Plant Physiological Responses to Engineered Nanoparticles

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Abstract

Plants are reared in and around the world for a variety of purposes. The peasant community cultivates the same crop in continuous manner that result in more economic losses due to multiple reasons. The common among them may be diseases by pathogenic microorganisms and parasites (insect pests, nematodes), micronutrient deficiency and weeds. The green revolution introduced a number of agrochemicals to improve the crop yield, but prolonged use turned these complex organic compounds into recalcitrant and xenobiotics of ecosystem. The demand for sustainable agriculture has been introduced to improve the yield and meet the supplies as required. The rise in synthesis of particles of nanoscale with wide range of metal oxides such as Ag, Au, Al, Cd, Ce, Cu, Co, Fe, G, Ni, Mg, Pt, Pd, Mn, Ti, Zn was known to be beneficial in different fields. The nanoparticle synthesis is known to be done by different approaches like physical, chemical and biological (plant materials, bacteria and fungi). The nanoparticle applications in the field of agriculture are not as popular as compared to other allied aspects (medicine, pharmacy). There is progress in laboratory-level studies that could make nanoparticle-based products in agriculture as a substitute to agrochemicals. This chapter is intended to discuss the developments in the field of nanoparticles as a success story that proved the potential of nanoscale components as plant growth stimulants, fungicide, pest control, weedicides and micronutrient supply.

Keywords

Agrochemicals • Crop plants • Growth responses • Phytohormones • Phytotoxicity

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1 Introduction

Plants are known to be autotrophic growing by acquiring solar energy and other requirements from substratum via the root system. The underground part root absorbs mineral nutrients required for growth and development from soil. The physiology and phenology of plants responds to the availability of mineral nutrients in the form of growth and reproduction. The deficiency and excess in minerals in plants expressed as symptoms, leads to several ill effects. Agriculture, an important source of food and feed around the globe, is facing challenge with increase in human population. The advent of the green revolution in 1970 changed the scenario to be profitable for the peasant community. The extensive use of synthetic chemicals developed an alarm to save the ecosystem. The series of approaches lead to go with smart/climate-resilient crops for reducing the threats for upcoming generations (Khan et al. 2017).

Nanoscale materials are natural or man-made/engineered forms that serve superior to bulk form. The nanoparticle (NPs) exist in size range <100 nm with spherical, tubular, irregular in shape found in single, fused or agglomerated forms in homologous or heterogeneous composition (Table 1). Nanotechnology has been applied in the field of farming systems to improve the yields of crop with minimizing the inputs. To overcome hazardous fertilizers, pesticides/insecticides, weedicides/herbicides, fungicides, and antibiotics nanoscale materials are exploited as a part of sustainable agriculture (Tables 2, 3, 4 and 5). The common fact is the applied fertilizers for nitrogen and phosphorus are absorbed by plants (30–50%) and the efficiency of absorption is low, and the possibility of interference with substratum increases and creates havoc. The nanoscale fertilizers increased the nutrient absorption efficiency with enhanced crop productivity. The important problem of agriculture is weed, pathogens (virus, fungi, bacteria, pests, nematodes) that reduce the crop yield.

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Table 1 Engineered nanomaterials and their types

Engineered nanomaterials (ENMs)	Types
Carbon-based nanomaterials	Carbon nanotubes (CNTs): single walled carbon nanotube (SWCNT), multi walled carbon nanotube (MWCNT) and Graphene and fullerenes (C60 and C70)
Metal based nanomaterials (Inorganic)	Zero-valent metals (such as Au, Ag, and Fe ENMs), Metal oxides (nano-ZnO, TiO_2 and CeO_2), and Metal salts (such as nano silicates and ceramics)
Quantum dots	CdSe and CdTe
Nanosized polymers (Organic)	Dendrimers, liposomes and polystyrene
Organic—inorganic hybrids	Metal organic frameworks, covalent organic frameworks

Table 2 Engineered nanomaterials and their uptake by plants

Mode	Types	
Cuticle (size: 0.6–4.8 nm)	Lipophilic (non-polar) Hydrophilic (polar)	Leaves
Stomata (size: 20 nm)	Stomatal aperture through apoplast	
Lateral root junction	Apoplastic pathway	Roots
Cell–cell contact	Symplastic pathway	

Table 3 Impact of nanoparticles on plant productivity

Nanoparticles	Plant productivity	Reference
Nano-zinc oxide (nZnO) and nano-silicon (nSi)	Improved salt resistance in plant, load of annual crop and quality of mango fruit	Elsheery et al. (2020a, b)
Urea doped hydroxyapatite nanoparticles (Ur@HANP)	Proved alternative for N and P fertilizers	Pradhan et al. (2020)
Titanium NPs (Ti-NPs)	Alleviated As-induced toxic responses in *Vigna radiata* L	Katiyar et al. (2020)
Molybdenum oxide nanoparticles (MoO_3-NPs)	Effective on the productivity of common bean plant	Osman et al. (2020)
Calcium tetraborate nanocrystals-Boron (B) nano-fertilizer (NF) - lettuce (*Lactuca sativa*) and zucchini (*Cucurbita pepo*) growth and physiology	Effective at plant productivity on B-limited soils	Meier et al. (2020)
Iron (III) oxide (Fe_2O_3) NMs applied to wheat plants in a hydroponics	Efficient in plant growth	Al-Amri et al. (2020)
Zinc oxide nanoparticles (ZnONPs) and zinc ions (Zn^{2+})	Reduced total As in rice	Ma et al. (2020)
Zinc oxide nanoparticles (ZnO-NPs)	Reduce toxicity of Cd in tomato plants	Faizan et al. (2020)
Fe_3O_4 nanoparticles (NPs)	Protective role of NPs for microbes and plant (maize) roots	Yan et al. (2020)
Manganese (III) oxide nanoparticles (MnNPs)	Alleviate salinity stress in *Capsicum annuum* L	Ye et al. (2020)

Table 4 Impact of nanoparticles formulation with herbicides

Nanoparticles	Impacts	Reference
Poly(lactic-co-glycolic-acid) (PLGA) with atrazine on potato	Herbicide was effective and alternative to inhibit weed growth	Schnoor et al. (2018)
Fullerenol nanoparticles (FNP) with paraquat on honey bee (*Apis mellifera carnica*)	Antioxidative effects with protection against oxidative stress	Kojic et al. (2020)
Different NMs (Fe, Mn_3O_4, SiO_2, Ag, and MoS_2) on spinach	Proved to enhance photosynthesis and potential as nanofertilizer	Wang et al. (2020a, b)
Spinach, apple and corn leaves Glyphosate (Gly) on cysteamine-modified gold nanoparticles (AuNPs-Cys)	Evaluated the Gly distribution on plant tissues	Tu et al. (2019)
Triazine + ZnO-NPs on Corn	Determination of traces of herbicide	Li et al. (2017)
Poly(ε-caprolactone) nanocapsules with neem oil	Environmentally friendly formulation for applications in agriculture	Pasquoto-Stigliani et al. (2017)
Herbicides: imazapic and imazapyr Alginate/chitosan and chitosan/tripolyphosphate nanoparticles	Encapsulation of herbicides improved mode of action and reduced toxicity	Maruyama et al. (2016)
Gold nanoparticles (AuNPs) and nanosheets - triazine herbicides (prometryn, atrazine, terbumeton and secbumeton) in spiked maize	Au/LDH nanohybrids can also be applied to extract other analytes	Li et al. (2018)
Paraquat on novel nanoparticles of pectin, chitosan, and sodium tripolyphosphate (PEC/CS/TPP)	Efficient and formulation of NPs showed herbicide activity in maize/mustard	Rashidipour et al. (2019)
Metolachlor water-based mPEG − PLGA nanoparticle formulation	Polymeric nanoparticles served pesticide carrier on *O. sativa*, *Digitaria sanguinalis* with low environmental impact	Tong et al. (2017)
2,4-dichlorophenoxy acetic acid (2,4-D) mesoporous silica nanoparticles (MSNs)	Nanoformulation showed good bioactivity on target plant cucumber (*C. sativus* L.) and wheat (*T. aestivum* L.)	Cao et al. (2018)
Poly(ε-caprolactone) (PCL) nanocapsules containing atrazine	Nanocapsules potentiated the post-emergence control of *Amaranthus viridis* (slender amaranth) and *Bidens pilosa* (hairy beggarticks)	Sousa et al. (2018)
Polycaprolactone nanocapsules (PCL) containing pretilachlor	Barnyard grass found cytotoxicity and rice-no toxic effect	Diyanat et al. (2019)
Plant virus nanoparticles (VNPs) and virus-like particles (VLPs): tobacco mild green mosaic virus (TMGMV), cowpea mosaic virus (CPMV), Physalis mosaic virus (PhMV), mesoporous silica nanoparticles (MSNPs) and poly(lactic-co-glycolic acid) (PLGA) formulation	Plant viruses were superior to synthetic mesoporous silica nanoparticles and poly(lactic-co-glycolic acid) for the delivery and controlled release of pesticides	Chariou et al. (2019)
Mesoporous silica nanoparticles (MSNs) - Diquat dibromide (DQ)	Exhibited herbicidal activity against *Datura stramonium* L	Shan et al. (2019)

The synthetic chemicals are applied to reduce the burden of diseases, and in turn, the chemical forms target the beneficial agents. There are several reports on nanomaterials as effective control efficacies and improved crop yields (Khan et al. 2015a, b, 2019). The efficiency of engineered nanoparticles (ENPs) is focused to highlight the merits on plant physiology that increase the crop yields with multifarious applications. The need of sustainable farming to protect the environment with high yields from different crop plants is investigated to feed the growing human population. The nanoscale particles are reported for alternatives to reduce the burden of agrochemicals. The reports on use of ENPs to boost plant physiological responses and enhance the yield and quality of crop, medicinal and ornamental plants (herbs, shrubs and trees) were evaluated to prove the efficiency in different conditions (Figs. 1 and 2). In this chapter, the role of ENPs in test plants is presented in different categories, viz.: (1) Plant growth responses, (2) Fertilizer effects in different plants, (3) Nano-harvest, (4) Phytoaccumulation, and (5) Toxicity effects.

2 Plant growth responses to engineered nanoparticles

Improved metabolic profile

The soil amended with cadmium sulfide nanoparticles (CdS-NPs) was used for broad bean (*Vicia faba* L.) plant cultivation and evaluation of the phenotypic, biochemical

Table 5 Impact of nanoparticles formulation for insecticides

Nanoparticles	Insecticidal activity	References
Chitosan and agrochemical loaded chitosan (spinosad and permethrin) nanoparticles	More effective with a lasting residual effect on *Drosophila melanogaster*	Sharma et al. (2019)
Pesticide (ferbam)-gold nanoparticles (AuNPs)	NP's served as carrier for delivering pesticides	Hou et al. (2016)
Carboxylic multiwall carbon nanotubes (CMNTs) as adsorbent to remove fenvalerate	Showed stability and non-aggregatable as adsorbent	Naeimi et al. (2016)
Carboxymethyl chitosan modified carbon nanoparticles (CMC@CNP), as carrier for emamectin benzoate (EB)	Test NP performance based on pH-responsive controlled release. The release of EB was sustained, steady and prolonged persistence time on maize with *Mythimna separate*	Song et al. (2019)
Nanoformulation (NF) of thiamethoxam (TMX) - cellulose nanocrystals (CNCs)	Insecticidal activity against *Phenacoccus solenopsis*	Elabasy et al. (2020)
Copper-based nanopesticide Kocide 3000	Effective on genes related to detoxification and reproductive system of *Daphnia magna* (water flea)	Aksakal and Arslan (2020)
Zinc oxide nanoparticles (ZnO NPs) and silica nanoparticles (SiO_2 NPs) against: adults of rice weevil (*Sitophilus oryzae* L.); red flour beetle (*Tribolium castaneum* Herbst.) and cowpea beetle (*Callosobruchus maculatus* F.)	Proved potential as stored seed protectant	Haroun et al. (2020)
Silica nanoparticles (SiO_2-NPs) against *Sitophilus oryzae, Rhizopertha dominica, Tribolium castaneum,* and *Orizaephilus surinamenisis*	NPs were effective than conventional pesticides	El-Naggar et al. (2020)
Silver nanoparticles (AgNPs) from leaf extract of *Holostemma ada-kodien*	Toxic against *Anopheles stephensi, Aedes aegypti*, and *Culex quinquefasciatus* and Antimicrobial activity	Alyahya et al. (2018)
Fe_2O_3NPs on Bt-transgenic scotton	Increased the Bt-toxin in leaves and roots	Nhan et al. (2016)
Neem oil-loaded zein nanoparticles	Mortality effects on *Acanthoscelides obtectus*, *Bemisia tabaci* and *Tetranychus urticae*	Pascoli et al. (2020)

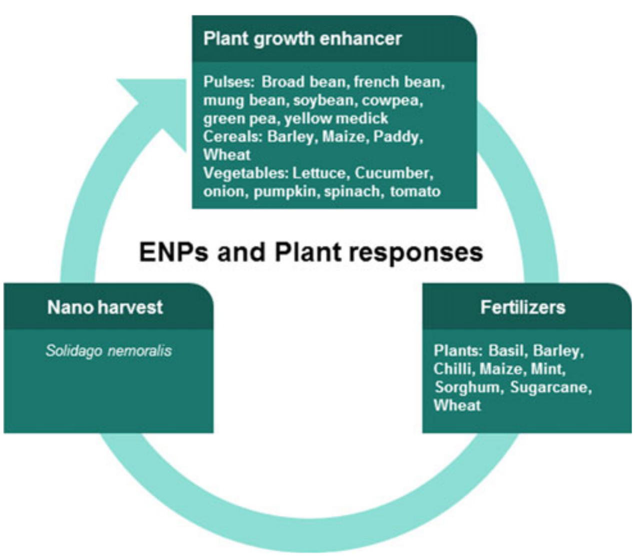

Fig. 1 Impact of engineered nanoparticles (ENPs) in different plants

and metabolic responses. The findings of study proved the alleviation of toxicity by CdS-NP in soil and without change in phenotypic effects in broad bean plant and upregulation of antioxidative metabolic profiles of the leaves (Tian et al. 2020). Another study investigated the role of iron oxide nanoparticles (Fe_3O_4-NPs) on phloem-sap metabolite composition in pumpkin (*Cucurbita maxima* L.) plants. The results showed that the test NPs were translocated to the aerial parts of plants with increased metabolites in phloem sap and improved oil composition of the plant (Tombuloglu et al. 2020). The reports of studies on plants like broad bean and pumpkin proved treatment with test NPs enhanced metabolites that alleviate toxicity and improved oil composition.

Recovery from drought

The study explored the impact of silicon nanoparticles (Si-NPs) on seedlings of barley (*Hordeum vulgare*) treated

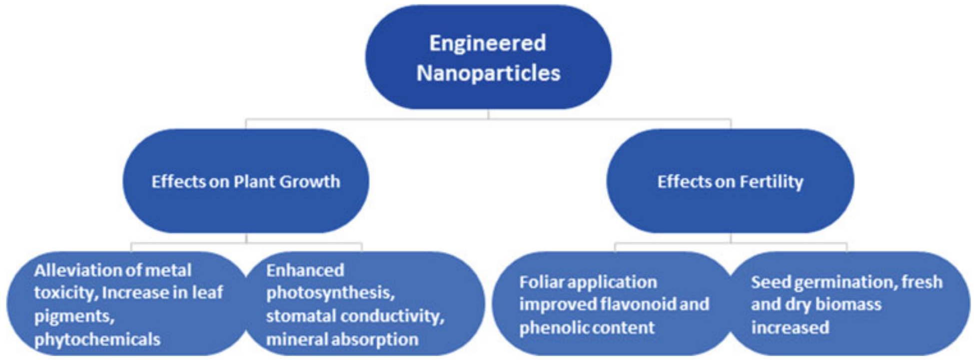

Fig. 2 Physiological responses to engineered nanoparticles (ENPs) by test plants

with different drought intensities and recovery from drought stress. The findings showed NP aggregates formation in plant tissues, pores of large size in roots and stomata in leaves were closed rapidly. There was an increase in total chlorophyll and carotenoid content of leaves in the test plants. The plants showed changes in antioxidant enzymes, cell injury, osmolyte, metabolite profile and the membrane stability indices. The study proved that application of NPs directly in soil was suitable for post-drought recovery of barley plants (Ghorbanpour et al. 2020).

Counteract membrane damage

The effects of engineered nanoparticles such as Ag, Co, Ni (metals) and CeO_2, Fe_3O_4, SnO_2, TiO_2 (metal oxides) on seedlings of basil (*Ocimum basilicum* L.) grown in mix of 20% sandy soil and 80% peat were investigated by Antisari et al. (2018). The results indicated that the test metal-NPs were accumulated in the roots and the selected NPs, i.e., Ag, Co, CeO_2 and Ni, were translocated from the root to shoot, leaves and then to edible part of the test plant. The relative short exposure accumulated Ca in roots that counteracted the membrane damage by nanoparticles (Antisari et al. 2018).

Induced root formation

The study carried out by Ahmad et al. (2020) on ZnO and CuO-ENPs application on in vitro formation of root, antioxidant (non-enzymatic) activities and steviol glycosides (SGs) in Candyleaf (*Stevia rebaudiana*) regenerants. The results of NP treatment showed that the percentage of rooting and SGs—rebaudioside A and stevioside—were increased. The phytochemical studies (flavonoid content, phenolic content) and 2,2-diphenyl-1-picryl hydrazyl (DPPH)-free radical scavenging activity were high in regenerants. The biochemical and morpho-physiological responses of candyleaf were proved to elicit defense against test ENPs (Ahmad et al. 2020).

Increased in vitro regeneration

The study by Zia et al. (2020) analyzed the effect of silver nanoparticles (AgNPs) on in vitro regeneration of carnation cultivars cv. *Noblessa*, cv. *Antigua* and cv. *Mariposa*. The number of shoots/explant of cv. *Noblesse* and cv. *Antigua* and cv. *Mariposa* showed the highest regeneration rate. The study concluded that test nanoparticles were effective for increasing in vitro shoot multiplication and regeneration of plants (Zia et al. 2020).

Improved yield and nutritional quality

The effects of $nCeO_2$ and nCuO on yield and nutritional quality of cucumber by foliar application was studied by Wang et al. (2020a, b) in three week-old cucumber seedlings grown in soil. The test plants were evaluated for parameters such as Ce, Cu and other nutritional elements, stomatal conductance (Gs), transpiration rate (E), net photosynthesis rate (Pn), yield, fruit size, weight and firmness. The results showed increase in the fresh weight and reduced Zn content in test plant fruits treated with nanoparticles (Hong et al. 2016). Another study by Wang et al. (2020a, b) on Chinese scallion (*Allium fistulosum*) plants from soil amended with CuO particles [nano (nCuO), bulk (bCuO) and $CuSO_4$] grown in greenhouse conditions. These plants were used to evaluate the allicin content, nutrient element and enzymatic antioxidants. The test plants showed enhanced nutrient and allicin contents in scallion by nCuO treatment and suggested the use of nanofertilizer for onion crop (Wang et al. 2020a, b).

Further, the bulbs of *Allium cepa* were assessed for mitotic index (MI) and chromosomal aberrations (CAs) after treatment with TiO_2 and ZnO-NPs, and their mixtures (1:1) by Fadoju et al. (2020). The results of recovery test in treated bulbs showed transient CAs induced by both NPs and the frequency of aberrations was high. The finding proved the potential of tested NPs to induce mutation in somatic cells of bulbs of *A. cepa* (Fadoju et al. 2020). In a study by Bakshi et al. (2019), the tomato plants were grown in sewage sludge amended with nano-TiO_2 in agricultural soil. The NP-treated plants showed increase in growth parameters like leaf biomass (142%), fruit yield (102%). The test plants were found with decrease in tannin, lignins of leaf and increase in carbohydrate levels, change in elements like Fe, B, P, Na and Mn in stem, leaves and changes were less in fruits. The tomato fruits showed no significant Ti enrichment, and TiO_2-NPs proved safe in improving growth and biochemical parameters (Bakshi et al. 2019).

Further, the study by Noori et al. (2020) investigated tomato seedlings (*Lycopersicon esculentum*) for physiological and molecular responses upon exposure to AgNPs and silver nitrate ($AgNO_3$) in hydroponic media for 7 days. The results showed 2–7 times decrease in growth rate and increase in H_2O_2 and malondialdehyde in exposed plants than control. There was decrease in enzymatic antioxidant (50%) and upregulation of genes of ethylene-inducing xylanase (EIX), peroxidase (POX) and phenylalanine ammonia-lyase in test plants (Noori et al. 2020).

Improved photosynthesis

The bean (*Phaseolus vulgaris* L.) plants were sprayed and applied in soil with CeO_2-NPs by Salehi et al. (2018). The results showed absorption of test NPs in dose-dependent manner; the uptake and translocation by plants was through both roots and leaves that increased Ce content. The spraying lowered stomatal density and increased stomatal length, and alteration in photosynthesis and the electron transport chain. The increase in Ce content induced accumulation of osmolytes (proline), phytosiderophores (muconate and mugineate) and proteins involved in folding or turnover. The spray mode of NPs in bean plants was effective compared to soil application (Salehi et al. 2018).

Amelioration of Cd toxicity

The cowpea plants were evaluated by Ogunkunle et al. (2020) for Cd toxicity after foliar treatment of nano-TiO_2 in six episodes. The results showed that NPs promoted parameters in roots and leaves like chlorophyll b, total chlorophyll content and stress enzymes. The seeds were with increase in Zn, Mn and Co levels and the roots, shoots and grains showed decrease in Cd levels in NP-treated plants after Cd stress. The nano-TiO_2 foliar application proved its ameliorative potential in cowpea plants for Cd toxicity (Ogunkunle et al. 2020).

Lian et al. (2020) investigated maize (*Zea mays* L.) crop production in Cd-contaminated soils by application of TiO_2-NPs. The results showed that root exposure enhanced Cd uptake and created phytotoxicity in the test plant. The foliar exposure decreased shoot Cd content and alleviated Cd-induced toxicity by test NPs through increase in activities of superoxide dismutase (SOD) and glutathione S-transferase (GST) and upregulation of citrate cycle, galactose, alanine, aspartate, glutamate, glycine, serine and threonine metabolism. Sharifan et al. (2020) investigated the uptake and accumulation of surface charge of ENP cerium oxide nanoparticles (CeO_2-NPs) and cadmium (Cd) in the presence of inorganic phosphorous in soybean seedlings grown in hydroponic system. The results showed mutual effect of test NPs and Cd-affected phosphate level in treated plants.

Increase in seed number

The green pea (*Pisum sativum*) plants were grown in soil by Ochoa et al. (2017) amended with nano-CuO, bulk-CuO (bCuO) and $CuCl_2$ and indole-3-acetic acid (IAA). The results showed that NPs reduced the number of plants and pod biomass by about 50%. The results suggested that the nutritional quality of test pea pods was improved by use of nano-CuO and bCuO (Ochoa et al. 2017). The effect on seed germination and growth performance of pea (*P. sativum*) by treatment by poly(vinylpyrrolidone) (PVP) stabilized on platinum nanoparticles (Pt:PVP) was investigated. The germination rate was decreased, and the other parameters like dormancy period, arbuscular mycorrhizal fungi and rhizobial colonization in treated plants were decreased. The results proved that the average number of seeds was increased to 163.5% and the average seed weight was decreased by 66.7% (Rahman et al. 2020).

Decreased fertilizer use

The greenhouse experiments by Pandorf et al. (2020) were conducted to study the growth of romaine lettuce (*Lactuca sativa*) and nitrate leaching through soil by using 2D graphite carbon nanoparticles (CNPs). Then, the NPs were combined with fertilizer and the effect on yield, nitrate leaching and nutrient uptake by lettuce plant was evaluated by applying in the soil. The results showed that test NP lowered fertilizer dose and decreased nitrate infiltration through the soil (Pandorf et al. 2020).

Improved germination

The germination of *Vigna radiata* was studied by Jung et al. (2020) of single and binary mixtures of CdO, CuO nanoparticles under humidity 70–80%. The results showed the germination rate of bean was high at 80% humidity and less with single metal NP exposure in both humidity levels. The metal accumulation rate was high with the nCuO than nCdO in treated bean plants (Jung et al. 2020). Pariona et al.

(2017) reported the germination and early growth of oak (*Quercus macdougallii*) by application of citrate coated two types of Fe_3O_4-NPs. The germination was increased 33%, and the growth, dry biomass and chlorophyll concentration were enhanced. The study suggested that NPs treatments could improve reforestation of threatened forestry species (Pariona et al. 2017).

The investigation of ZnO and TiO_2 nanomaterial synthesis was attempted to increase the rate of transplant production in eggplant, pepper and tomato. The results showed the effect of nanomaterials gel-coated seedlings on parameters like mean germination time, and germination coefficient of variation was reduced. The performance of growing transplants was efficient for the safer production of transplants by gel-coated nanomaterials on test plants (Younes et al. 2020).

Increased plant biomass

The effects on hydroponically grown *Nigella arvensis* L. by application of engineered aluminum and nickel oxide (Al_2O_3 and NiO-NPs) nanoparticles on parameters like growth, oxidative stress and activities of antioxidants were investigated by Chahardoli et al. (2020). The less concentrations increased plant biomass, and the high levels of the test nanoparticles decreased *N. arvensis* biomass. There was an increase of enzymatic antioxidants such as ascorbate peroxidase (APX), catalase (CAT), superoxide dismutase (SOD) and peroxidase (POD) in roots and shoots. The parameters like scavenging activity by 2,2-diphenyl-1-picryl hydrazyl (DPPH), capacity of total antioxidant, reducing power, iridoids, saponin and phenols in treated plants were increased by test NPs. The application of NiO-NPs on test plants inhibited the antioxidant activities, secondary metabolites formation, total antioxidant capacity, scavenging activity by DPPH and total saponin content (Chahardoli et al. 2020).

Effect on plant microbiota

Vitali et al. (2019) explored the poplar (*Populus nigra*) plants for the effect of silver nanoparticles (AgNPs) application. The test plant microbiota levels in leaf and root were evaluated after NP treatment. The results showed increase in bacteria and fungi in the treated leaf and reduced the bacterial and fungal biodiversity in the root. The study showed the phyllosphere and rhizosphere poplar-associated microbiota of a tree species from a polluted environment (Vitali et al. 2019).

Increase in plant root and shoot

The sludge conditioned in soil with single and binary mixture of nanoparticles (Ag_2O, TiO_2) was investigated by Singh and Kumar (2020a, b) for effect on spinach plants grown in pot experiments. The Ag_2O NPs treated plants showed no growth effects. The root length and fresh weight were increased in spinach at high concentration of single and binary mixture of TiO_2NPs. The binary mixture and TiO_2 increased total chlorophyll content and decreased with higher tendency of root surface adsorption by Ag_2O. The study of single and binary mixture of NPs reported no acute toxicity in the treated spinach. The spinach leaves grown in sludge enriched with NPs were found unsafe for consumption due to accumulation of Ag and Ti metals (Singh and Kumar 2020a, b).

The study assessed the role of nano-zerovalent iron (FeO nanoparticles) on sunflower (*Helianthus annuus*) plants cultivated in soil with hexavalent chromium (Cr IV). The amelioration of Cr toxicity in sunflower plants by application of test NPs was evaluated by Mohammadi et al. (2020). The results revealed that the higher concentration of test nanoparticles increased plant morphological and physiological parameters and decrease in Cr uptake. The factors like bioaccumulation (BAF) and translocation (TF) in root and shoot tissues were reduced. The results of NP-treated plants under Cr toxicity were found through reduced Cr uptake and increased activity by SOD, CAT, POX and APX detoxification enzymes (Mohammadi et al. 2020).

Mitigation of chilling stress

The effects on sugarcane leaves treated with NPs of silicon dioxide (nSiO_2), zinc oxide (nZnO), selenium (nSe), graphene nanoribbons (GNRs) as foliar sprays were investigated by Elsheery et al. (2020a, b). The ameliorative effects of NPs against chilling stress in test plants for photosynthesis and photoprotection were evaluated. The results of NPs application reduced the adverse chilling effects in treated seedlings by the increased PS-II photochemical efficiency (Fv/Fm), maximum photo-oxidizable PS-I (Pm), photosynthetic gas exchange and the chlorophyll and carotenoid content. It was proved that among the tested NPs, nSiO_2 showed higher amelioration effects to mitigate chilling stress in sugarcane (Elsheery et al. 2020a, b).

Improved defenses

The foliar spray of Fe_3O_4-NPs on *Nicotiana benthamiana* plant was reported for the increased (both dry and fresh) weights, activation of antioxidants and upregulation of salicylic acid (SA) synthesis. The accumulation of endogenous SA in test plants conferred the plant resistance against *Tobacco Mosaic Virus* (TMV) infection (Cai et al. 2020). The exposure of tobacco (*Nicotiana tabacum*) seedlings to AgNPs and ionic silver was investigated by Stefanic et al. (2020) for the physiological effects, changes in ultrastructure and proteomics. The results revealed high toxicity in treated seedlings due to oxidative stress parameters by ionic Ag than nanosilver. The root cells showed the presence of silver in the nanoparticle form. The leaf chloroplasts of treated plantlets were changed that altered rate of photosynthesis. The majority of primary metabolism proteins was up-regulated that helped to cope with silver-induced toxicity through enhanced energy production and reinforced defense in treated plants (Stefanic et al. 2020).

Kokina et al. (2020) demonstrated that the five-weeks-old yellow medick (*Medicago falcata* L.) plants grown using hydroponics with Fe_3O_4-NPs. The results of treatment induced increase in root length, chlorophyll a fluorescence in yellow medick. The parameters that conferred resistance to powdery mildew disease (fungal) were reduced genome instability, genotoxicity and expression of miR159c (Kokina et al. 2020).

Responses of nanoparticles treated paddy

Peng et al. (2020) examined the effects on paddy soil and rice plants under flooded condition by ZnO, CuO and CeO_2 nanoparticles (NPs) for the bioavailability and translocation. The results showed that test NPs enhanced redox potential of paddy soil. The NPs induced the elements (Cu and Ce) accumulation in rice roots. The Zn concentration in shoots was high by ZnO-NPs with translocation factor—1.5. The root cortex accumulated Zn and Cu was accumulated in the root exodermis in the NPs treated plants (Peng et al. 2020).

Wu et al. (2020) reported hydroponic cultivation of rice (*Oryza sativa* L.) seedlings for comparative evaluation of the metallic (AgO-NPs) and sulfidized (Ag_2S-NPs) silver nanoparticles. The test NPs were investigated for iron plaque formation and effects of silver uptake in seedlings. The results revealed iron plaque in seedlings and the AgO and Ag_2S-NPs bioavailability. The study alarmed concern for the wetland plants for Ag_2S-NPs exposure. The high Fe levels facilitate bioavailability of Ag_2S-NP in Fe-rich environments (Wu et al. 2020). The rice seedlings in a hydroponic were investigated for arsenite (As(III)) or arsenate (As(V)) and CuO-NPs or Cu(II) accumulation by Wang et al. (2019). Cu in both forms were found to reduce the total As accumulation, and Cu(II) was more effective than CuO-NPs in rice tissues. The results proved that nano-enabled agrichemicals were alternative to conventional metal salts in agriculture for safe application (Wang et al. 2019).

Zhang et al. (2020a, b) reported on the heavy metals chemical speciation and micronutrient bioavailability in paddy soil by TiO_2-NPs, ZnO-NPs and CuO-NPs by flooding–drying simulation. The results showed that the NPs addition increased pH, Eh and electrical conductivity (EC) in soil. The acid-soluble fraction showed increase in the Zn and Cu concentrations that led to enhanced bioavailability of test metals in the soil. The NPs treated soil showed decrease in Cd bioavailability with the TiO_2-NPs and increase by ZnO and CuO-NPs (Zhang et al. 2020a, b). The ZnO-NPs toxicity in rice seedlings by using sodium nitroprusside (SNP, a NO donor) was investigated for the regulatory mechanisms of nitric oxide (NO) in counteracting test NPs toxicity by Chen et al. (2015). The results showed reduced accumulation of Zn, production of reactive oxygen species and lipid peroxidation. The test seedlings showed increase in reduced glutathione and activities by peroxidase, catalase and ascorbate peroxidase. The study provided evidence for NO in amelioration of test NPs phytotoxicity in rice seedlings (Chen et al. 2015).

The germination and growth of rice (*O. sativa* L., cv. Swarna) seedlings were evaluated by Gupta et al. (2018) for phytostimulatory effect by silver nanoparticles (AgNPs). The results showed that tested concentrations of NPs promoted both the shoot and root growth and increased the length and biomass, phenolic metabolites, chlorophyll-a and carotenoid contents of seedlings. The study showed changes in activities of catalase (CAT), ascorbate peroxidase (APX) and glutathione reductase (GR) and gene expression of antioxidative enzymes in seedlings (Gupta et al. 2018).

The study by Zhang et al. (2020a, b) evaluated the phytotoxicity and cadmium (Cd) migration in *O. sativa* by TiO_2-NPs in the soil–rice system. The high Cd content decreased the height and biomass of test plants and metal enrichment in paddy soil. The increase in height, biomass and the total chlorophyll in the leaves was reported at tillering stage. The booting stage showed reduction of malondialdehyde (MDA) by 15–32% and the peroxidase (POD) activity 24–48%. The leaves (booting and heading stage) and the catalase (CAT) activity in the tillering stage were reduced. The results suggested that Cd migration was found promoted by TiO_2-NPs in the soil–rice system (Zhang et al. 2020a, b).

Responses of nanoparticle-treated wheat plants

The wheat (*Triticum aestivum* L.) plants were investigated for bioaccumulation and translocation of NPs, growth, photosynthesis and gas exchange by application of biochar supplemented with cerium oxide nanoparticles (CeO_2NPs) by Abbas et al. (2020). The results indicated that CeO_2NPs promoted the plant growth by triggering photosynthesis, transpiration and stomatal conductance in dose-dependent manner. The biochar amendment with CeO_2NPs reduced the accumulation of Ce and alleviated the phytotoxic effects on wheat plant growth. The findings proved that NPs bioavailability to plants could be inhibited by supplementation of biochar (Abbas et al. 2020).

Khan et al. (2020a, b) investigated the wheat (*T. aestivum* L.) plant growth and uptake of Cd grown in pot under ambient conditions in Cd-contaminated soil by Si-NPs at different water levels. The results showed that NP application improved the wheat plant growth and photosynthesis, reduced the Cd levels in wheat grains and the oxidative stress in leaves. The different parameters like hydrogen peroxide production, leakage of electrolytes and malondialdehyde were reduced and superoxide dismutase and peroxidase activities by NPs application on wheat plants. The test NPs improved in wheat plant growth and reduced oxidative stress and Cd in tissues in dosage-dependent manner (Khan et al. 2020a, b).

The study by Zhang et al. (2018) examined the effect of nCu exposure on the root morphology, physiology and gene transcription levels of wheat (*T. aestivum* L.). The results showed decrease in relative growth rate of roots and the formation of lateral roots. The nitrogen uptake was increased, and auxin was accumulated in lateral roots of test plants. The antioxidant (proline) was induced that scavenged excess reactive oxygen species and alleviation of Cu phytotoxicity (Zhang et al. 2018). In a study by Rico et al. (2020), two generations of wheat plants were exposed to low or high nitrogen soil amended with CeO_2-NPs. The results of NP treatment showed change in DNA/RNA metabolites, i.e., thymidine, uracil, guanosine, deoxyguanosine, adenosine monophosphate in test plants. The wheat grains exhibited decrease in Fe concentration by 13–16% (Rico et al. 2020).

The mesoporous silica nanoparticles (MSNs) effects were evaluated in wheat and lupin plants by Sun et al. (2016) for the growth and development. The results of NP application increased rate of germination and plant biomass. The growth of test plants was accompanied with enhanced total protein, chlorophyll and rate of photosynthesis was increased (Sun et al. 2016). The study of wheat (*T. aestivum* L.) in a greenhouse under drought and non-drought conditions was evaluated by use of urea coated with ZnO-NPs or bulk ZnO by Dimkpa et al. (2020a, b). The drought treatment and NP application on wheat plants affected parameters like time of panicle initiation was increased, grain yield reduced, and uptake of Zn, nitrogen (N), and phosphorus (P) was inhibited. The drought-treated plants with ZnO-NPs reduced panicle initiation, and bulk ZnO showed no effect on panicle initiation. The NPs coated urea increased grain yield by 51% and uncoated urea enhanced to 39%. The coated ZnO-NPs increased Zn uptake to 24% in plants and 8% with uncoated ZnO. The coated bulk ZnO applied to test plants enhanced Zn uptake to 78% and uncoated increased to 10%. The Zn treatment to plants of without drought showed no change in time for panicle initiation. The findings demonstrated that NPs coated urea increases the performance of treated plants and accumulation of Zn. This study suggested application of nanoscale micronutrients as an approach for better crop yield (Dimkpa et al. 2020a, b).

3 Engineered nanoparticles as fertilizers in different plants

The factorial-based randomized design was applied to study the morphology and biochemistry of basil (*Ocimum basilicum* L.) plants by Abbasifar et al. (2020) through treatment with Zn and Cu-NPs. The results of nutrient treatments (4000 ppm) Zn-NPs and (2000 ppm) Cu-NPs improved the plant morphology. The leaves of treated basil plants showed increase in chlorophyll-a, b, total chlorophyll and carotenoid. The total phenolic and flavonoid content and antioxidant activity was improved by test NPs. The foliar application of the Zn and Cu-NPs improved the quantity and quality in basil (Abbasifar et al. 2020).

Linares et al. (2020) investigated the seedlings growth of *Hordeum vulgare* in soil with AgNPs. The shoot and root tissues of barley were evaluated for Ag bioconcentration and distribution after exposure to test NPs. The bioconcentration values of Ag were high in the plants grown in soil from OECD than the Delacour. The morphological changes in barley seedlings were small shoots and short, thick roots after exposure to NPs. It was concluded that early diagnosis of test NP exposure was plant structural responses in seedlings in biosolid-amended soils (Linares et al. 2020).

A study on the application of bulk and nanoparticles—zinc oxide, titanium oxide and silver on chilli seeds cv. PKM 1 by using template-free aqueous solution was performed by Kumar et al. (2020). The nanoparticles effects were analyzed by parameters like electrical conductivity, antioxidant enzymes, i.e., catalase and lipid peroxidase, germination (%), shoot, root length and seedling vigor. The results of 1000 mg kg^{-1} ZnO-NPs treated chilli seeds showed the increase in germination and seedling vigor (Kumar et al. 2020).

Kubavat et al. (2020) performed a study based on chitosan-nanoparticle (CN) prepared and incorporated with potassium (CNK) to tested pot trials of *Zea mays* plant. The different doses of K-formulation were investigated on NP-treated maize plants. The accumulation was increased in fresh (51%) and dry biomass (47%) in amended soils with reduced potassium rates (75% CNK). The CNK improved root growth by enhancing porosity, water conductivity and friability of soil. The nano-formulation and the treatment showed no deleterious effects on test plant but improved carbon-cycling activity (Kubavat et al. 2020). The composites of microcrystalline cellulose, chitosan and alginate biopolymers along with ZnO nanoparticles were tested by Martins et al. (2020) for their potential for controlled release of Zn. The study was reported by growing the maize plants in four agriculture soils with distinct pH and organic matter. The conventional Zn salts applied was leached from the soil, and Zn was less labile for ZnO-NPs. The ZnO-biopolymers supplied Zn better than forms applied to test plants. The plants grown in acidic soil with poor Zn and ZnO-NPs/alginate beads resulted in steady Zn concentration. The results indicated avoidance of early stage Zn toxicity and the Zn requirement of maize plant were done by ZnO-NPs/alginate beads (Martins et al. 2020).

The investigation of germination and development of seedling in corn after seed priming with ZnO-NPs, bulk ZnO and $ZnCl_2$ were evaluated by Neto et al. (2020). The seed priming promoted germination, root length, dry biomass, seedling growth 25% by NP and 12%-$ZnCl_2$ than control. The bulk ZnO seed priming showed similar growth with the control. The NP seed priming was an alternative that supported the delivery of essential micronutrient (Zn) to seedlings of corn (Neto et al. 2020). The peppermint (*Mentha piperita* L.) plants were treated with different fertilizers, i.e., control, chemical fertilizer, arbuscular mycorrhiza fungus, 50% chemical fertilizer + arbuscular mycorrhiza fungus - *Glomus mosseae*, nano-chelated fertilizer, 50% chemical fertilizer + nano-chelated fertilizer, nano-chelated fertilizer + arbuscular mycorrhiza fungus to evaluate desirable essential oil production and reduce chemical inputs by Ostadi et al. (2020). The results showed the impacts of growth parameters, i.e., plant height, number of lateral branches per plant and leaf greenness with increased N, P, K and Fe contents in test plant. The increase of peppermint dry matter, essential oil content and yield revealed the use of integrative chemical fertilizers with nanofertilizers as an alternative and eco-friendly approach (Ostadi et al. 2020).

Gomaa et al. (2020) has carried the field experiments on growth, yield of sorghum by addition of mineral, nano-fertilization and different weed control. The application of NPK mineral and NPK nanoparticles fertilizers revealed the high yield of sorghum was achieved by hand hoeing one time with herbicide (Gomaa et al. 2020). The study performed by Alimohammadi et al. (2020) evaluated the yield of sugarcane (*Saccharum officinarum*) by application of urea and nano-nitrogen chelate (NNC) fertilizers and nitrate leaching from soil. The results showed that nitrate leaching was high with urea and low for NNC. The sugarcane stem height was increased by application of both fertilizers in increased doses (Alimohammadi et al. 2020).

The foliar application of ZnO-NPs and $ZnSO_4$ on winter wheat (*T. aestivum* L.) was evaluated by Sun et al. (2020) for increasing the Zn content in the grain. ZnO-NPs increased the Zn in the wheat grain was in limit for human consumption. The results demonstrated that ZnO-NPs fertilizer increased Zn in wheat grain and contributed for improved human nutrition (Sun et al. 2020). The effect of zinc nanofertilizer was evaluated by Prajapati et al. (2018) for growth and yield of wheat (*T. aestivum* L.). The experiments were seed treatment, foliar application and seed treatment + foliar application of bulk Zn and nano-Zn. The results showed that the seed treatment followed by three foliar sprays of ZnO-NPs after sowing proved to enhance the height, number of effective tillers, length of spike, test weight, yields of grain and straw along with grain and straw zinc content and uptake by grain and straw (Prajapati et al. 2018).

The integrative effects of wheat and nutrient acquisition were evaluated by Dimkpa et al. (2020a, b) in soil under treatments, i.e., drought, organic fertilizer (OF) and nano- vs. bulk ZnO particles. The drought effect reduced chlorophyll levels, delayed panicle emergence, reduced grain yield treatment of nano- and bulk ZnO reported to alleviate stress with increase in chlorophyll, accelerated panicle emergence under drought, increased grain yield and OF also increased chlorophyll levels, increased yield under drought and counteracted with Zn. The results of the study demonstrated that drought effects in food crops were alleviated by ZnO particles and Zn-rich OF and found potential mitigation strategies for sustaining food production (Dimkpa et al. 2020a, b).

4 Nano-harvest with engineered mesoporous silica nanoparticles (MSNPs).

Solidago nemoralis hairy root cultures were performed for harvesting of polyphenolic flavonoids using engineered mesoporous silica nanoparticles (MSNPs) functionalized with both titanium dioxide (TiO_2) and amines (NH_2) to promote cellular internalization. The results of the study demonstrated continuous isolation of biomolecules from living and functioning plant cultures (Khan et al. 2020a, b).

5 Phytoaccumulation of Engineered Nanoparticles (ENPs) in Plants

The different behaviors of leaf samples from *Dittrichia viscosa* and *Cichorium intybus* for the phytoaccumulator characteristics were studied by Abdallah et al. (2020) to evidence sequestration of heavy metals as nanoparticles from autogenous environment, i.e., steel manufacturing company. The results showed different behaviors of phytoaccumulation in *Dittrichia viscosa* and nanoparticle composition. The levels of heavy metals NPs estimated from the nearby industries and *Cichorium intybus* plants were similar (Abdallah et al. 2020).

6 Phytotoxic Effects of Engineered Nanoparticles (ENPs) in Different Plants

The results of study performed by Falco et al. (2020) on leaves of broad bean (*Vicia faba*) exposed to silver nanoparticles (AgNPs) revealed that the photochemical efficiency of photosystem II (PS-II) was reduced. The NPs increased the non-photochemical quenching and decrease in stomatal conductance (*Gs*) and CO_2 assimilation with overproduction of reactive oxygen species (ROS). The photosynthesis process was affected negatively by accumulation of NPs in the leaves of bean plants (Falco et al. 2020).

A study performed by Mylona et al. (2020) to test the impacts of Ag-NP for sensitive responses and toxicity on the seagrass (*Cymodocea nodosa*). The results showed changes in the cytoskeleton, endoplasmic reticulum, ultrastructure of seagrass treated with test NPs. The function of photosystem II, markers of oxidative stress and cell viability were altered in test plants. The leaf, rhizome, root elongation and protein content in seagrass were decreased, and antioxidant enzyme activity was increased (Mylona et al. 2020).

The *in-vitro* grown seedlings of *Abelmoschus esculentus* (okra) were investigated by Baskar et al. (2020) for phytotoxic effects by metal oxide NPs such as nickel oxide (NiO), copper oxide (CuO) and zinc oxide (ZnO). The tested NPs suppressed plant growth in a concentration-dependent manner. The results showed decrease in chlorophyll content, length of shoot and root, enhanced ROS and malondialdehyde (MDA), altered anthocyanin, total phenols and flavonoids in the NP-treated seedlings of *A. esculentus*. Among the tested Ni-NPs toxicity was high than CuO and ZnO-NPs in the treated seedlings (Baskar et al. 2020).

Yang et al. (2020) performed study on the rice (*O. sativa* L.) plants grown under hydroponic condition to assess for phytotoxicity of copper oxide nanoparticle (CuO-NPs) for seven days of exposure. The treated plants were found with suppressed growth rate, increased malondialdehyde (MDA) content and electrical conductivity in shoots. The leaf chlorophyll-a, b, carotenoid, catalase and superoxide dismutase were decreased. The results of the study reported effective CuO-NPs concentration that affected the growth and development of rice seedlings through oxidative damage and decrease in chlorophyll and carotenoid synthesis (Yang et al. 2020).

Priester et al. (2017) studied growth of soybean (*Glycine max*) in soil enriched with $nCeO_2$ or nZnO. The results showed increase in lipid peroxidation and ROS and decrease in total chlorophyll that damaged leaf. The quantum efficiency of PS-II and seed protein remained unchanged by test NP on soybean plants. The NPs generated stress and damage in soybean leaves (Priester et al. 2017). The seed yield of *Glycine max* (cv. Kowsar) grown in soil with N-fixing bacteria (*Rhizobium japonicum*) inoculant was evaluated by Yusefi-Tanha et al. (2020) for CuO-NPs (25, 50 and 250 nm) phytotoxicity. The results showed the differential alteration of antioxidant enzymes such as APX, CAT, POX, SOD and MDA dependent on the type, concentration and interactions of copper compound (Yusefi-Tanha et al. 2020).

The study performed by Singh and Kumar (2020a, b) showed growth of *Spinacia oleracea* by the treatment of single and binary mixture of CuO and ZnO-NPs in the soil. The results revealed the adverse effects of test NPs on spinach plant biomass and fresh weight (Singh and Kumar 2020a, b). The physiology and biochemistry of spinach plants after foliar application of lead oxide nanoparticles (PbO-NPs) on lead (Pb) accumulation and associated health risks were evaluated by Natasha et al. (2020). The results showed accumulation of Pb decreased in leaf pigments; dry weight and the activities of catalase and peroxidase were increased. The translocation was limited toward root tissues in test plants by NPs. The foliar deposition of metal-enriched particles (PM) affects growth of spinach and ingestion of metal-contaminated vegetables results in health issues (Natasha et al. 2020).

7 Conclusion

Nanoparticles are reported to replace the bulk forms in coming generations as the concern to get enhanced outputs from agriculture to feed increasing human population. The nanoparticles efficacy is dosage-dependent manner and required in small quantities to get benefits. The abiotic/biotic stresses are important hurdles of the present agroecosystem around the planet; the nanoparticles are important tools to boost yields. The engineered nanoparticles (ENPs) attracted the community of researchers to investigate the effects in variety of plant habits. The findings support the nanoscale particles improve the variety of physiological aspects such as germination, in vitro regeneration, metabolic profile, leaf, shoot, fruit and root growth, antioxidant (enzymatic and non-enzymatic) levels, nutrient uptake, colonization of microbiota, defenses against diseases, essential oil and amelioration of stress (drought, chilling and metal). The nanomaterials were applied to plants either sole or in combination with biochar, AM fungi, chemical fertilizer that enhanced efficiency of plant uptake resulted in high yields. The market for nanofertilizers, nanopesticides, nano-herbicides and other nano-agrochemicals is near to conquer and revolutionize the yields.

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