mg L^{-1}, promoted algae growth and enhanced photosynthetic efficiency via increasing exciton trap efficiency and quantum yield for electron transport. The introduction of CNTs appeared to alleviate the adverse effects of Cu, Cd, or Zn on microalgae, indicated by algae growth, total chlorophyll content, and photosynthetic indices.

Carbon nanotubes loaded with agrochemicals are investigated for its use as a safer alternative in agriculture (De Oliveira et al., 2018). The report by Vithanage et al. (2017), point out the contradictory effects of CNTs on plants physiology, since CNTs can act as plant growth inducers causing enhanced plant dry biomass and root/shoot lengths. At the same time, CNTs can cause negative effects on plants by forming ROS in plant tissues, consequently leading to cell death. Enhanced seed germination with CNTs is related to the water uptake process. CNTs can be positioned as micro-tubes inside the plant body to enhance the water uptake efficiency. However, due to its ability to act as a slow-release fertilizer and plant growth promoter, CNTs are emerging as a novel nano-carbon fertilizer.

Laboratory and greenhouse studies were conducted by Haghighi and da Silva (2014) to study the effect of CNTs on the germination and seedling growth of tomato, onion, turnip and radish. Seeds were germinated in four concentrations of CNTs (0, 10, 20 and 40 mg L^{-1}). The same concentrations were used in a greenhouse to study the response of seedling growth. CNTs at 10 - 40 mg L^{-1} improved tomato and onion germination more than for radish and turnip, the highest germination percentage (GP) in tomato and onion being 8 and 95%, respectively. In radish, the control showed the highest GP (96%) under laboratory conditions. CNTs at 40 mg L^{-1} had a deleterious and toxic effect on onion and radish seed germination. In the greenhouse experiment, the fresh weight of radish seedlings decreased as the CNTs concentration increased.

The positive effects of CNTs on plant growth were documented by the initial studies reported by several research groups, which point out an increase of some variables, such as increases in the length of onion roots and cucumber (Cañas et al., 2008). CNTs were found to penetrate tomato seeds and affect their germination and growth rates. The germination was found to be dramatically higher for seeds that germinated on medium containing CNTs (10–40 μg mL^{-1}) compared to control. Analytical methods indicated that CNTs are able to penetrate the thick seed coat and support water uptake inside seeds, a process which can affect seed germination and growth of tomato seedlings (Khodakovskaya et al., 2009).

MULTIWALL CARBON NANOTUBES

The effects of MWCNTs (20, 100, and 500 mg L^{-1}) on carbon (C) and nitrogen (N) metabolism in maize were studied by Hu et al. (2021). The results showed that 100 mg L^{-1} increased shoot fresh and dry weight, and seedling length of corn plants, while other doses showed no significant effects. Also improved the chlorophyll content, transpiration rate, stomatal conductance, and intercellular CO_2 concentration, by 50.6%, 60.8%, 47.2%, and 32.1%, respectively. Activities of key enzymes including sucrose synthase, sucrose phosphate synthase and phosphoenolpyruvate, were all upregulated by 100 mg L^{-1} MWCNTs, which contributed to the increase of the accumulation of carbohydrates (sugar and starch), soluble protein, and N in plants. These findings suggest that MWCNTs can improve plant growth by regulating the key enzymes involved in C and N metabolism, enhancing the carbohydrate production, the use of N and improving plant growth.

MWCNTs are increasingly finding novel uses in agriculture, as delivery devices, and as slow-release fertilizers. To investigate this possibility Ke et al. (2021) examined interactions with glyphosate, a widely used herbicide that is attracting increasing concern over its potential for non-target effects. It was examined potential synergistic effects on hydroponically grown *Arabidopsis thaliana*. Single treatments did not affect plant growth significantly or did only mildly. However, combined treatment significantly affected both plant root and shoot growth. High-level content of malondialdehyde and up-regulated of metabolic antioxidant molecules in plants indicated that the combined group caused the strong oxidative damage, while the decreased of antioxidant enzyme activities indicated an imbalance between ROS and the antioxidant defense system due to the continuously generated ROS. The synergistic effect observed was attributed to the accumulation of glyphosate resulting from the permeability and transportability of the CNTs.

The article by Darvishzadeh and Hosseini (2020) reports the effects of 4 MWCNTs levels including 0 (control), 50 (low concentration), 100 (moderate concentration), and 200 (high concentration) mg L^{-1} evaluated on morphological and anatomical characteristics of stem, root and leaf in two Okra cultivars namely Bamia and Emerald. In both cultivars, the value of height and biomass of shoot and root increased with 50 and 100 mg L^{-1} MWCNTs. Root and shoot diameters in both cultivars more affected by increased cortex thickness and central cylinder were with 50 and 100 mg L^{-1}. This study showed that the thickness of mesophylls and spongy layers increased at low level of MWCNTs, however these parameters were decreased with moderate and high levels of MWCNTs in both cultivars. Stomata size increased value in low and moderate levels of MWCNTs in Bamia cultivar. Also the diameter of xylem and phloem increased with 50 and 100 mg L^{-1}, but decreased with high MWCNTs level.

The effects of MWCNTs on physiological responses, plant growth, and Cd/Pb accumulation was explored by Oloumi et al. (2018), on seedlings of three plant species including *Brassica napus*, *Helianthus annus,* and *Cannabis sativa*. MWCNTs application effectively improved root and shoot growth inhibited by Cd and Pb salts. In *B. napus*, total chlorophyll (Chl) content increased by both MWCNTs 10 and 50 mg L^{-1} exposure under Cd or Pb stress. MWCNT at 10 mg L^{-1} mitigated the deleterious effects of Cd ions on the total Chl content of *H. annus* and *C. sativa*. Whereas higher concentrations of MWCNTs decreased Chl content under either Cd or Pb treatments on sunflower seedlings.

The paper by Yousefi et al. (2017) reports the effects of different dosages of MWCNTs on seed germination of hopbush, a medicinal plant. The results show that MWCNTs can improve seed germination percentage (GP), mean germination time (MGT), root and stem lengths, as well as fresh and dry weights of root and stem. When no drought stress was applied, GP of 10 and 200 mg L^{-1} nano carbon treatments was found to be 100%, and MGT in all treatments had a marked decrease as compared to the control. The best results were gained at zero osmotic pressure, in which the effect of MWCNTs was maximal at 30 mg L^{-1}. Increasing the level of drought stress revealed that 50 and 100 mg L^{-1} of MWCNTs could more favourably affect both parameters and seed germination. Therefore, nano-priming with MWCNTs can be recommended for enhancing seed germination and plant growth of hopbush, an evergreen shrub suitable for desert conditions.

SINGLEWALL CARBON NANO-TUBES

Velikova et al. (2021) studied the concentration-dependent effect of foliar application of copolymer-grafted SWCNTs on the structural and functional characteristics of intact pea plants. Abundant epicuticular wax generation on both leaf surfaces was observed after 300 mg L^{-1} treatment. Swelling of both the granal and the stromal regions of thylakoid membranes was detected after the application of 100 mg L^{-1} and was most pronounced after 300 mg L^{-1}. Higher SWCNTs doses lead to impaired photosynthesis in terms of lower proton motive force generation, slower generation of non-photochemical quenching and reduced zeaxanthin content; however, the photosystem II function was largely preserved. These results clearly indicate that SWCNTs affect the photosynthetic apparatus in a concentration-dependent manner. Low doses (10 mg L^{-1}) of SWCNTs appear to be a safe suitable objective for the future development of nanocarriers for substances that are beneficial for plant growth.

The report by Sun et al. (2020) in which was evaluated the effect of SWCNTs on soybean seeds, revealed that under osmotic potentials of 0, -0.3, -0.6 with PEG 6000, the germination percentage of SWCNTs-treated seeds was higher than the control treatment. The fresh weight of SWCNTs treated seeds were evidently higher than that of the controls under the osmotic potentials of 0, -0.3 and -0.6 MPa. The root and shoot length were also longer than control in SWCNTs treated seeds at 0, -0.3 and -0.6 MPa, therefore they suggest that SWCNTs enhanced drought tolerance during germination.

Zhang et al. (2017) evaluated SWCNTs and MWCNTs on rice seedling. They found that both CNTs accelerate leaf growth and development at a low concentration (20 mg L^{-1}), and increased chlorophyll content and net photosynthetic rate. Quantitative realtime polymerase chain reaction results indicated that both SWCNTs and MWCNTs significantly increased expression of genes associated with chloroplast development and cell sizes. Further analysis revealed that the ABA content decreased and the gibberellin content increased, while the content of O^{-2} and H_2O_2 was slightly elevated and the activities of antioxidative enzymes (SOD, EC and POD), were differently modulated after treatments with the CNTs. These results suggest a possible link between ROS and plant hormones under CNTs treatment to promote rice seedlings growth.

GRAPHENE OXIDE NANO-PARTICLES

Analyzing the joint phytotoxicity of GO and arsenic species on wheat and tomato, Cao et al. (2021) reported that one mechanism of enhanced arsenic phytotoxicity, could be GO-induced up-regulation of the aquaporin and phosphate transporter related genes expression, which would lead to the increased accumulation of As (III) and As (V) in plants. In addition, co-exposure with GO resulted in more severe oxidative stress than single As exposure, which could subsequently induce damage in root plasma membranes and compromise key arsenic detoxification pathways such as complexation with glutathione and efflux. The authors suggest that plants co-exposure to GO and As also led to more significant reduction in macro- and micronutrient content.

In the study reported by Di Zhang et al. (2021), carnation cut flowers were used a model to evaluate the protective effects of SWCNT, graphene quantum dots (GQD), and fullerenes (C60) on the antioxidant activity and senescence of plant cells. They found that 1 mg·L^{-1} C60 and 25 mg·L^{-1} GQD extended the vase life (VL) of carnation by approximately 10%. SWCNT cannot be absorbed and transported by plant vascular tissue, and higher concentrations of SWCNT can block vascular tissue, leading to decreased VL. Physiological tests shown that the malondialdehyde and hydroxyl radical (OH) levels significantly decreased after the GQD and C60 treatments, and the main factors that cause cell damage changed from H_2O_2 to OH.

Gao et al. (2020) assessed the potential effects of foliar GO sprays on photosynthesis and antioxidant systems in Cd-stressed lettuce. They found that the foliar application of 30 mg L^{-1} of GO could significantly reduce signs of Cd_2^+ toxicity in lettuce; it also was observed an increased net photosynthetic rates, stomatal conductance, transpiration rates, chlorophyll content, primary maximum photochemical efficiency of photosystem II, actual quantum yield, photosynthetic electron transport rates, ribulose-1,5-bisphosphate carboxylase and oxygenase concentrations, and biomass in Cd_2^+-stressed lettuce treated with GO. In addition, the foliar application of 30 mg L^{-1} of GO reduced the accumulation of ROS and H_2O_2, malondialdehyde content, and the activity of antioxidant enzymes.

Chen et al. (2018) investigated the phytotoxicity of unfunctionalized GO and amine-functionalized graphene oxide (G-NH_2) on wheat in the concentration range from 125 to 2000 μg mL^{-1}. The results found that the incubation with both nanomaterials did not affect the final seed germination rate. The exposure to GO at a high concentration (above 1000 μg mL^{-1}) resulted in a severe loss of morphology of seedlings, and a decrease in root and shoot length, biomass, along with obvious damage to plant tissue structures (root, stem, and leaf) when compared with the control. GO induced increased damage to root cells, which was determined by electrolyte leakage. Conversely, the plant growth was enhanced under G-NH_2 exposure, and the root and stem lengths were increased by 19.27% and 19.61% at 2000 μg mL^{-1}, respectively.

CONCLUDING REMARKS

Nanoparticles, both metallic and carbon-based can boost agricultural production by improving nutrient use efficiency with nanoformulations of fertilizers; agrochemicals for crop enhancement, detection and treatment of diseases, host-parasite interactions at the molecular level using nanosensors, plant disease diagnostics, contaminants removal from soil, and water, postharvest management of vegetables and flowers, and reclamation of salt-affected soils. NT currently represents a new frontier for modern agriculture, and undoubtedly will become a very important tool in the near future by offering many innovative nanomaterials for application directly to the field. The goal of nanomaterials in agriculture is to reduce the number of chemicals applied, minimize the benefits of nutrients in fertilization, and increase crop yields for the management of pests and nutrients. The applications of metallic or carbon-based nanomaterials can be of great significance in the current context of global food shortages.

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