Chapter 14
Nanoparticles and Their Effects on Growth, Yield, and Crop Quality Cultivated Under Polluted Soil

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1 Introduction

Nanotechnology is a novel and scientific approach that leads to the development of valuable nanomaterials (NMs) (Mali et al. 2020). It covers several aspects of agriculture, food security, disease treatment, new tools for pathogen detection, effective delivery systems, and packaging materials (Khan and Siddiqui 2020; Raghib et al. 2020). During the last several decades, it has grown to prominence as cutting-edge technology, serving as a convergent science that brings together diverse fields (environmental science, energy, plant science, materials physics, and nanomedicine) and human welfare sectors (Gugliotti et al. 2004). Specifically, nanotechnology has the ability to bring practical answers to varied agricultural issues. According to McCalla (2001), by 2025, the global population could surpass eight billion. Thus, feeding the ever-increasing human population is a significant concern for the twenty-first century. The crop productivity and quality are being confronted by the booming human population, weather instability, shrinking prime agricultural area, and irrigation water (Prasad et al. 2017). Many people of the world directly or indirectly depend on agriculture produce. For addressing the increasing challenges of food security and sustainable production, notable nano-techno advancements have been developed in recent years in the field of agriculture (Usman et al. 2020) (Fig. 14.1).

Nanoparticles can be identified into three main categories based on source, namely, natural, incidental, and engineered or manufactured NPs (Nowack and Bucheli 2007). The first category has existed since the beginning of the earth and is emitted from natural activities like volcanic eruptions, forest fires, dust storms, and photochemical reactions. The second form of NPs is anthropogenic, usually

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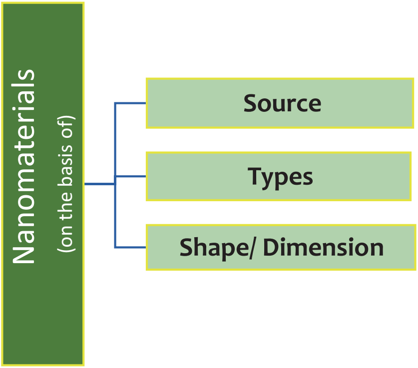

Fig. 14.1 Nanomaterials classified mainly on these bases

emanating from gasoline/diesel exhaust, coal combustion, and industrial exhausts (Uddin et al. 2013). The third form is produced by reducing the metal to its nuclear size. NP synthesis includes a few techniques, such as physical, chemical, and biological (Asanithi et al. 2012; Siddiqi et al. 2018). The synthesis techniques for a variety of NPs were developed and progressed to the molecular level (Gugliotti et al. 2004). Due to the small size of NPs, the ratio of surface area to volume increases (relative to bulk forms), improving the biochemical reactivity and conferring unusual and valuable physical properties. It is a potential rising field of science with brilliant applications in both basic and applied sciences (Ali et al. 2014).

1.1 Nanoparticle Use in Agriculture

The farming sector is the mainstay of any developing country, and crops are among the significant sources of important nutrients for both humans and animals (Rajput et al. 2021b; Ranjan et al. 2021). Nano-technological innovations can boost modern agriculture in a more productive, cost-effective, and eco-friendly way (FAO 2002). Among the various forms of NPs, inorganic NPs (metals: 29%, metal oxides: 26%, CNTs and fullerenes: 6%) constitute over half of total farming uses (Peters et al. 2016).

Numerous nano-agricultural products are presently being made to eliminate the conventional toxic chemical usage. Metals, containing NPs like Fe, Mg, Zn, Cu, and Mn, are put forward as fertilisers at low doses and as pesticides at higher doses (Liu et al. 2016) as these metals are necessary for cellular function but toxic above a threshold (Marschner 2011). For instance, ZnO and CuO NPs render potential as fertilisers as they provide bioavailable essential metals and as pesticides because of dose-dependent toxicity (Alamri et al. 2022; Rajput et al. 2021a, c; Shende et al. 2021). Over the recent decade, many nano-enabled patents and products have been produced to control plant disease and increase crop yields, namely, nanopesticides, nanosensors, and nanofertilisers, also nano-enabled remediation strategies for contaminated soils (Mali et al. 2020). Gogos and his team (2012) studied the use of NPs

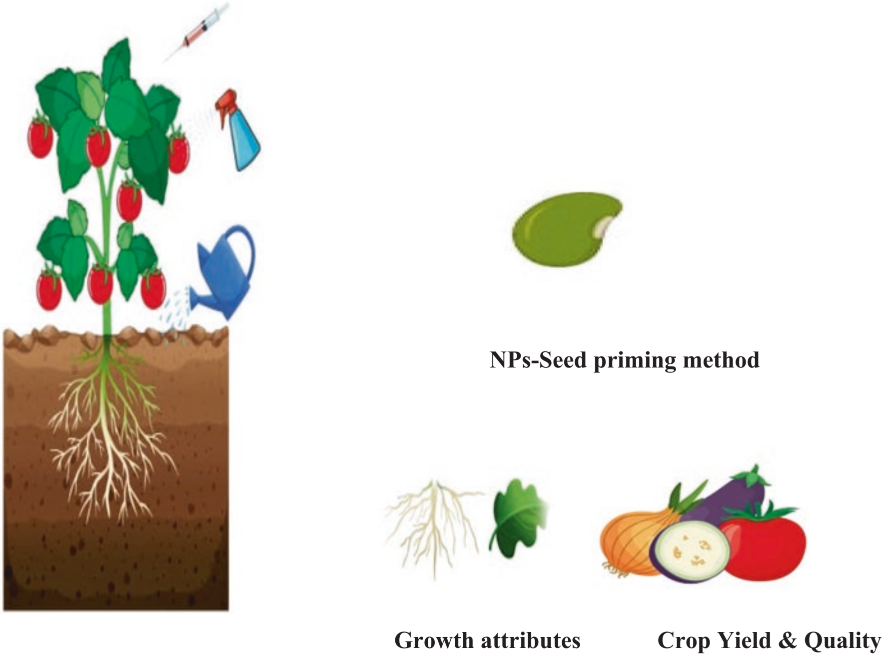

Fig. 14.2 Common NP treatment applications (inoculation based, foliar spray, soil irrigation, seed priming) and altering growth, yield, and quality attributes

in plant protection, and nutrition found that NPs could assist deliver pesticides, fertilisers and also detect plant disease and pollutants (Fig. 14.2).

There are various methodologies by which plants can be exposed to NPs, such as the direct injection of NPs into plant tissue (Corredor et al. 2009), amendment of NPs in the form of biosolids (Fayiga and Saha 2017), soil amendment, or irrigating plants with NP suspensions (Raghib et al. 2020). NPs can infiltrate living tissues, migrate to various parts of the plant system, and accumulate in underground and aerial parts. In the soil matrix, NPs move via the apoplastic or symplastic area to enter the epidermis of roots, pass through the cortex, and ultimately translocate to the stem and leaves through the xylem and phloem (Pérez-de-Luque 2017), therefore often causing a widespread impact on the plant system.

The NP absorption, translocation to different aerial parts, and their toxicity on plant system depend on bioavailability, solubility, exposure time, plant species, chemical composition, surface structure, aggregation dose, type, concentration, shape, and size of NPs (Ruttkay-Nedecky et al. 2017). Therefore, different plant species have a different response to the same NPs and may vary significantly with plant growth stages and treatment methods (Rastogi et al. 2017). Moreover, NP interaction with the plant cell results in gene expression modification and related biological pathways, which ultimately alter plant growth and development (Ghormade et al. 2011). Plants are a crucial part of all ecosystems, and their interaction with NPs is a critical aspect of the risk assessment (Yang et al. 2017). Once entered into the soil system, NPs may alter soil quality by affecting nutrient release in target soils, soil organic matter, and soil biota, and they can be utilised by the successive crops due to their gradual nutrient release. ENMs (engineered nanomaterials) and organic contaminants transferred and accumulate from the soil to the edible parts of crops (Deng et al. 2014). Da Silva (2014) also reported NPs affecting terrestrial plants in conjunction with metals.

1.2 Pollutants/Contaminants in Soil

Soil is a valuable resource as it serves numerous vital tasks such as life support, food production, carbon storage, water purification, and biodiversity preservation (Blum 2005).

Safe and healthy soil is necessary for the sustainable development of human society. However, our soil is under grave threat. Rapid industrialisation and different human activities, such as industrial waste discharge, sewage irrigation, and improper use of chemical pesticides and fertilisers, have resulted in an increased build-up of toxic metals/metalloids and persistent organic pollutants in soil over the past decades (Naikoo et al. 2021) (Fig. 14.3).

1.3 Use of Nanoparticles in Soil Pollution Remediation

The advancement of nanotechnology has provided new inspiration and ideas for polluted soil phytoremediation. NPs can help with phytoremediation by eliminating contaminants directly, enhancing pollutant phytoavailability, and boosting plant development. For example, nanoscale zero-valent iron (nZVI) particles have been employed to remove a variety of contaminants from the soil. Fullerene NPs can increase pollutant phytoavailability (Song et al. 2019). Therefore, the immobilisation or remediation of toxic HMs from polluted agricultural fields is regarded as a profound, imperative, and imperious issue (Dar et al. 2017). Therefore, soil remediation using plants and NPs in combination primarily involves two factors. One factor is to absorb heavy metals or metalloids from the soil while another affecting the internal structure of plants in order to promote growth (Deng et al. 2017). There is a variable influence of NPs on metal and metalloid uptake because of the type and application method as well as the plant and HM species involved (Usman et al. 2020). Ag NPs mitigate the deleterious effects of HMs in crop plants and may assist in the bioremediation of contaminated environments by enhancing remediating plants growth (Azeez et al. 2019; Deng et al. 2017).

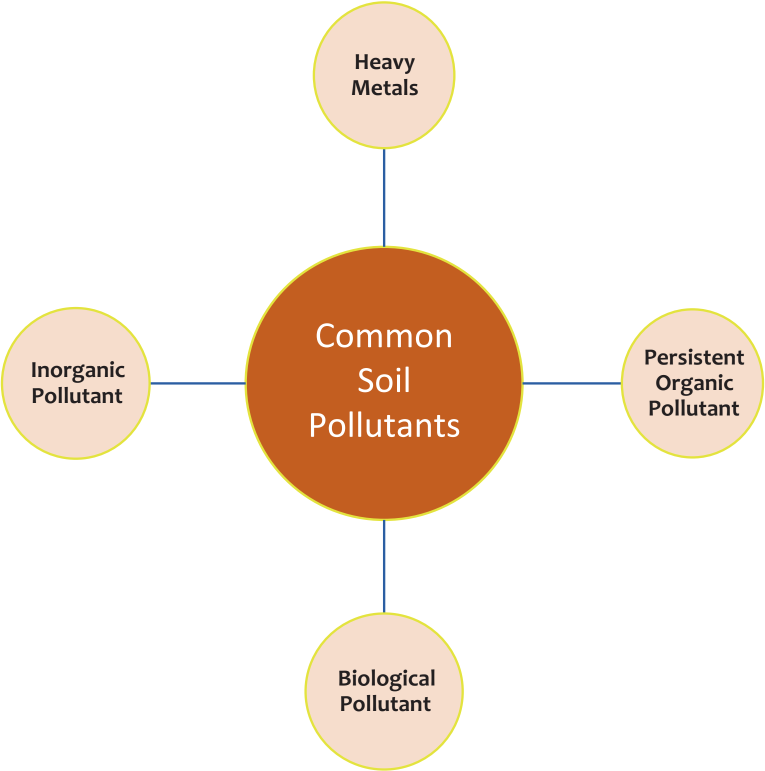

Fig. 14.3 Common soil pollutants

2 Effect of NPs on the Growth of Crop Plants

Nanotechnology serves as a platform to deliver agrochemicals and several macromolecules needed to boost plant growth and stress tolerance (Mali et al. 2020). Various NPs documented both enhancive and inhibitive effects on plant development (Yang et al. 2017)**.** In agriculture, nanobiopolymers have found massive use, such as soil health maintenance, reduction of agrochemical doses (after seed coating), and acting as a growth promoter (Baker et al. 2017). Many studies reported the application of NPs promoting earlier plant germination and enhancing plant production. Plant metabolism was boosted by NPs due to their unique properties (Nair et al. 2012). The extent to which NPs in soil promote or restrict plant growth appears to be related to plant type, NP type, and concentrations (Yoon et al. 2019). The exposure period to NPs is also an influencing factor for plant growth. Plant growth is aided by NPs, although some NPs show toxic effects as well. Increased water uptake by CNTs (carbon nanotubes) can boost plant growth and seed germination. CNTs (carbon nanotubes) can boost plant growth and seed germination by increasing water uptake. Their key role as nanofertiliser can improve the farming sector, although the harmful effects of CNTs may decrease the variety of agricultural-wise essential microorganisms and enhance the bioavailability of toxic metals in agro crops (Vithanage et al. 2017). The unique characteristics of NPs allow them a specific adsorption effect which leads to unrestricted plant growth in soil polluted with HMs. Excessively high NP concentrations, on the other hand, can impair plant growth (Chen et al. 2017).

2.1 Positive Aspects Concerning the Growth

The soybean crop treated with TiO_2 NPs in cadmium-contaminated soil depicted an increase in photosynthetic rate, growth, and biomass, as well as application till 300 mg kg^{-1}enhanced the biomass (Singh and Lee 2016). Tomato plant growth was improved by amendment of sewage sludge containing nano-TiO_2 (Bakshi et al. 2019). Zand et al. (2020a) observed enhanced shoot biomass of *Sorghum bicolor* crop grown under Sb-contaminated soil exposed to TiO_2 NPs, most significant increment at 500 mg kg^{-1} TiO_2 NPs treatment. With the addition of 100–500 mg kg^{-1} TiO_2 NPs, total plant biomass increased marginally. Likewise, adding 5 g kg^{-1} nHAP (nano-hydroxyapatite) to the soil can raise soil pH, fix Pb, and increase the biomass, thus promoting *Lolium perenne* growth (Ding et al. 2017). In addition to this, Fe NP treatment accelerated plant growth when grown in Cd-contaminated soil. Wheat morphological characteristics and dry biomass of shoots, roots, spike husks, and grains were improved by exogenous administration of Fe NPs (Hussain et al. 2019). Exogenous and soil application of ZnO NPs boosted growth and photosynthesis in *Triticum aestivum* cultivated in Cd-contaminated soil (Hussain et al. 2018; Raghib et al. 2020). Similarly, ZnO NPs showed significant improvement in the development of the sunflower in soil irrigated over a longer duration with polluted wastewater than the control (Seleiman et al. 2020). Mustard and cabbage crops with nZVI treatment promote plant growth by increasing biomass of roots, stems, and leaves in Cr-contaminated soil (Su et al. 2016). In like manner, nZVI-treated soils exhibited better growth of barley plants in arsenic polluted soil. Studies have shown nZVI at 10% concentration has the best immobilisation effect and limited arsenic availability, hence favouring the growth of *Hordeum vulgare* (Gil-Díaz et al. 2017).

Under cadmium-contaminated soil, nano-ZVI similarly enhanced dry weight of leaf, stem, and root of *Boehmeria nivea* (Gong et al. 2017). A low concentration of nZVI (100–500 mg kg^{-1}) effectively promotes growth by enhancing shoot biomass in *Lolium perenne* L. under Pb-polluted sediment (Huang et al. 2018). Si NPs improved the dry biomass of shoots, roots, spikes, and grains by 24–69%, 14–59%, 34–87%, and 31–96% in foliar spray and by 10–51%, 11–49%, 25–69%, and 27–74% in soil-amended Si NPs, respectively, in *Triticum aestivum* growth under Cd-polluted soil (Ali et al. 2019a).

Furthermore, colloidal silica NPs preserve soil fertility by ensuring homogeneous distribution of groundwater within the soil, and several metallic NPs, such as

CNTs, improve seed germination, resulting in healthy plant growth (Rai et al. 2018). *Moringa oleifera* growing in Cd- and Pb-polluted soil exposed to Ag NPs promoting germination and tolerance indices, also improved growth and vigour index (Azeez et al. 2019). Graphene oxide (GO) NPs applied to *Triticum aestivum* cultivated under arsenic-polluted soil slightly increased the germination rate and the root number (Hu et al. 2014).

2.2 Negative Aspects Concerning the Growth

The high dose of TiO_2 NPs (1000 and 1500 mg kg^{-1}) markedly inhibits seedling emergence and *S. bicolor* growth (Zand et al. 2020a). Likewise, a higher concentration of TiO_2 NPs showed a reduction in fresh and dry biomass, chlorophyll content, and plant height (Singh and Lee 2016). Huang et al. (2018) reported that a higher concentration of nZVI (1000 and 2000 mg kg^{-1}) caused a decline in total chlorophyll content, leaf physiological structure, and root biomass, thus inhibiting *Lolium perenne* growth in lead-polluted sediments. Plant growth is hindered by the presence of Ag in the soil.

Despite the limited transfer of Ag NPs, the high- and low-dose treatments significantly reduce root development of both monocot and dicot crop species, viz. wheat and rape, compared to the control (Pradas del Real et al. 2016). *Brassica rapa* sown in arsenic-polluted soil when treated with CNTs reported a reduction in fresh and dry biomass (Awad et al. 2019). *Triticum aestivum* showed adverse effects when exposed to As (V) soil and GO (graphene oxide) NPs. GO NPs directly affected the shoot length, and As (V) enhanced the impact of GO. Thus, it induced a significant reduction in fresh weight and chlorophyll contents (Hu et al. 2014).

2.3 No Effect Concerning the Growth

The addition of nano-HAP on *Lolium perenne* L. and celery (*Apium graveolens*) showed no significant growth rate (Ding et al. 2017; Yang et al. 2020). The treatment of nano-CeO_2 to *Helianthus annuus* plant in spiked boron soil did not produce a significant effect on plant biomass (Tassi et al. 2017). Similarly, *Glycine max* in cadmium-contaminated soil showed no significant change in root biomass to CeO_2 NPs (Rossi et al. 2017). Also, the application of silver and silver sulphide NPs (present in biosolids) to *Lactuca sativa* showed no significant differences in the aerial biomass (Doolette et al. 2015) (Table 14.1).

Table 14.1 Effect on crop growth

NMs/NPs type	Crop type	Soil pollutant/ contaminant	Effect on crop growth	References
GO NPs	*Triticum aestivum*	Arsenic	Moderately increased germination rate and root number; reduced fresh weight, shoot length, and chl contents	Hu et al. (2014)
Silver and silver sulphide NPs	*Lactuca sativa*	Biosolids	No significant changes	Doolette et al. (2015)
nZVI	Cabbage, mustard	Hexavalent chromium	Accelerated growth and biomass	Su et al. (2016)
TiO_2 NPs	Soybean	Cadmium	Increased plant biomass, photosynthetic rate and growth till TiO_2 NPs (300 mg kg^{-1}); reduction in plant heights, chl content, and fresh and dry biomass at higher levels	Singh and Lee (2016)
CNTs	*Brassica rapa*	Arsenic; lead; heavy metals	CNT-HM enhanced growth; CNT-As decreased growth	Awad et al. (2019)
CeO_2 NPs	*Glycine max*	Cadmium	Total dry weight slightly higher	Rossi et al. (2017)
$nCeO_2$	*Helianthus annuus*	Boron	No significant effect on plant biomass	Tassi et al. (2017)
nZVI	*Lolium perenne*	Lead	Chl content decreased with the increase of nZVI; low nZVI (100–500 mg/kg) favours growth, but high nZVI (1000 and 2000 mg/kg) inhibits the growth	Huang et al. (2018)
ZnO NPs	*Triticum aestivum*	Cadmium	Increased photosynthesis and growth	Hussain et al. (2018)
ZnO NPs	*Oryza sativa*	Cadmium	Improved growth; high dose increased total biomass	Zhang et al. (2019)
Ag NPs	*Moringa oleifera*	Cadmium; lead	Promoted germination and tolerance indices; enhanced growth; improved vigour index; increased chl a, b, and carotenoid contents	Azeez et al. (2019)
nHAP	*Apium graveolens*	Cadmium	No significant effect on growth	Yang et al. (2020)
TiO_2 NPs	*Sorghum bicolor*	Antimony	TiO_2 NPs (100–500 mg kg^1) increased plant biomass and slightly altered total chl contents**;** TiO_2 NPs (1000 and 1500 mg kg^{-1}) inhibited germination and growth	Zand et al. (2020a)
nZVI	*T. repens*	Cadmium	nZVI (600 mg kg^{-1}) boosted shoot biomass and Chl a/Chl b ratio; inhibitory effect on germination and growth at higher dose	Zand et al. (2020b)

Chl denotes chlorophyll; PBDEs denotes polybrominated diphenyl ethers

3 Effect of NPs on the Yield of Crop Plants

Nanotechnology products, like nanopesticides, nanoherbicides, nanobionics, etc., increase crop production. Nanobiotechnology offers new tools for manipulating and improving crop output using NPs. Smart delivery of agrochemicals enhances the yield by optimising water and nutrient conditions (Mali et al. 2020). Advancement in nanoscience has implemented new methods for the molecular management of diseases, increasing the yield through nanofertilisers/nanoinsecticides with efficient resource (water and soil) use (Peters et al. 2016). Modern farming has been using enormous pesticides to boost productivity. However, according to the UN's Food and Agriculture Organization (FAO), pests and diseases rob 20–40% of global crop production each year, despite the application of about two million tonnes of pesticides (King 2017).

Further, NP-mediated gene transformation and delivery of macromolecules that activate gene expression in plants can be used to improve agriculture even more (Mali et al. 2020). NPs could potentially act as a magic bullet, containing substances such as beneficial genes, herbicides, and organics that target specific plant parts to boost yield (Marchiol et al. 2014). However, other works reported that NPs enhance yield characteristics in plants. Seed priming with mineral NPs has the potential to alter the nutrient content of seeds, hence impacting yield (Rui et al. 2018).

3.1 Positive Aspects Concerning Yield

Nano-titanium dioxide (present in sewage sludge) enhanced tomato fruit yield (Bakshi et al. 2019). The uptake of copper NPs and iron NPs improved wheat yield. Besides, Cu NP uptake enhances stress tolerance in wheat variants, consequently leading to better yield of wheat crop (Yasmeen et al. 2017). Foliar application of iron NPs improved wheat productivity when cultivated in cadmium-contaminated soils (Hussain et al. 2019). Under a similar environment, the highest dry weight of grain reported at 100 mg/kg of Fe NPs (Adrees et al. 2021). Moreover, the exogenous and soil-applied zinc oxide NPs can promote wheat productivity in Cd-polluted soil (Hussain et al. 2018; Khan et al. 2019). Likewise, ZnO NPs application to sunflowers significantly improved the yield in soil watered with polluted effluent for a lengthy period of time.

Foliar application with Zn NPs enhanced the seed yield ha^{-1}, 100-seed weight, the number of seeds per head, the head diameter, and sunflower oil yield by 19.2%, 6.7%, 9.2%, 5.7%, and 214 kg ha^{-1}, compared to the untreated plants. Additionally, ZnO NPs can mitigate the harmful influence of toxic metals on sunflower productivity (Seleiman et al. 2020). Moreover, applying silicon NPs by seed priming, foliar spray, and soil amendment methods may increase the productivity of wheat (*Triticum aestivum*) cultivated under cadmium-contaminated soil (Ali et al. 2019a). Fluoride contamination in soil reduces yield by suppressing grain development, thereby

Table 14.2 Effect on crop yield

NMs/NP type	Crop type	Soil pollutant/ contaminant	Effect on crop yield	References
Silver and silver sulphide NPs	*Lactuca sativa*	Biosolids	No significant differences in dry weight of plant at harvest	Doolette et al. (2015)
ZnO NPs	*Triticum aestivum*	Cadmium	Increased yield	Hussain et al. (2018)
Ag NPs	*Moringa oleifera*	Cadmium; lead	Improved productivity	Azeez et al. (2019)
ZnO NPs	*Oryza sativa*	Cadmium	No difference found at ripe and harvest process	Zhang et al. (2019)
Ag NPs	*Capsicum annuum*; *Lactuca sativa*; *Raphanus sativus*	Sludge	Reduced lettuce and radish yield and no change in chilli yield	Li et al. (2020)

inhibiting reproduction and panicle development in rice crops. Thus, nano-Si-priming efficiently restored the harvest of grains (Banerjee et al. 2021). Besides, nano-silicon-mediated stimulation of yield has observed in *T. aestivum* and *Z. mays* seedlings exposed to cadmium-contaminated soil and insect infestation, respectively (El-Naggar et al. 2020). Root exposure with Ag NPs in sludge-amended soil throughout a life cycle declined the lettuce and radish harvest by 42% and 61% (Li et al. 2020).

3.2 Negative Aspects Concerning Yield

The application of silver NPs containing sludge could negatively influence crop production of both wheat and rape crops (Pradas del Real et al. 2016).

3.3 No Effect Concerning Yield

No significant differences reported in aerial biomass of *Lactuca sativa* at harvest as transformed silver NPs (present in the applied biosolids) had very little bioavailability to lettuce plant (Doolette et al. 2015) (Table 14.2).

4 Effect of NPs on the Quality of Crop Plants

According to a United Nations directive, global nutritional security and climate change measures in the agriculture sector must be taken in the twenty-first century (King 2017). So far, several types of NPs have been examined, with encouraging results in terms of improving quality. Further enhancement in terms of quality can be accomplished using NP-mediated gene transformation and delivery of macromolecules that induces gene expression in plants (Mali et al. 2020). Besides affecting morphology and biochemistry, it also influences the nutritional content of both natural and transgenic crops.

Nanotoxicity in crops can be visualised as a reduction in plant hormone concentration when specific NPs, such as CeO_2 NPs and CNTs, interact with them (Hao et al. 2016). Furthermore, crop nutrients (e.g., amino acids, proteins, fats, and sugars) are essential components of nutritional quality and are also influenced by different NPs (Yang et al. 2017). The use of nanotechnology to develop new foliar fertilisers could help synchronised agro crop nutrient management (Li et al. 2016). The NPs function as a magic bullet, hence serving as a smart delivery system for agricultural administration, explicitly about crop nutrition (Marchiol et al. 2014). Nutrient management and synchronised release and uptake of nutrients in agriculture crops are possible using nanofertilisers, reducing nutrient losses (Rai et al. 2018). The NP application for agricultural practice becomes even more challenging under the condition of accumulation in edible plant parts like fruits and seeds and modulation in nutrient composition (Yang et al. 2018).

4.1 Positive Aspects Concerning Quality

The unique photocatalytic and antimicrobial qualities of titanium dioxide make it effective for controlling and suppressing plant diseases, indirectly responsible for quality improvement. For example, cucumbers showed a reduction in infection when exposed to TiO_2 (Cui et al. 2009; Servin et al. 2015). The uptake of copper and iron NPs in wheat boosted the quality, reflected through increased sugar content (Yasmeen et al. 2017). The application of iron NPs on wheat crop in cadmium-contaminated soil demonstrated alleviation of toxic effects of Cd and reduced Cd contents in grains and tissues, while enhanced grain Fe biofortification in a dose-additive manner application of Fe NPs (Hussain et al. 2019). Same as reported earlier, Fe NPs augmented the quality of wheat grains. The highest concentration of Fe and least Cd content is found in the root, shoot, and grain at 100 mg/kg of Fe NPs (Adrees et al. 2020). In addition, the use of zinc oxide NPs and iron NPs reduced the amount of Cd in roots, shoots, and wheat grains.

The amount of Cd in grain was found to lower the Cd threshold level when exposed to higher NP treatment. Both ZnO NPs and Fe NPs increased the Zn and Fe amount in plants, especially in grains depicting use in cereals' biofortification. Hence, it will improve the nutrient content in seeds eliminating hidden hunger (Rizwan et al. 2019). Both foliar and soil application of ZnO NPs showed a simultaneous decline and increment of Cd and Zn content in tissues and grains. The amount of Cd in wheat grains declined by 30–77% and 16–78% with foliar and soil amendment of ZnO NPs, respectively. Overall, the zinc NPs play a significant role in increasing nutrients and decreasing Cd toxicity in the wheat crop, as reported by many studies (Hussain et al. 2018). ZnO NPs possess the potential to simultaneously reduce both arsenic and cadmium in rice grains cultivated in As- and Cd-co-contaminated rice paddies (Ma et al. 2020).

The ZnO NPs amendment to Cd-polluted soil has the potential to increase Zn while minimising Cd accumulation in tissues and grains by lowering the bioavailable soil Cd. About 78%, 64%, and 103% greater Zn concentrations observed in shoots, roots, and grains at the highest NPs (100 mg/kg), respectively, and the same exposure resulted in minimum Cd content in the wheat crop (Khan et al. 2019). Sunflower cultivated in polluted soil when exposed to ZnO NPs significantly boosted quality by enhancing the sunflower oil percentage, oleic acid, and oleic/linoleic acids ratio. It also showed a reduction of Cd, Cu, Cr, and Pb contents and significantly enhanced Zn and Fe (Seleiman et al. 2020). Similarly, foliar spray of 100 mg/L ZnO NPs significantly diminished the Cd content in rice crop by 30% and 31% in shoot and root, respectively, and enhanced Zn concentrations in tissues (Ali et al. 2019b). Likewise, foliar exposure of ZnO NPs (100 mg/L) showed the lowest Cd and highest Zn contents; therefore, the amount of Zn increased by 56%, 101%, and 106% in roots, shoots, and grains, respectively, at 100 mg/L of ZnO NP exposure.

The amount of Cd in grain decreased by 26%, 81%, and 87% when exposed to ZnO NPs at 25, 50, and 100 mg/L. Consequently, it could minimise Zn deficiency, thus improving the wheat crop quality (Adrees et al. 2020). Si NPs with higher concentrations were effective in lowering Cd levels in grains. The foliar spray of Si NPs diminished the Cd level in shoots, roots, and grains by 16–58%, 19–64%, and 20–82%, respectively, whereas soil-applied Si NPs declined the Cd contents in shoots, roots, and grains by 11–53%, 10–59%, and 22–83%, respectively. Thus, Si NPs reduced Cd and increased Si contents in matured grains of wheat (Ali et al. 2019a). Fluoride contamination resulted in an excessive build-up of fluoride in the spikelet sap, which prevented rice grains from hardening.

The addition of Si NPs increased the bioavailability of nutrients such as silicon, potassium, zinc, copper, iron, nickel, manganese, selenium, and vanadium boosted seedling health even during prolonged fluoride stress. Thus, by lowering fluoride bioaccumulation, Si NPs effectively alleviated molecular damage and restored quality, especially in edible grains (Banerjee et al. 2021). High concentration graphene oxide (GO) NPs (10 mg/L) reduce arsenic uptake in wheat crops (Hu et al. 2014). The addition of nZVI decreased Cr content in cabbage mustard tissues (Su et al. 2016). A low level of nZVI accelerated Fe translocation by the shoot of *Lolium perenne* grown in Pb-polluted sediment (Huang et al. 2018). The amount of Cd and Pb uptake significantly reduced in *Moringa oleifera* when exposed to Ag NPs (Azeez et al. 2019).

4.2 Negative Aspects Concerning Quality

The use of nano-TiO_2 particles increased Cd bioaccumulation in soybean plants (Singh and Lee 2016). Also, high Ti concentrations in plant tissues lead to competition between Ti and Fe for ligands and proteins, resulting in Ti phytotoxicity (Lyu et al. 2017). Thus, a higher concentration of Ti NPs likely caused iron deficiency symptoms in a plant, leading to poor quality. Simultaneous impacts of antimony and excessive TiO_2 NPs in soil showed increased toxicity and enhanced Sb accumulation capacity in plants. More significant Sb accumulation found in shoots than roots suggested that *S. bicolor* aerial parts were the preferential Sb storage organ (Zand et al. 2020a)**.** Also, CeO_2 NPs had no effect on Cd accumulation, although Cd boosted Ce accumulation in soybean plant tissues, especially roots and older leaves (Rossi et al. 2017).

Higher levels of nano-CeO_2 resulted in a detrimental effect on the boron nutritional status in sunflowers (Tassi et al. 2017). Further, K and Mg content in leaves of lettuce declined when exposed with Ag NPs (present in sludge), suggesting unintended residual transgenerational effects (Li et al. 2020). Nano-ZVI increased the accumulation capacity for Cd in *T. repens* (Zand et al. 2020b)**.** Besides, the addition of a high amount (500 mg kg^{-1}) of ZnO NPs in the low Cd-polluted soil could facilitate Cd accumulation, exceeding the permitted Cd concentration limit in Chinese rice (0.2 mg kg^{1}) (Zhang et al. 2019). The translocated CNTs bound with Pb or As in cabbage plants led to toxicity (Awad et al. 2019). Low concentration (0.1 and 1 mg/L) GO NPs boosted As uptake in the wheat plant (Hu et al. 2014). A high concentration of nZVI caused Fe absorption suppression because the iron uptake pathway and translocation from root to shoot were reported to be blocked by nZVI. It also increased the potential of *Lolium perenne* to accumulate Pb (Huang et al. 2018).

4.3 No Effect Concerning the Quality

No detrimental effect on boron's nutritional status in the plant, indicating a counteraction by nano-CeO_2 showing a reduced NP availability for plant uptake when high levels of boron were present in soil (Tassi et al. 2017). Barley in arsenic-polluted soils, when treated with nZVI, did not show any adverse effects regarding the nutrient content (Gil-Díaz et al. 2017). Bakshi et al. (2019) reported no significant Ti accumulation and no nutrition change in tomato fruits. The nano-HAP application showed no change in Cd concentrations in the celery plant (Yang et al. 2020). Also, exposed to Ag NPs (present in sludge) retained their nutritional status (Ca, K, Mg, P, Fe, Mn, and Zn), including protein and amino acid levels in chilli fruits and radish roots (Li et al. 2020) (Table 14.3).

Table 14.3 Effect on crop quality

NMs/ NP type	Crop type	Soil pollutant/ contaminant	Effect on crop quality	References
GO NPs	*Triticum aestivum*	Arsenic	Low dose (0.1 and 1 mg/L) improved whereas high dose (10 mg/L) declined As uptake	Hu et al. (2014)
nZVI	Cabbage; mustard	Hexavalent chromium	Decreased Cr content in tissues and accelerated Fe absorption	Su et al. (2016)
TiO_2 NPs	Soybean	Cadmium	Higher Cd uptake and bioaccumulation	Singh and Lee (2016)
CNT	*Brassica rapa*	Arsenic; Lead	Enhanced toxicity	Awad et al. (2019)
nZVI	*Lolium perenne*	Lead	Increased accumulation capacity of Pb; high dose of nZVI suppressed Fe absorption, while low dose accelerated Fe translocation by shoot	Huang et al. (2018)
ZnO NPs	*Triticum aestivum*	Cadmium	Increased and decreased concentration of Zn and Cd, respectively	Hussain et al. (2018)
Ag NPs	*Moringa oleifera*	Cadmium; lead	Uptake of Cd and Pb reduced	Azeez et al. (2019)
nHAP	*Apium graveolens*	Cadmium	No significant change	Yang et al. (2020)
ZnO NPs	*Oryza sativa*	Cadmium	High dose increased bioavailable Cd	Zhang et al. (2019)
Ag NPs	*Capsicum annuum*; *Lactuca sativa*; *Raphanus sativus*	Sludge	Nutritional quality is minimally affected in chilli fruits and radish roots, whereas K and Mg declined in lettuce leaves	Li et al. (2020)
nZVI	*T. repens*	Cadmium	Accumulation capacity increased for Cd	Zand et al. (2020b)
TiO_2 NPs	*Sorghum bicolor*	Antimony	Accumulation of Sb in shoots which enhances the toxicity	Zand et al. (2020a)

5 Conclusion and Future Outlook

Nanotechnology offers farmers better solutions to their problems by ensuring ecological sustainability and economic stability. Globally, many countries have anticipated that nanotechnology has the ability to maximise harvest and agricultural efficacy in an eco-friendly manner, even in an adverse environment. The usage of nanotechnology would be critical in nourishing a burgeoning population with diminishing natural resources. However, before NPs are widely used, their adverse effects must be assessed and addressed.

The number of publications dealing with NPs has increased exponentially, although research about the impact of single NPs on plants explicitly dominates.

Increased anthropogenic activities have resulted in harmful pollutants being released into the agro-environment, either intentionally or unintentionally. An increase in production (yield) with the least and efficient use of NPs in an already polluted terrestrial environment is now the main cynosure of agriculture scientists. The present chapter summarises the research progress by using several NPs via seed priming, foliar spraying, and soil amendment. We also listed the outcomes of different NPs on plants and reviewed progress mainly from three aspects: positive, negative, and no change under polluted soil. Several studies implied NPs could competitively adsorb the bound contaminants from soil and increase pollutants' concentrations, causing accumulation in crops. As a result, they are significantly affecting morphology, harvest, and quality.

These might also depend on soil property, plant variety, and the property of NPs. Most previous studies only focused on the interaction of plants with NPs or soil pollutants alone. However, the knowledge regarding their combined effects on the quality of crops is still minimal and henceforth is undoubtedly a new research direction. Researchers have found both beneficial and adverse impacts of NPs on higher plants, but very little work has been done to assess this under polluted soil. Various studies reported positive effects of low dosage, which showed a non-significant control effect, while excessive dosage enhances the harmful effects in crops. Besides, the increasing number of research demonstrates the negative impact of NPs, such as inhibited germination, growth and delayed ripening, etc. Micronutrient content in NP-treated crops suggested they could significantly alter the crop quality and yield. Future studies should address the following, considering polluted soil environment:

(a) Toxicity of NPs
(b) Lack of soil or field-based studies with NPs and more studies required in various types of contaminated fields as the behaviour of NPs differs significantly in laboratory conditions and the natural environment
(c) Limited nanoresearch with essential crop nutrients
(d) More extended growth experiments till harvest/maturity would be necessary to investigate the outcome of crop yield
(e) To study more cultivars as the responses found to be different among species and cultivars, and probing the role of NPs with varied crops, still await the acquisition of information
(f) Simultaneous potential accumulation of NPs and contaminants in crops

References

M. Adrees, Z.S. Khan, S. Ali, M. Hafeez, S. Khalid, M.Z. Ur Rehman, A. Hussain, K. Hussain, S.A.S. Chatha, M. Rizwan, Simultaneous mitigation of cadmium and drought stress in wheat by soil application of iron nanoparticles. Chemosphere **238**, 124681 (2020)

M. Adrees, Z.S. Khan, M. Hafeez, M. Rizwan, K. Hussain, M. Asrar, M.N. Alyemeni, L. Wijaya, S. Ali, Foliar exposure of zinc oxide nanoparticles improved the growth of wheat (Triticum aestivum L.) and decreased cadmium concentration in grains under simultaneous Cd and water deficient stress. Ecotoxicol. Environ. Saf. **208**, 111627 (2021)

S. Alamri, M.H. Siddiqui, S. Mukherjee, R. Kumar, H.M. Kalaji, M. Irfan, T. Minkina, V.D. Rajput, Molybdenum-induced endogenous nitric oxide (NO) signaling coordinately enhances resilience through chlorophyll metabolism, osmolyte accumulation and antioxidant system in arsenate stressed-wheat (Triticum aestivum L.) seedlings. Environ. Pollut. **292**, 118268 (2022). https://doi.org/10.1016/j.envpol.2021.118268

M.A. Ali, I. Rehman, A. Iqbal, S. Din, A.Q. Rao, A. Latif, T.R. Samiullah, S. Azam, T. Husnain, Nanotechnology, a new frontier in agriculture. Adv. Life Sci. **1**(3), 129–138 (2014)

S. Ali, M. Rizwan, A. Hussain, M.Z. ur Rehman, B. Ali, B. Yousaf, L. Wijaya, M.N. Alyemeni, P. Ahmad, Silicon nanoparticles enhanced the growth and reduced the cadmium accumulation in grains of wheat (Triticum aestivum L.). Plant Physiol. Biochem. **140**, 1–8 (2019a)

S. Ali, M. Rizwan, S. Noureen, S. Anwar, B. Ali, M. Naveed, E.F. Abd-Allah, A.A. Alqarawi, P. Ahmad, Combined use of biochar and zinc oxide nanoparticle foliar spray improved the plant growth and decreased the cadmium accumulation in rice (Oryza sativa L.) plant. Environ. Sci. Pollut. Res. **26**(11), 11288–11299 (2019b)

P. Asanithi, S. Chaiyakun, P. Limsuwan, Growth of silver nanoparticles by DC magnetron sputtering. J. Nanomater. **2012**, 963609 (2012)

Y.M. Awad, M. Vithanage, N.K. Niazi, M. Rizwan, J. Rinklebe, J.E. Yang, Y.S. Ok, S.S. Lee, Potential toxicity of trace elements and nanomaterials to Chinese cabbage in arsenic-and lead-contaminated soil amended with biochars. Environ. Geochem. Health **41**(4), 1777–1791 (2019)

L. Azeez, A.L. Adejumo, A. Lateef, S.A. Adebisi, R.O. Adetoro, S.O. Adewuyi, K.O. Tijani, S. Olaoye, Zero-valent silver nanoparticles attenuate Cd and Pb toxicities on Moringa oleifera via immobilization and induction of phytochemicals. Plant Physiol. Biochem. **139**, 283–292 (2019)

S. Baker, T. Volova, S.V. Prudnikova, S. Satish, N. Prasad, Nanoagroparticles emerging trends and future prospect in modern agriculture system. Environ. Toxicol. Pharmacol. **53**, 10–17 (2017)

M. Bakshi, C. Liné, D.E. Bedolla, R.J. Stein, R. Kaegi, G. Sarret, A.E.P. Del Real, H. Castillo-Michel, P.C. Abhilash, C. Larue, Assessing the impacts of sewage sludge amendment containing nano-TiO_2 on tomato plants: A life cycle study. J. Hazard. Mater. **369**, 191–198 (2019)

A. Banerjee, A. Singh, M. Sudarshan, A. Roychoudhury, Silicon nanoparticle-pulsing mitigates fluoride stress in rice by fine-tuning the ionomic and metabolomic balance and refining agronomic traits. Chemosphere **262**, 127826 (2021)

W.E. Blum, Functions of soil for society and the environment. Rev. Environ. Sci. Biotechnol. **4**(3), 75–79 (2005)

M. Chen, X. Qin, G. Zeng, Biodiversity change behind wide applications of nanomaterials? Nano Today **17**, 11–13 (2017)

E. Corredor, P.S. Testillano, M.J. Coronado, P. González-Melendi, R. Fernández-Pacheco, C. Marquina, M.R. Ibarra, J.M. de la Fuente, D. Rubiales, A. Pérez-de-Luque, M.C. Risueño, Nanoparticle penetration and transport in living pumpkin plants: In situ subcellular identification. BMC Plant Biol. **9**(1), 1–11 (2009)

H. Cui, P. Zhang, W. Gu, J. Jiang, Application of anatasa TiO_2 sol derived from peroxotitannic acid in crop diseases control and growth regulation, in *NSTI-Nanotech*, vol. 2, (2009), pp. 286–289

J.A.T. da Silva, Heavy metals and nanoparticles: Impact on protocorm-like body formation in hybrid cymbidium. Plant Tissue Culture Biotechnol. **24**(1), 47–55 (2014)

M.I. Dar, I.D. Green, M.I. Naikoo, F.A. Khan, A.A. Ansari, M.I. Lone, Assessment of biotransfer and bioaccumulation of cadmium, lead and zinc from fly ash amended soil in mustard–aphid–beetle food chain. Sci. Total Environ. **584**, 1221–1229 (2017)

R. Deng, D. Lin, L. Zhu, S. Majumdar, J.C. White, J.L. Gardea-Torresdey, B. Xing, Nanoparticle interactions with co-existing contaminants: Joint toxicity, bioaccumulation and risk. Nanotoxicology **11**(5), 591–612 (2017)

Y.Q. Deng, J.C. White, B.S. Xing, Interactions between engineered nanomaterials and agricultural crops: Implications for food safety. J. Zheijang Univ. Sci. A **15**(8), 552–572 (2014)

L. Ding, J. Li, W. Liu, Q. Zuo, S.X. Liang, Influence of nano-hydroxyapatite on the metal bioavailability, plant metal accumulation and root exudates of ryegrass for phytoremediation in lead-polluted soil. Int. J. Environ. Res. Public Health **14**(5), 532 (2017)

C.L. Doolette, M.J. McLaughlin, J.K. Kirby, D.A. Navarro, Bioavailability of silver and silver sulfide nanoparticles to lettuce (Lactuca sativa): Effect of agricultural amendments on plant uptake. J. Hazard. Mater. **300**, 788–795 (2015)

M.E. El-Naggar, N.R. Abdelsalam, M.M. Fouda, M.I. Mackled, M.A. Al-Jaddadi, H.M. Ali, M.H. Siddiqui, E.E. Kandil, Soil application of nano silica on maize yield and its insecticidal activity against some stored insects after the post-harvest. Nano **10**(4), 739 (2020)

FAO, The role of agriculture in the development of least-developed countries and their integration into the world economy. Commodities and Trade Division (2002)

A.O. Fayiga, U.K. Saha, Nanoparticles in biosolids: Effect on soil health and crop growth. Ann. Environ. Sci. Toxicol. **2**(2), 059–067 (2017)

V. Ghormade, M.V. Deshpande, K.M. Paknikar, Perspectives for nano-biotechnology enabled protection and nutrition of plants. Biotechnol. Adv. **29**(6), 792–803 (2011)

M. Gil-Díaz, J. Alonso, E. Rodríguez-Valdés, J.R. Gallego, M.C. Lobo, Comparing different commercial zero valent iron nanoparticles to immobilize As and Hg in brownfield soil. Sci. Total Environ. **584–585**, 1324–1332 (2017). https://doi.org/10.1016/j.scitotenv.2017.02.011

A. Gogos, K. Knauer, T.D. Bucheli, Nanomaterials in plant protection and fertilization: Current state, foreseen applications, and research priorities. J. Agric. Food Chem. **60**(39), 9781–9792 (2012)

X. Gong, D. Huang, Y. Liu, G. Zeng, R. Wang, J. Wan, C. Zhang, M. Cheng, X. Qin, W. Xue, Stabilized nanoscale zerovalent iron mediated cadmium accumulation and oxidative damage of Boehmeria nivea (L.) Gaudich cultivated in cadmium contaminated sediments. Environ. Sci. Technol. **51**(19), 11308–11316 (2017)

L.A. Gugliotti, D.L. Feldheim, B.E. Eaton, RNA-mediated metal-metal bond formation in the synthesis of hexagonal palladium nanoparticles. Science **304**(5672), 850–852 (2004)

Y. Hao, F. Yu, R. Lv, C. Ma, Z. Zhang, Y. Rui, L. Liu, W. Cao, B. Xing, Carbon nanotubes filled with different ferromagnetic alloys affect the growth and development of rice seedlings by changing the C: N ratio and plant hormones concentrations. PLoS One **11**(6), e0157264 (2016)

X. Hu, J. Kang, K. Lu, R. Zhou, L. Mu, Q. Zhou, Graphene oxide amplifies the phytotoxicity of arsenic in wheat. Sci. Rep. **4**(1), 1–10 (2014)

D. Huang, X. Qin, Z. Peng, Y. Liu, X. Gong, G. Zeng, C. Huang, M. Cheng, W. Xue, X. Wang, Z. Hu, Nanoscale zero-valent iron assisted phytoremediation of Pb in sediment: Impacts on metal accumulation and antioxidative system of Lolium perenne. Ecotoxicol. Environ. Saf. **153**, 229–237 (2018)

A. Hussain, S. Ali, M. Rizwan, M.Z. ur Rehman, M.R. Javed, M. Imran, S.A.S. Chatha, R. Nazir, Zinc oxide nanoparticles alter the wheat physiological response and reduce the cadmium uptake by plants. Environ. Pollut. **242**, 1518–1526 (2018)

A. Hussain, M. Rizwan, Q. Ali, S. Ali, Seed priming with silicon nanoparticles improved the biomass and yield while reduced the oxidative stress and cadmium concentration in wheat grains. Environ. Sci. Pollut. Res. **26**(8), 7579–7588 (2019)

M.R. Khan, Z.A. Siddiqui, Use of silicon dioxide nanoparticles for the management of Meloidogyne incognita, Pectobacterium betavasculorum and Rhizoctonia solani disease complex of beetroot (Beta vulgaris L.). Sci. Hortic. **265**, 109211 (2020)

Z.S. Khan, M. Rizwan, M. Hafeez, S. Ali, M.R. Javed, M. Adrees, The accumulation of cadmium in wheat (Triticum aestivum) as influenced by zinc oxide nanoparticles and soil moisture conditions. Environ. Sci. Pollut. Res. **26**(19), 19859–19870 (2019)

A. King, Technology: The future of agriculture. Nature **544**(7651), S21–S23 (2017)

M. Li, H.L. Liu, F. Dang, H. Hintelmann, B. Yin, D. Zhou, Alteration of crop yield and quality of three vegetables upon exposure to silver nanoparticles in sludge-amended soil. ACS Sustain. Chem. Eng. **8**(6), 2472–2480 (2020)

P. Li, Y. Du, L. Huang, N. Mitter, Z.P. Xu, Nanotechnology promotes the R&D of new-generation micronutrient foliar fertilizers. RSC Adv. **6**(73), 69465–69478 (2016)

R. Liu, H. Zhang, R. Lal, Effects of stabilized nanoparticles of copper, zinc, manganese, and iron oxides in low concentrations on lettuce (Lactuca sativa) seed germination: Nanotoxicants or nanonutrients? Water Air Soil Pollut. **227**(1), 42 (2016)

S. Lyu, X. Wei, J. Chen, C. Wang, X. Wang, D. Pan, Titanium as a beneficial element for crop production. Front. Plant Sci. **8**, 597 (2017)

X. Ma, H. Sharifan, F. Dou, W. Sun, Simultaneous reduction of arsenic (As) and cadmium (Cd) accumulation in rice by zinc oxide nanoparticles. Chem. Eng. J. **384**, 123802 (2020)

S.C. Mali, S. Raj, R. Trivedi, Nanotechnology a novel approach to enhance crop productivity. Biochem. Biophys. Rep. **24**, 100821 (2020)

L. Marchiol, A. Mattiello, F. Pošćić, C. Giordano, R. Musetti, In vivo synthesis of nanomaterials in plants: Location of silver nanoparticles and plant metabolism. Nanoscale Res. Lett. **9**(1), 1–11 (2014)

H. Marschner, *Marschner's Mineral Nutrition of Higher Plants* (Academic press, 2011)

A.F. McCalla, Challenges to world agriculture in the 21st century. UPDATE: Agricu. Resour. Econ. **4**(3), 1–2 (2001)

M.I. Naikoo, F. Raghib, M.I. Dar, F.A. Khan, K. Hessini, P. Ahmad, Uptake, accumulation and elimination of cadmium in a soil-Faba bean (Vicia faba)-Aphid (Aphis fabae)-Ladybird (Coccinella transversalis) food chain. Chemosphere **279**, 130522 (2021)

R. Nair, M.S. Mohamed, W. Gao, T. Maekawa, Y. Yoshida, P.M. Ajayan, D.S. Kumar, Effect of carbon nanomaterials on the germination and growth of rice plants. J. Nanosci. Nanotechnol. **12**(3), 2212–2220 (2012)

B. Nowack, T.D. Bucheli, Occurrence, behavior and effects of nanoparticles in the environment. Environ. Pollut. **150**(1), 5–22 (2007)

A. Pérez-de-Luque, Interaction of nanomaterials with plants: What do we need for real applications in agriculture? Front. Environ. Sci. **5**, 12 (2017)

R.J. Peters, H. Bouwmeester, S. Gottardo, V. Amenta, M. Arena, P. Brandhoff, H.J. Marvin, A. Mech, F.B. Moniz, L.Q. Pesudo, H. Rauscher, Nanomaterials for products and application in agriculture, feed and food. Trends Food Sci. Technol. **54**, 155–164 (2016)

A.E. Pradas del Real, H. Castillo-Michel, R. Kaegi, B. Sinnet, V. Magnin, N. Findling, J. Villanova, M. Carrière, C. Santaella, Fernández-Martínez, A. and Levard, C., Fate of Ag-NPs in sewage sludge after application on agricultural soils. Environ. Sci. Technol. **50**(4), 1759–1768 (2016)

R. Prasad, A. Bhattacharyya, Q.D. Nguyen, Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives. Front. Microbiol. **8**, 1014 (2017)

F. Raghib, M.I. Naikoo, F.A. Khan, M.N. Alyemeni, P. Ahmad, Interaction of ZnO nanoparticle and AM fungi mitigates Pb toxicity in wheat by upregulating antioxidants and restricted uptake of Pb. J. Biotechnol. **323**, 254–263 (2020)

P.K. Rai, V. Kumar, S. Lee, N. Raza, K.H. Kim, Y.S. Ok, D.C. Tsang, Nanoparticle-plant interaction: Implications in energy, environment, and agriculture. Environ. Int. **119**, 1–19 (2018)

V.D. Rajput, T. Minkina, A. Fedorenko, N. Chernikova, T. Hassan, S. Mandzhieva, S. Sushkova, V. Lysenko, M.A. Soldatov, M. Burachevskaya, Effects of zinc oxide nanoparticles on physiological and anatomical indices in spring barley tissues. Nano **11**(7), 1722 (2021a). https://doi.org/10.3390/nano11071722

V.D. Rajput, T. Minkina, A. Kumari, V.K. Singh, K.K. Verma, S. Mandzhieva, S. Sushkova, S. Srivastava, C. Keswani, Coping with the challenges of abiotic stress in plants: New dimensions in the field application of nanoparticles. Plan. Theory **10**(6), 1221 (2021b). Available at: https://www.mdpi.com/2223-7747/10/6/1221

V.D. Rajput, A. Singh, V.K. Singh, T.M. Minkina, S. Sushkova, Impact of nanoparticles on soil resource, in *Nanomaterials for Soil Remediation*, ed. by A. Amrane, D. Mohan, T. A. Nguyen, A. A. Assadi, G. Yasin, (Elsevier, 2021c), pp. 65–85

A. Ranjan, V.D. Rajput, T. Minkina, *Nanotechnology in Sustainable Agriculture, Soil Chemistry and Remediation of Polluted Soil* (Springer, 2021), pp. 173–196. https://doi.org/10.18485/green_economy_4ir.2021.ch7

A. Rastogi, M. Zivcak, O. Sytar, H.M. Kalaji, X. He, S. Mbarki, M. Brestic, Impact of metal and metal oxide nanoparticles on plant: A critical review. Front. Chem. **5**, 78 (2017)

M. Rizwan, S. Ali, B. Ali, M. Adrees, M. Arshad, A. Hussain, M.Z. ur Rehman, A.A. Waris, Zinc and iron oxide nanoparticles improved the plant growth and reduced the oxidative stress and cadmium concentration in wheat. Chemosphere **214**, 269–277 (2019)

L. Rossi, W. Zhang, A.P. Schwab, X. Ma, Uptake, accumulation, and in planta distribution of coexisting cerium oxide nanoparticles and cadmium in Glycine max (L.) Merr. Environ. Sci. Technol. **51**(21), 12815–12824 (2017)

M. Rui, C. Ma, J.C. White, Y. Hao, Y. Wang, X. Tang, J. Yang, F. Jiang, A. Ali, Y. Rui, W. Cao, Metal oxide nanoparticles alter peanut (Arachis hypogaea L.) physiological response and reduce nutritional quality: A life cycle study. Environ. Sci. Nano **5**(9), 2088–2102 (2018)

B. Ruttkay-Nedecky, O. Krystofova, L. Nejdl, V. Adam, Nanoparticles based on essential metals and their phytotoxicity. J. Nanobiotechnol. **15**(1), 1–19 (2017)

M.F. Seleiman, M.A. Alotaibi, B.A. Alhammad, B.M. Alharbi, Y. Refay, S.A. Badawy, Effects of ZnO nanoparticles and biochar of rice straw and cow manure on characteristics of contaminated soil and sunflower productivity, oil quality, and heavy metals uptake. Agronomy **10**(6), 790 (2020)

A. Servin, W. Elmer, A. Mukherjee, R. De la Torre-Roche, H. Hamdi, J.C. White, P. Bindraban, C. Dimkpa, A review of the use of engineered nanomaterials to suppress plant disease and enhance crop yield. J. Nanopart. Res. **17**(2), 1–21 (2015)

S.S. Shende, V.D. Rajput, A.V. Gorovtsov, P. Saxena, T.M. Minkina, V.A. Chokheli, H.S. Jatav, S.N. Sushkova, P. Kaur, R. Kizilkaya, Interaction of nanoparticles with microbes, in *Plant-Microbes-Engineered Nano-Particles (PM-ENPs) Nexus in Agro-Ecosystems: Understanding the Interaction of Plant, Microbes and Engineered Nano-Particles (ENPS)*, ed. by P. Singh, R. Singh, P. Verma, R. Bhadouria, A. Kumar, M. Kaushik, (Springer International Publishing, Cham, 2021), pp. 175–188

K.S. Siddiqi, A. Husen, R.A. Rao, A review on biosynthesis of silver nanoparticles and their biocidal properties. J. Nanobiotechnol. **16**(1), 1–28 (2018)

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

B. Song, P. Xu, M. Chen, W. Tang, G. Zeng, J. Gong, P. Zhang, S. Ye, Using nanomaterials to facilitate the phytoremediation of contaminated soil. Crit. Rev. Environ. Sci. Technol. **49**(9), 791–824 (2019)

H. Su, Z. Fang, P.E. Tsang, J. Fang, D. Zhao, Stabilisation of nanoscale zero-valent iron with biochar for enhanced transport and in-situ remediation of hexavalent chromium in soil. Environ. Pollut. **214**, 94–100 (2016)

E. Tassi, L. Giorgetti, E. Morelli, J.R. Peralta-Videa, J.L. Gardea-Torresdey, M. Barbafieri, Physiological and biochemical responses of sunflower (Helianthus annuus L.) exposed to nano-CeO_2 and excess boron: Modulation of boron phytotoxicity. Plant Physiol. Biochem. **110**, 50–58 (2017)

I. Uddin, P. Poddar, U. Kumar, N. Phogat, A novel microbial bio-milling technique for the size reduction of micron sized Gd2O3 particles into nanosized particles. J. Green Sci. Technol. **1**(1), 48–53 (2013)

M. Usman, M. Farooq, A. Wakeel, A. Nawaz, S.A. Cheema, H. ur Rehman, I. Ashraf, M. Sanaullah, Nanotechnology in agriculture: Current status, challenges and future opportunities. Sci. Total Environ. **721**, 137778 (2020)

M. Vithanage, M. Seneviratne, M. Ahmad, B. Sarkar, Y.S. Ok, Contrasting effects of engineered carbon nanotubes on plants: A review. Environ. Geochem. Health **39**(6), 1421–1439 (2017)

J. Yang, W. Cao, Y. Rui, Interactions between nanoparticles and plants: Phytotoxicity and defense mechanisms. J. Plant Interact. **12**(1), 158–169 (2017)

J. Yang, F. Jiang, C. Ma, Y. Rui, M. Rui, M. Adeel, W. Cao, B. Xing, Alteration of crop yield and quality of wheat upon exposure to silver nanoparticles in a life cycle study. J. Agric. Food Chem. **66**(11), 2589–2597 (2018)

L. Yang, B. Liu, Y. Lu, F. Lu, X. Wu, W. You, B. Huang, Bioavailability of cadmium to celery (Apium graveolens L.) grown in acidic and Cd-contaminated greenhouse soil as affected by the application of hydroxyapatite with different particle sizes. Chemosphere **240**, 124916 (2020)

F. Yasmeen, N.I. Raja, A. Razzaq, S. Komatsu, Proteomic and physiological analyses of wheat seeds exposed to copper and iron nanoparticles. Biochim. Biophys. Acta **1865**(1), 28–42 (2017)

H. Yoon, Y.G. Kang, Y.S. Chang, J.H. Kim, Effects of zerovalent iron nanoparticles on photosynthesis and biochemical adaptation of soil-grown Arabidopsis thaliana. Nano **9**(11), 1543 (2019)

A.D. Zand, A.M. Tabrizi, A.V. Heir, Co-application of biochar and titanium dioxide nanoparticles to promote remediation of antimony from soil by Sorghum bicolor: Metal uptake and plant response. Heliyon **6**(8), e04669 (2020a)

A.D. Zand, A.M. Tabrizi, A.V. Heir, Incorporation of biochar and nanomaterials to assist remediation of heavy metals in soil using plant species. Environ. Technol. Innovation **20**, 101134 (2020b)

W. Zhang, J. Long, J. Li, M. Zhang, G. Xiao, X. Ye, W. Chang, H. Zeng, Impact of ZnO nanoparticles on Cd toxicity and bioaccumulation in rice (Oryza sativa L.). Environ. Sci. Pollut. Res. **26**(22), 23119–23128 (2019)