Chapter 12
Nanomaterial Impact on Plant Morphology, Physiology and Productivity

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Abstract Nanoparticles (NPs) have a remarkable impact on plants. Plants respond to NPs in many ways, including stimulation and inhibition. The responses could be clearly observed via the changes in plants' morphological, physiological, and productive indicators. This chapter focuses on the morphological changes in plants and seedlings' growth and the fresh and dry weight of plants and seedlings. In addition, the chapter concentrates on the number and lengths of roots, shoots, and leaves. Different modifications that occur due to NPs' influence on flowers, pods, and grain are also covered. The chapter further discusses the interaction mechanism of NPs with seed germination, plant development, and reproduction by interacting with plant cells' surfaces. The biochemical interaction series that could stimulate the plants internally are also discussed. Furthermore, the chapter provides details on the negative and positive effects of NPs on various plant parts, including root, stem, leaf, flower, and fruit. The impacts of different nanomaterials (NMs) include carbon, titanium dioxide, silver, zinc oxide, copper oxide, silica, cerium dioxide, aluminum oxide, selenium, gold, fullerene, and iron, on plants are demonstrated in this chapter. The material's particle size, concentration as well as plant species are also taken into account. All the previously mentioned effects demand more research to realize the mechanisms that occur in plants as a result of treatment with various NPs.

Keywords Fruits · Leaves · Nanoparticles · Nanoparticle response · Plant morphology · Root growth · Seed germination · Stems

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12.1 Introduction

Humans have intelligently utilized plant organs for a variety of uses, including food and medicine (fruits, seeds, roots, stems, and leaves), clothes (flowers), furniture (trunks), and paper (trunks). In addition, plant leaves absorb carbon dioxide and produce renewable oxygen (Ali et al. 2021). These plant organs are affected by numerous factors such as temperature, light, nutrients, and water (Patil et al. 2021, Shafiq et al. 2021).

The study of the shape, size and placement of plant organs such as seeds, roots, stems, leaves, flowers, and fruits is known as plant morphology (Hossain et al. 2020). Recent researchers have demonstrated the significant impact of nanotechnology on plant morphology, including particle size, shape, and material concentration (Singh et al. 2015). These variables might influence not only plant morphology but also seedling germination and phytotoxicity. As a result, nanotechnology can alter the present synthetic framework used in modern agriculture systems (Arora 2018, Kerry et al. 2017; Prasad et al. 2017; Shang et al. 2019; Usman et al 2020).

This chapter describes the influence of NPs on plant morphology. It covers the mechanism of seed interaction with NPs, explains the recent experimental results of the effect of NPs on seed germination and root growth, and discusses how NPs of different elements and their oxides affect the morphology of stem, leaves, flowers, and fruit.

12.2 Mechanism of NPs Interaction in Seed

The plant growth inhibitory or stimulatory effects are produced by interacting between the surface charges of NMs/NPs and the surface charges of plant cells. However, that interaction with metal NPs differs depending on the features of NPs, such as the metal nature, concentrations of NPs, phase growth, and plant species (Pérez-de-Luque 2017).

NPs can induce seed germination and develop many parts of a plant (Juárez-Maldonado et al. 2019). Seed germination is the foundation-initiated stage for plants' growth, development, and productivity (Hossain et al. 2020). NPs-treated seeds achieve high germination by improving seed absorption and water retention (Juárez-Maldonado et al. 2019) (Fig. 12.1).

The bio-stimulation effect is demonstrated in two stages. The first stage is implemented via the interaction of surface charges of a physicochemical nature. Following this stage and as a second stage, a series of biochemical stimuli are triggered via the entry of NPs and NMs into the plant cells due to alteration of the cellular membrane (Ali et al. 2021). Figure 12.2 shows the most probable effect of nanoparticles on plant parts.

12.3 Effect of NPs on Seed Germination and Root Growth

12.3.1 Carbon-Based NPs

Utilizing carbon-based nanomaterials (CNTs) raised water uptake for the seed via passing it from the seed coat and then reaching to shoots and leaves (Omar et al. 2019) which favorably affects the germination percentage and plant growth via capitalizing on the efficiency of water uptake moreover increasing some substantial nutrients uptake (Singh et al. 2015). This stimulatory effect can be explained by producing microspores by the CNTs (Ali et al. 2021; Sanborn et al. 2018). This mechanism has been applied to enhance seed germination and root growth, and final plant growth for several crops, such as hybrid Bt cotton, *Phaseolus mungo* L., *Brassica juncea* L., tomato (*Lycopersicum esculentum* Mill), and rice (*Oryza sativa* L.) which increased the biomass of rice plants and the germination rate of seeds by 90% within 20 days, compared with 71% in the control sample (Ali et al. 2021).

The results of the research show the role of CNTs as a promoter of rice seedling growth, activation effects on root elongation, and seed germination in zucchini species (Aslani et al. 2014). In addition10-40 mg/L CNTs significantly increased seed germination, vegetative biomass, and tomato plant growth (Remedios et al. 2012). Also, the influence of MWCNT (50 μg/ml) on tomato roots was observed in fresh and dry mass and gene expression variety (Predoi et al. 2020).

In addition, MWCNTs increased the germination of previously treated seedlings, as confirmed by transmission electron microscopy (TEM) and Raman spectroscopy (Singh et al. 2015).

As well as the treatments by single-walled carbon nanohorns (SWCNHs) increased seed germination in some crop species: maize, tobacco, switchgrass, rice, tomato cell cultures, Barley, Wheat, and soybean (Ali et al. 2021). On the contrary, no effect was found for treatment by SWCNTs (84 h) for roots of cucumber seedlings (Aslani et al. 2014).

12.3.2 Titanium Dioxide NPs

The impact on the morphology of plants is varied on the type of NPs and the method of application (Hossain et al. 2020). However, the essential key to promoting the seed germination rate is the permeation of NMs into the seed (Aslani et al. 2014). The best effects were at 2500 mg/L when applying the concentrations from 2500 to 40,000 mg/L to senescent seeds.

Titanium dioxide NPs have promoted seed germination through their more capacity to the carriage of water to the internal tissues and increased the metabolism of the seed reserves as indicated for the NPs of Ag and graphene (Juárez-Maldonado et al. 2019).

At 250–4000 mg/L, TiO_2 nanoparticles substantially increase the germination rate and germination index of naturally aged spinach seeds. TiO_2 NPs increases the seedling's dry weight and seedling vigor index considerably. (Predoi et al. 2020). In addition, titanium dioxide NPs facilitate water absorption and consequently quicken seed germination (Ali et al. 2021).

Treated seeds with TiO_2 NPs provided plants with three times higher photosynthetic rates, 73% more dry weight, a 45% increase in chlorophyll compared to the control over the germination period of 30 days (Aslani et al. 2014).

When spinach roots are exposed to TiO_2 NPs, increased plant growth has been observed by improving nitrogen metabolism that promotes the adsorption of nitrate and photosynthetic rate (Predoi et al. 2020). There was a correlation between the growth rate of spinach and the size of the materials, so the smaller NMs produce better germination (Siddiqui et al. 2020). Foliar application with 20 g/L TiO_2 NPs increased root and stem length, ear mass biomass, flowering, and seed number of wheat (Predoi et al. 2020).

Application of TiO_2 NPs for seedlings plants canola stimulated the growth of radicle and plumule, root, and seed germination. However, it inhibited root elongation in cucumber (Khana et al. 2019). Titanium dioxide NPs at 60 mg/L (bulk and nanosized) encouraged seed germination percentages of the sage plants. This concentration could gain the lowest mean germination time. However, higher concentrations did not do that. Therefore, the vigor index of sage was raised by using TiO_2 NPs to seeds compared to the control and bulk TiO_2 treatments (Aslani et al. 2014).

12.3.3 Silver NPs

Silver NPs had positive or negative effects on vascular plants, such as seed germination, root growth, and plant biomass. These effects were related to the concentration and the shape of NPs (Aslani et al. 2014). Furthermore, these effects may be attributed to chemical precursors. Therefore, plant extractions are involved in the biosynthesis method which is widely used to synthesize NPs. Figure 12.1 illustrates the schematic presentation for biosynthesized Ag NPs using leave extraction. The approach demonstrated well-controlled particle concentration and size (21–42 nm), as well as particle dispersion. They are spherical in shape and uniformly distributed (Bamsaoud et al. 2021). This method may aid in reducing the negative effects of NPs.

Many researchers have observed the effects of silver NPs on plants growth. For example, silver NPs show harmful effects on seed germinations, root, and shoot growth on species of Chinese cabbage (*Brassica campestris*), rice (*Oryza sativa* L.), and Mung bean (*Vigna radiata* L. Wilczek) at concentrations of 3000 g/mL, 4500 g/mL and 6000 g/mL, respectively (Yan and Chen 2019). On the other hand, silver NPs positively affected seed germination and the root growth of zucchini plants in hydroponic solution. At the same time, it observed a decrease in plant biomass and transpiration in the presence of Ag NPs (Aslani et al. 2014).

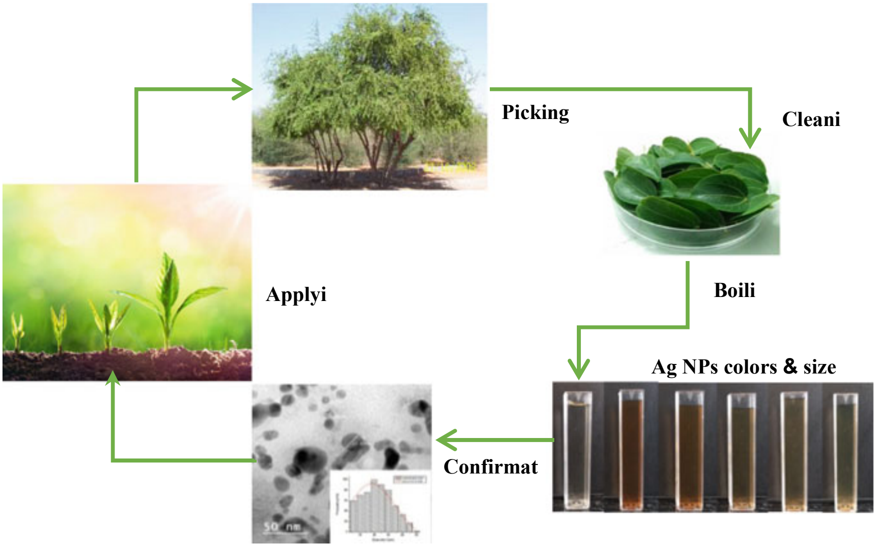

Fig. 12.1 Schematic presentation for biosynthesis, characterization, and plant application of synthesized silver nanoparticles using leaf extract

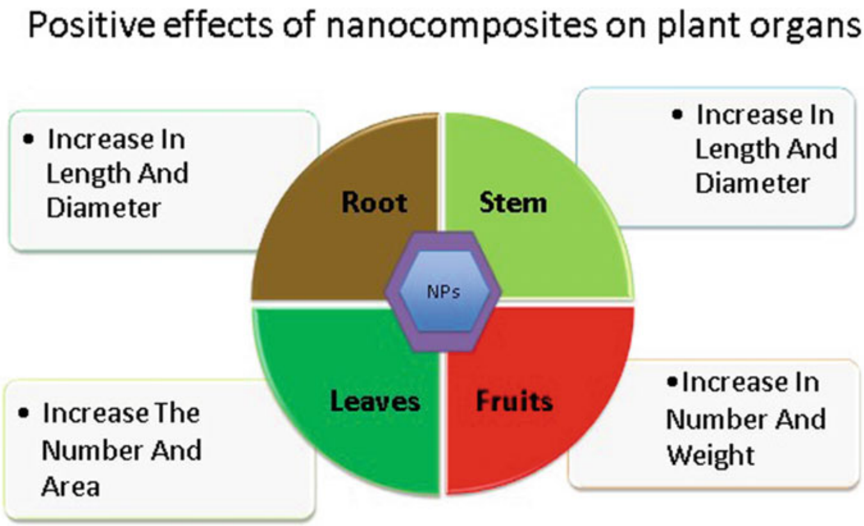

Fig. 12.2 The most probable effect of nanoparticles on plant parts

It has been certified that Ag NPs with sizes of up to 29 nm had harmful effects on the germination of cucumber seeds and lettuce. Still, no toxic effect has been observed on the germination of barley and ryegrass exposed to Ag NPS (Yan and Chen 2019). The number of studies about the effect of Ag NPS in two varieties of wheat and barley noted an increase in germination ratio stem length and reduced length root compared to the control (Al-Hadede et al. 2020).

Treatment with 75 ppm Ag NPs application on wheat plants resulted in a negative response for fresh root weight and root length. At the same time, a positive response was observed to cowpea (50 ppm) and brassica plants (Yan and Chen 2019). Silver NPs promoted growth and increased root nodulation. Low concentrations of Ag NPs (10–20 g/mL) improved seedling development and seed germination in fenugreek plants (Predoi et al. 2020).

12.3.4 Zinc Oxide NPs

Plants required low concentrations of ZnO NPs for the normal developmental process. On the other hand, higher levels of Zn in plants can cause toxic effects such as inhibition of cell elongation and division, the reduction of growth and plant biomass, curling and rolling of young leaves, chlorotic and necrotic leaf tips, wilting, and root growth inhibition (Predoi et al. 2020). For example application of ZnO NPs resulted in a dose-dependent inhibition of seed germination in cabbage. During seed germination in wheat, lower concentrations of ZnO NPs were more beneficial. However, the lower concentration does not inhibit seedling growth and cell division in onions (Khana et al. 2019).

Similarly, the germination of cucumber seeds increased 10% by ZnO-NPs compared to the control (Velasco et al. 2020). In addition, lower concentrations of ZnO NPs improve seed germination in soybean, wheat, tomato, and onion. Also, ZnO NPs with (50 nm) particle size positively affected the rooting of rapeseed in contrast with the impact of Zn^{+2} ions (Khana et al. 2019).

Using ZnO NMs on different plants increased root length (4.2%), shoot length (15.1%). In addition, ZnO NPs application on the coffee plants had a positive effect by increasing the fresh weight of roots (37%) (Predoi et al. 2020).

The biogenic ZnO-NPs influenced the shoot and root length of maize seedlings at 14 DAS. The treatment which effectively increased root length was 25 mg/L (T25). In contrast, the 200 mg/L (T200) concentration of ZnO-NPs exerted an inhibiting effect (Buono et al. 2021).

Biological synthesis of ZnO NPs has been prepared using brown seaweed *Turbinaria* ornata. (Turner) J. Agardh extracts to promote rice seed quality and crop yield. ZnO NPs at (10 mg/L) showed that they have been prompt in the seed germination (100%), root length (185 mm) root width (0.5 mm) compared to control (Itroutwar et al. 2019).

12.3.5 Copper Oxide NPs

Cu NPs up to 1000 mg/L have detrimental impacts on the seedling growth of mung bean (Vigna radiata L. Wilczek) and wheat, and may reduce the biomass of zucchini by 90% relative to the control compared to the higher concentration (Omar et al. 2019). Also using higher concentrations of Cu NPs reduce shoot and root growth of soybean, decrease germination rate and biomass in Oryza sativa L. and it could inhibit seed germination in cucumber (Predoi et al. 2020). On the other hand, it was indicated that soil amendments with metallic Cu NPs up to 600 mg/kg significantly increased lettuce seedling growth up to 91% without toxic effects (Omar et al. 2019).

The *Sesbania virgata* (Cav.) Pers seeds were subjected to different concentrations of CuO NPs. The results showed that CuO NPs induced a considerable change in seed temperature and a reduction in root length. This was signalized metabolic damage and changes in energy dissipation and plant growth (Santos et al. 2021).

12.3.6 Iron Oxide NPs

The research results showed that nα-Fe_2O_3 was effective on seed germination (89.17%) due to the role of iron in germination and increasing biomass of *Oenothera biennis L.* (Asadi-Kavan et al. 2020). Furthermore, nano zero-valent iron utilized promoted the elongation of the root system in *A. thaliana* (Khana et al. 2019). Predoi et al. (2020) indicated that the foliar and root usage of Fe_2O_3 NPs increase root elongation.

12.3.7 Silica NPs

Lower amounts of nano SiO_2 (in the concentration of 8 g/L) increased the germination of seeds in tomatoes by 22.16%, mean germination time, seed germination index, seed vigor index, fresh seedling weight, and dry weight. In addition, with a significant impact on root growth through the main length of roots, seedlings lateral root number, and diameter of root collar (Predoi et al. 2020). Similarly, rice seed germination was induced with Si NPs, while quantum dots arrested the germination (Aslani et al. 2014).

Increases in seed germination caused by Si NPs in maize are related to enhanced nutritional availability to seeds (Singh et al. 2015). For example, in *Changbai larch* (*Larix olgensis* Henry) seedlings, Si NPs improved seed germination traits, including percent germination and germination rate, length, fresh and dry mass of root and shoot (Siddiqui et al. 2020). Also, in tall wheatgrass (*Thinopyrum intermedium* L.), using Si NPs for Pre-chilling seeds breaks inertia, promotes seed germination, and increases vigor index, mean germination time, and dry weight seedling roots and shoots (Al-Hadede et al. 2020).

Additionally, using Si-NPs in seed priming and seed soaking increased seedling biomass and vigor index along with seedling root and shoot length of *Helianthus annuus* L. (Omar et al. 2019). Germination and growth of soybean (*Glycine max* L.) were improved by increasing nitrate reductase activity and enhancing seeds' ability to absorb and utilize water and nutrients (Siddiqui et al. 2020). The positive effects on seed germination, length, and dry weight of root and shoot in rice (Oryza sativa L.) seedlings were observed when Si-NPs were used (Elshayb et al. 2021).

12.3.8 Cerium Dioxide NPs

The results of the effect of CeO_2 on seeds of tomato (*Lycopersicon esculentum* Mill.), cucumber (*Cucumis sativus* L.), and corn (*Zea mays* L.) found that CeO_2 NPs (2000 mg/L) meaningfully decreased corn germination (about 30%). The germination of tomato and cucumber was reduced by 30 and 20%, respectively (Ali et al. 2021). On the other hand, adding cerium dioxide, NPs can raise plant biomass and prompt anthocyanin production, yet showed little impact on root lengthening (Khana et al. 2019).

12.3.9 Aluminum Oxide NPs

Al_2O_3 NPs at concentrations up to 4000 mg/L had no significant toxic effects on seed germination, root elongation of Arabidopsis thaliana L. (Remedios et al. 2012). Al_2O_3 NPs (The aqueous suspension) improved the root growth of radish. On the contrary, the root growth decreased in cucumber (Hossain et al. 2020).

12.3.10 Selenium NPs

Correlation of Se NPs with selenate in *Nicotiana tabacum* L. showed that Se NPs invigorated organogenesis and expanded the advancement of the root by up to 40% compared to the impact of aqueous selenate (Khana et al. 2019).

12.3.11 Gold NPs

Maize aged seeds' exposure to photosynthesized gold NPs (5–15 mg/L) significantly improved their germination and physiology without any toxicity (Elemike et al.

2019). In addition, enhanced seed germination in (*Boswellia ovalifoliolata* Balakr and A.N. Henry) (Singh et al. 2015), *Arabidopsis thaliana* L. (Remedios et al. 2012), lettuce and cucumber, *Brassica juncea* L. and *Gloriosa superba* L. (Predoi et al. 2020). On the other hand, it resulted in cultures of barley with addition Au NPs decreased biomass, yellow leaves, and dark roots (Khana et al. 2019).

12.4 Effect of NPs on Shoots

In botany, the stem is the plant axis that carries buds and shoots with leaves and roots at its base. The stem's primary duties are to sustain the leaves by transporting the leaves' products to other plant sections, especially the roots, and conveying water and nutrients to the leaves. The stem is a component of a plant that is frequently exposed to NPs when NPs are used as soil fertilizers by which NPs enter through the root system (Ali et al. 2019; Abbas et al. 2021a, b). Seed treatments with NPs, such as priming and soaking, may also potentially produce morphological changes in the stem. (Bamsaoud and Bahwirth 2017; Mutlu et al. 2018; Choudhary et al. 2019; Galaktionova et al. 2020; Ramesh et al. 2021). On the other hand, NPs could enter the stem and roots through the leaves system when foliar spraying is used (Haytova 2013; Deshpande et al. 2017; Ali et al. 2019). Therefore, the various effects of NMs on a plant stem need to be recognized since the stem, on the other hand, is believed to be capable of photosynthesis.

Numerous reports in the literature confirm that nano-forms of applied materials positively affect plant stem morphology, mainly stem length, while just a few reports reveal negative consequences (Kasote et al. 2019; Rahman et al. 2020). The most frequent materials in their nano-form are metal and metal compounds. These NMs could affect the hypocotyl and plumule or/and stem diameter (Choudhary et al. 2019; Khan et al. 2020) and/or length as well as other physiological characteristics of the stem. In general, without referring to all the reported nanomaterial-based agriculture treatments, researchers found an increase in plant height, which most likely relates to a change in stem length (Behboudi 2018; Bhatia et al. 2014; Choudhary et al. 2019; Dhoke et al. 2013; Khan et al. 2021; Sharifi et al. 2016; Shinde 2020). However, the ambiguity of claiming that activating various enzymes by some NPs may cause an increase in the length of the plant stem necessitates additional research activity to prove or/and understand the precise reason.

One of the reactions of plants to NPs materials, according to published studies, is an increase in the length of the stem. Dhoke et al. (2013) observed a substantial rise in the stem of mung (*Vigna radiate* L.) when ZnO, nano FeO, and nano-ZnCuFe-oxide particles were applied by foliar spray (Dhoke et al. 2013). Plants treated with Zn Fe Cu oxide NPs had a 15.71% increase in shoot length, whereas plants treated with FeO NPs had a 10.25% increase and ZnO NPs had a 6.47% increase in shoot length compared to control. When a foliar spray of Fe NPs was given to forage maize (*Zea mays* L.), a significant increase in plant height was observed (Saedpanah et al. 2016). Fe NPs enhance plant height by 23% compared to the control, while Zn increases plant height by 5%, respectively. In a different study, the height of forage maize (*Zea mays* L.) was increased by 37% and 24% compared to the control when nano-Fe and nano-Zn were applied individually (Sharifi et al. 2016). Ali et al. (2019) observed an increase in shoot length after foliar spraying wheat (*Triticum aestivum* L.) using Si NPs. Tovar et al. (2020) combined nutrients into iron NPs and applied them to Corn (*Zea mays* L.) seedlings. After 30 days, all samples were identical in terms of stem length compared to the control. The height of maize plants rises by around 20% when Zn NPs are employed as a soil fertilizer and foliar spray, compared to control (Abbas et al. 2021a, b).

Regarding the method of treating seeds with NPs, Bamsaoud and Bahwirth (2017) observed an increase in the length of hypocotyls of *Cucurbita pepo* L. when seeds were treated with silver NPs prepared via *neem* extraction. The highest length of hypocotyls (increased by 12% to control) was noted for seeds treated with silver NPs prepared using Neem. Furthermore, when seeds were immersed in chemically produced silver NPs, the hypocotyls of wheat grains *Triticum aestivum* L. increased by 12%. (Bahwirth and Bamsaoud 2020). Maswada et al. (2018) performed experiments on Sorghum seeds. The seed priming with nano-Fe_2O_3 was more effective than seed soaking in enhancing seedling growth, and the experiments showed that the seedling length increased by 33%. The experiments of Raj and Chandrashekara showed that the higher plant height of Cotton (*Gossypium hirsutum* L.) was around 24% higher than the control gave. In their experiments, the seeds were treated with chelated nano ZnO followed by foliar application of 1000 ppm nano ZnO (Raj and Chandrashekara 2019). Joshi et al. (2021) primed tomato seeds (cv. Sagar) with Selenium NPs by mixing Se NPs solution with 400 tomato seeds. The experiment's findings revealed a substantial increase in plant height (51.2%) for treated tomato seeds compared to control ones. Nematzadeh's studies showed that silver NPs treatment at 80 ppm concentration did not prevent germination at high salinity despite a progressive increase in salinity levels. The stem of *Satureja hortensis* L. increased by 15% compared to the control (Nejatzadeh 2021). Due to the small size, NPs reach the branch through stomates or the base of trichomes in the leaves (Eichert et al. 2008; Uzu et al. 2010). Even though NMs caused a significant difference in stem traits, no research is available and directly studies the considerable reasons for improving plant stem.

12.5 Effect of NPs on Leaves

The leaves consist of stomata or cuticles that allow entering the NPs > 10 nm. Their transfer through the cellular membrane occurs by apoplastic (between 50 and 200 nm) and symplastic (between 10 and 50 nm) routes into the vascular system of the plant (Ali et al. 2021). There are essential factors that affect the existence of NPs on the leaf's surface, such as leaf morphology and its chemical composition, the presence of trichrome, and the existence of leaf exudates (Al-Hadede et al. 2020). The fullerene transmission in the plants is similar to the route of nutrients and water through the xylem (Aslani et al. 2014). In addition, the fullerene existed as black aggregates form in seeds and roots compared to the stems and leaves for rice seeds (Sanborn et al. 2018). The spinach leaves grew better with titanium-oxide NPs through foliar spray (Hossain et al. 2020). The fresh weight of the leaves coffee plant is increased when applied ZnO NPs in percentages of 95% as compared to control (Predoi et al. 2020). The favorable effect of nano-FeO and nano-ZnCuFe oxide was observed on the growth of mung (*Vigna radiate* L.) seedling and leaf and pod dry weight on soybean yield (Asadi-Kavan et al. 2020). Likewise, the number of leaves increased in percentage by 21.42% compared to control plants when applying nano-Fe-EDTA. Magnetic Fe-NPs by Low concentrations increases significantly the chlorophyll contents in sub-apical leaves of soybeans under hydroponic conditions. In contrast, the high amount of iron oxide (Fe_3O_4) as a magnetic nanomaterial harmed plant growth (Predoi et al. 2020). The nano-organic iron chelated fertilizers demonstrated high absorption, increase in photosynthesis, aided in the transfer of iron photosynthate, and expansion in the leaf surface area of peanut plants (Singh et al. 2015).

Agronomic use efficiency for nano-SiO_2 is higher for foliar application than soil application (Predoi et al. 2020). When seedlings were treated with SiO2 NPs, their photosynthetic rate increased. Carbonic anhydrase activity and photosynthetic pigment production both contributed to this rise. (Siddiqui et al. 2020). Using Si-NPs as fertilizer with different concentrations promoted plant height, leaf number, and root length of *Solanum lycopersicum* L. (Predoi et al. 2020). As well as advertised net assimilation rate (NAR), leaf area index (LAI), relative growth rate (RGR), and yield of soybean plants but did not affect height, leaves number, or stem diameters of plants (Siddiqui et al. 2020). It is suggested that the accumulation of Si in leaves is beneficial in maintaining leaves upright and stretching leaf surfaces to capture maximum sunlight, thus optimizing photosynthesis (Predoi et al. 2020). When nano SiO_2 was applied to Changbai larch (*Larix olgensis* Henry) seedlings, it further developed seedling development and chlorophyll biosynthesis (Singh et al. 2015). Adding low concentrations of CeO_2 NP (125 and 250 mg/kg) prompted grain creation, though significant measures of Ce are collected in grains and leaves (Ali et al. 2021).

Al_2O_3 NPs had no significant toxic effects on root elongation and some leaves of Arabidopsis thaliana at concentrations up to 4000 mg/L (Remedios et al. 2012). Using Au NPs resulted in a better crop yield through a favorable influence on the number of leaves, leaf area, plant height, and sugar and chlorophyll content (Singh et al. 2015). On the contrary, during in vitro cultures of Barley, Au NPs supplementation resulted in dark roots, yellow leaves, and decreased biomass (Khana et al. 2019).

12.6 Effect of NPs on Flowers

The flower is a stem bearing leaves that are specialized for sexual reproduction. Many scientists have discussed the effect of NMs on flowers, particularly in terms of increasing their number or their opening speed. Table 12.1 shows the NMs that increased the number of flowers or their opening speed.

12.7 Effect of NPs on Fruits

The researchers used many nanocomposites with different concentrations on different plant species to study their effect on production and increase the yield. Table 12.2 shows the nanocomposites and their concentrations and the extent of the increase in the production of different plant species.

12.8 Conclusion and Prospects

Nanotechnology has excellent potential for multidisciplinary studies in agriculture, including improving the agricultural industry. Despite the research that focuses on realizing the beneficial effects of NPs on plants, it is still incomplete. The effects of NPs differ from one plant to another and is dependent on the technique of production, application, size, shape, and concentrations, according to the data obtained. Also, biological nanocomposites have positive and negative effects that must be studied carefully. For example, soaking seeds into NPs improves germination, growth, and production characteristics. NMs can be exploited to overcome different stresses size, and concentrations of NPs did not show any adverse effects; on the contrary, they showed beneficial currents.

On the other hand, it has been observed that more significant quantities of NPs/NMs are hazardous to plant development, which ultimately depends on particle size. Therefore, in future research, a checkpoint might be established to define the threshold concentration of particular NPs/NMs of a specific size, and the alternative combinations need to be checked. There is a broad scope for green nano-feeding crop plants considering the nanotoxicity effects of NMs/NPs reported. Consequently, green NMs/NPS may be utilized as a source of nutrients for crops and can play an essential part in greener nano feeding for environmental sustainability.

As a future view, promoting the activation of multidisciplinary joint collaborative efforts, combining complementary professional skills such as plant biologists, geneticists, chemists, biochemists, and engineers, may offer new possibilities in phytotechnology. For example, in agriculture, genes have been changed in many plants to improve genetic traits and resistance to diseases and pests. Also, involving

Table 12.1 The effect of different NPs on the flowers of various plants

References	Concentration	Size (nm)	Materials	Effect on plant	Plant species
Marchiol et al. (2016)	500–1000 mg/ kg	25	CeO_2	the reduction in number of spikes/ plant	Barley (*Hordeum vulgare* L.)
Naing et al. (2021)	25 mg/ L	–	Ag	Improvement of flower longevity	Carnation (*Dianthus carphyllus* L.)
Atefepour et al. (2021)	15 mg/ L	20	Ag	shelf-life improved	Gerbera (*Gerbera jamesonii* Bolus ex Hooker f.)
Asgari et al. (2014)	2.5 gr/L	–	Nano-potash (K)	quality improved	Narcissus (*Narcissus tazatta* L.)
Laware and Raskar (2014)	20 –30 mg./mL	18	ZnO	Early flowering	Onion (*Allium cepa* L.)
Prasad et al. (2012)	1000 ppm	25	Zone		Peanut (*Arachis hypogaea* L.)
Reza et al. (2014)	6–12 g	–	Fe, P, and K	Increased Flowers number	Saffron (*Crocus sativus* L.)
Kisan et al. (2015)	500–1000 ppm	50	ZnO	increased leaf length, width, surface area	Spinach (*Spinacia oleracea* L.)
Khodakovskaya et al. (2013)	50–200 μg/mL	10–25	C	Increased number of flowers	Tomato (*Solanum lycopersicom*, L. Mill)

Table 12.2 The effect of different NPs on the fruits of various plants

References	Concentration	Size (nm)	Nanoparticles	Effect on plant	Plant species
Das et al. (2016)	1.6–2.1 mg/g	100–200	FeS_2	Fresh weight (biomass) (g)	Alfalfa (*Medicago sativa* L.)
Kumar et al. (2013)	10 µg/ml	24	Au	Increases yield of fruit/seed	Arabidopsis (*Arabidopsis thaliana* (L.) Heynh)
Salama et al. 2019	30 ppm	–	ZnO	the highest yield of seeds	Bean (*Phaseolus vulgaris* L.)
Das et al. (2016)	1.6–2.1 mg/g	100–200	FeS_2	Increase yield	Beetroot (*Beta vulgaris* L.)
Kole et al. (2013)	–	47.2	$C_{60}(OH)_{20}$	The yield increased by increasing the length, weight and number of fruits	Bitter Melon (*Momordica charantia* L.)
Arora et al. (2012)	10 ppm	300–600	Au	increase in seed yield	Brassica (*Brassica juncea* L.)
Das et al. (2016)	1.6–2.1 mg/g	100–200	FeS_2	Increase yield	Carrot (*Daucus carota* L.)
Mahajan et al. (2011)	1 ppm	20	ZnO	Increased yield	Chickpea (*Cicer arietinum* L.)
Merghany et al. (2019)	6 ml	9.165, 8.254 and 8.205 (N, P and k)	Liquid nano NPK		Cucumber (*Cucumis sativus* L.)
Sabet and Mortazaeinezhad (2018)	0.5–1 g/L	–	Fe–N	Increased yield and weight of 1000 grains	Cumin (*Cuminum cyminum* L.)

(continued)

Table 12.2 (continued)

References	Concentration	Size (nm)	Nanoparticles	Effect on plant	Plant species
Raliya and Tarafdar (2013)	10 ppm	1.2–6.8	ZnO	Increases biomass	Custer bean (*Cyamopsis tetragonoloba* L)
Younes et al. (2019)	0.1, 0.2, and 0.3 g/L	–	Graphene	Increases number of fruits/plant and fruit yield (ton/hectare)	Eggplant, (*Solanum Melongena* L)
Abbas et al. (2021a, b)	0.0015 g/ L	30	ZnO	Increases grain yield and 100-grain weight	Maize (*Zea mays* L.)
Mahajan et al. (2011)	20 ppm	20	ZnO	Increased yield	Mung Bean (*Vigna radiata* L.)
Ibrahim and Al Farttoosi (2019)	0.009 g/L	–	B		
Das et al. (2016)	1.6–2.1 mg/g	100–200	FeS_2	increase in the seed yield	Mustard (*Brassica juncea* (L.) Czern
Rahman et al. (2020)	1 mM	3.2 ± 0.8	Pt	average number of seeds produced per plant increased	Pea (*Pisum sativum* L.)
Tarafdar et al. (2014)	0.1 mM	15–25	Zn	Improved The grain yield	Pearl Millet (*Pennisetum americanum* L.)
Prasad et al. (2012)	0.13 g /L	25	ZnO	Increased pod yield	Peanut (*Arachis hypogaea* L.)
Liu et al. (2005)	0.5 g/L	–	CaCO	The highest yield	
Younes et al. (2019)	0.1, 0.2, and 0.3 g/L	–	Graphene	Increases number of fruits/plant and fruit yield (ton/hectare)	Pepper, (*Capsicum annuum* L.)

(continued)

Table 12.2 (continued)

References	Concentration	Size (nm)	Nanoparticles	Effect on plant	Plant species
Sohrab et al. (2016)	636 mg/ tree and 34 mg /tree respectively	50	Zn and B	Increased number of fruits per tree, and fruit yield	Pomegranate (*Punica Granatum* L.)
Tahmasbi et al. (2011)	0.05 g/L	–	Ag	Produced higher yield	Potato *Solanum tuberosum subsp. andigenum* (Juz. & Bukasov) Hawkes
Mahmoud Abdel Wahab et al. (2019)	60 and 50 ppm, respectively	410	FeO-ZnO	Increase root weight and diameter	Red radish (*Raphanus sativus* L.)
Liu et al (2009)	5 mM	4–10	SiO2	Increased grain weight	Rice (*Oryza sativa* L.)
Anusuya et al. (2019)	0.5% $ZnSO_4$	–	Zn	Increased productivity	
Seleiman et al. (2020)	-	18	ZnO	Increase yield	
Das et al. (2016)	1.6–2.1 mg/g	100–200	FeS_2	Increase in the number of pods and seeds	Sesamum (*Sesamum indicum* L.)
Sheykhbaglou et al. (2010)	0.5 g/L	–	Fe_2O_3	Increased grain yield	Soybean (*Glycine soja Sieb.* Et Zucc.)
Khodakovskaya et al. (2013)	0.05–0.2 g/L	25	C	Improved fruit yield	Tomato (*Solanum lycopersicom*, L. Mill)
Asma et al. (2019)	0.088 mg/L	–	Ag	Increases yield/plant (g),	
Younes and Nassef (2016)	10, 20, 40 ppm	–	Ag	reduced the fruit number per plant, fruit diameter, average fruit weight,	
Razzaq et al. (2016)	25 ppm	10–20	Ag	Increasing grain number /spike and crop yield	Wheat (*Triticum aestivum* L)

(continued)

Table 12.2 (continued)

References	Concentration	Size (nm)	Nanoparticles	Effect on plant	Plant species
Shafaqat et al. (2019)	–	≤50	Si s	Increases the yield and reduce the Cd in the grains	
Behboudi et al. (2018)	30–60 ppm	40 ± 9.5	SiO_2	Increased Final yield	
Rico et al. (2014)	500 mg/kg	8 ± 1 (rod) and 231 ± 16 (particle)	CeO_2	Improved grain yield	
Hafeez et al. (2015)	30 ppm	12- 20	Cu	Increase grain yield	
Bakhtiari et al. (2015)	0.04% w/v	–	Fe_2O_3		

the plant extracts in synthesizing NPs is the safest material for agriculture that remains an open framework with promising results.

References

Abbas HH, Esmat H, Noufal IM et al (2021a) Effect of traditional sources of Zn and ZnO-nanoparticles foliar application on productivity and P-uptake of maize plants grown on sandy and clay loam soils. Env Biodiv Soil Secur 5:59–72. https://doi.org/10.21608/jenvbs.2021.58802.1127

Abbas MS, Akmal M, Khan KS et al (2021b) Zn Ferti-fortification of wheat (*Triticum Aestivum* L.) using Zinc enriched compost and biochar in rainfed area. Commun Soil Sci Plant Anal 30:16

Al-Hadede LT, Khaleel SA, Hasan SK (2020) Some applications of nanotechnology in agriculture. Biochem Cell Arch 20:1447–1454. https://doi.org/10.35124/bca.2020.20.1.1447

Ali S, Mehmood A, Khan N (2021) Uptake, translocation, and consequences of nanomaterials on plant growth and stress adaptation. J Nanomater 2021:1–17. https://doi.org/10.1155/2021/6677616

Ali S, Rizwan M, Hussain A et al (2019) Silicon nanoparticles enhanced the growth and reduced the cadmium accumulation in grains of wheat (*Triticum aestivum L.*). Plant Physiol Biochem 140:1–8

Anusuya N, Ravichandran V, Sritharan N (2019) Influence of zinc sulphate and zinc EDTA on grain zinc, growth and yield parameters, of rice genotypes. Madras Agric J 106:160–164. https://doi.org/10.29321/MAJ2019.000240

Arora NK (2018) Agricultural sustainability and food security. Environ Sustainability 2018:217–219. https://doi.org/10.1007/s42398-018-00032-2

Arora S, Sharma P, Kumar S et al (2012) Gold-nanoparticle induced enhancement in growth and seed yield of *Brassica juncea*. Plant Growth Regul 66:303–310

Asadi-Kavan Z, Khavari-Nejad RA, Iranbakhsh A, Najafi F (2020) Cooperative effects of iron oxide nanoparticle (α-Fe_2O_3) and citrate on germination and oxidative system of evening primrose (*Oenothera biennis* L.). J Plant Interact 15:166–179

Asgari S, Moradi H, Afshari H (2014) Evaluation of some physiological and morphological characteristics of *narcissus tazatta* under BA treatment and nano-potassium fertilizer. J. Chem Health Risks 4:63–70. https://doi.org/10.22034/JCHR.2018.544085

Aslani F, Bagheri S, Julkapli NM et al (2014) (2014) Effects of engineered nanomaterials on plants growth: an overview. Sci World J 3:1–33

Asma N, Crispin H, Mudassar I (2019) Impact of AgNPs on seed germination and seedling growth: a focus study on its antibacterial potential against *Clavibacter michiganensis* subsp. michiganensis Infection in *Solanum lycopersicum*. J Nanomater 2019:1–11. https://doi.org/10.1155/2019/6316094

Atefepour E, Saadatianb M, Asil MH, Rabieic B (2021) Effect of silver nano particles and 8-hydroxyquinoline citrate on the longer life of cut Gerbera (*Gerbera jamesonii*) 'Sunway' flowers. Sci Hortic 289. https://doi.org/10.1016/j.scienta.2021.110474

Bahwirth M, Bamsaoud S (2020) The effect of silver nanoparticles on the germination and growth of two cultivars of wheat *Triticum aestivum* L. Alandalus J Appl Sci 7:9–25

Bakhtiari M, Moaveni P, Sani B (2015) The effect of iron nanoparticles spraying time and concentration on wheat. Biol Forum 7:679–683

Bamsaoud S, Bahwirth M (2017) The effect of biologically synthesized silver nanoparticles on the germination and growth of *Cucurbita pepo* seedlings. J Arab Am Univ 34–3:4

Bamsaoud S, Basuliman M, Bin-Hameed A, et al (2021) The effect of volume and concentration of $AgNO_3$ aqueous solutions on silver nanoparticles synthesized using Ziziphus Spina–Christi leaf extract and their antibacterial activity. J Phys Conf Ser 1900(1):012005. IOP Publishing

Behboudi F, Tahmasebi Sarvestani Z, Kassaee MZ et al (2018) Improving growth and yield of wheat under drought stress via application of SiO_2 nanoparticles. J Agric Sci Technol 20:1479–1492

Bhatia S, Bahri S, Moitra S (2014) SiO_2 nanoparticles: effect on seedling biology. Int J Appl Eng Res 9:935–939

Buono DD, Michele DA, Costantino F et al (2021) Biogenic ZnO nanoparticles synthesized using a novel plant extract: application to enhance physiological and biochemical traits in maize. Nanomaterials 11:1270–1285

Choudhary RC, Kumaraswamy RV, Kumari S et al (2019) Zinc encapsulated chitosan nanoparticle to promote maize crop yield. Int J Biol Macromol 127:126–135. https://doi.org/10.1016/j.ijbiomac.2018.12.274

Das CK, Srivastava G, Dubey A et al (2016) Nano-iron pyrite seed dressing: a sustainable intervention to reduce fertilizer consumption in vegetable (*beetroot, carrot*), spice (*fenugreek*), fodder (*alfalfa*), and oilseed (*mustard, sesamum*) crops. Nanotechnol Environ Eng 1:1–14. https://doi.org/10.1007/s41204-016-0002-7

Deshpande P, Dapkekar A, Oak MD et al (2017) Zinc complexed chitosan/TPP nanoparticles: a promising micronutrient nanocarrier suited for foliar application. Carbohydr Polym 165:394–401

Dhoke SK, Mahajan P, Kamble R, Khanna A (2013) Effect of nanoparticles suspension on the growth of mung (*Vigna radiata*) seedlings by foliar spray method. Nanotechnol Dev 3:e1–e1. https://doi.org/10.4081/nd.2013.e1

Eichert T, Kurtz A, Steiner U, Goldbach HE (2008) Size exclusion limits and lateral heterogeneity of the stomatal foliar uptake pathway for aqueous solutes and water suspended nanoparticles. Physiol Plant 134:151–160

Elemike EE, Uzoh IM, Onwudiwe DC, Babalola OO (2019) The role of nanotechnology in the fortification of plant nutrients and improvement of crop production. Appl Sci 9:499–532. https://doi.org/10.3390/app9030499

Elshayb OM, Nada AM, Ibrahim HM et al (2021) Application of silica nanoparticles for improving growth, yield, and enzymatic antioxidant for the hybrid rice EHR1 growing under water regime conditions. Materials 14:1150–1169. https://doi.org/10.3390/ma14051150

Galaktionova LV, Lebedev SV, Terekhova NA et al (2020) Evaluation of the effect of SiO_2 and Fe_3O_4 nanoparticles on *Pisum sativum* seeds in laboratory and field experiments. bioRxiv. https://doi.org/10.1101/2020.08.31.275859

Hafeez A, Razzaq A, Mahmood T, Jhanzab HM (2015) Potential of copper nanoparticles to increase growth and yield of wheat. J Nanosci Adv Technol 1:6–11. https://doi.org/10.24218/jnat.2015.02

Haytova D (2013) A review of foliar of some vegetables crops. Annu Res Rev Biol 15:455–465

Hossain Z, Yasmeen F, Komatsu S (2020) Nanoparticles: synthesis, morphophysiological effects, and proteomic responses of crop plants. Int J Mol Sci 21:3056–3064. https://doi.org/10.3390/ijms21093056

Ibrahim NK, Al Farttoosi HAK (2019) Response of mung bean to boron nanoparticles and spraying stages (*Vigna radiata* L.). Plant Arch 19:712–715

Itroutwar PD, Govindaraju K, Tamilselvan S et al (2019) Seaweed-based biogenic zno nanoparticles for improving agro-morphological characteristics of rice (*Oryza sativa* L.). J Plant Growth Regul 39:717–728. https://doi.org/10.1007/s00344-019-10012-3

Joshi SM, De Britto S, Jogaiah S (2021) Myco-engineered selenium nanoparticles elicit resistance against tomato late blight disease by regulating differential expression of cellular, biochemical and defense responsive genes. J Biotechnol Jan 325:196–206. https://doi.org/10.1016/j.jbiotec.2020.10.023

Juárez-Maldonado A, Ortega-Ortíz H, Morales-Díaz AB et al (2019) Nanoparticles and nanomaterials as plant biostimulants. Int J Mol Sci 20:1–19. https://doi.org/10.3390/ijms20010162

Kasote DM, Lee JH, Jayaprakasha GK, Patil BS (2019) Seed priming with iron oxide nanoparticles modulate antioxidant potential and defense-linked hormones in watermelon seedlings. ACS Sustain Chem Eng 7:5142–5151

Kerry RG, Gouda S, Das G et al (2017) Agricultural nanotechnologies: current applications and future prospects. In: *Microbial biotechnology*. Springer, Singapore. pp 3–28

Khan I, Raza MA, Awan SA et al (2020) Amelioration of salt induced toxicity in *Pearl millet* by seed priming with silver nanoparticles (AgNPs): the oxidative damage, antioxidant enzymes and ions uptake are major determinants of salt tolerant capacity. Plant Physiol Biochem 156:221–232. https://doi.org/10.1016/j.plaphy.2020.09.018

Khan I, Awan SA, Raza MA et al (2021) Silver nanoparticles improved the plant growth and reduced the sodium and chlorine accumulation in *pearl millet*: A life cycle study. Environ Sci Pollut Res Int 28:13712–13724. https://doi.org/10.1007/s11356-020-11612-3

Khana MA, Khanb T, Mashwanic ZR et al (2019) Plant cell nanomaterials interaction: growth, physiology and secondary metabolism. Compr Anal Chem 84: 32–54. Elsevier, Amsterdam. https://doi.org/10.1016/bs.coac.2019.04.005

Khodakovskaya MV, Kim B, Kim JN et al (2013) Carbon nanotubes as plant growth regulators, effects on tomato growth, reproductive system, and soil microbial community. Small 9:115–123. https://doi.org/10.1002/smll.201201225

Kisan B, Shruthi H, Sharanagouda H et al (2015) Effect of nano-zinc oxide on the leaf physical and nutritional quality of spinach. Agrotechnol 5:135–138

Kole C, Kole P, Km R et al (2013) Nanobiotechnology can boost crop production and quality: first evidence from increased plant biomass, fruit yield and phytomedicine content in bitter melon (*Momordica charantia*). BMC Biotechnol 13:37–51. https://doi.org/10.1186/1472-6750-13-37

Kumar V, Guleria P, Kumar V, Yadav SK (2013) Gold nanoparticle exposure induces growth and yield enhancement in *Arabidopsis thaliana.* Sci Total Environ 461:462–468. https://doi.org/10.1016/j.scitotenv.2013.05.018

Laware SL, Raskar S (2014) Influence of zinc oxide nanoparticles on growth, flowering and seed productivity in onion. Int J Curr Microbiol Appl Sci 3:874–881

Liu C, Li F, Luo C et al (2009) Foliar application of two silica sols reduced cadmium accumulation in rice grains. J Hazard Mater 161:1466–1472

Liu X, Zhang F, Zhang S et al (2005) Responses of peanut to nano-calcium carbonate. J Plant Nutr Fert (china) 11:385–389

Mahajan P, Dhoke SK, Khanna AS (2011) Effect of nano-ZnO particle suspension on growth of mung (*Vigna radiata*) and gram (*Cicerarietinum*) seedlings using plant agar method. J Nanotechnol 696535.https://doi.org/10.1155/2011/696535

Mahmoud Abdel Wahab M, Abdelaziz SM, El-Mogy MM, Abdeldaym EA (2019) Effect of foliar Zno and Feo nanoparticles application on growth and nutritional quality of red radish and assessment of their accumulation on human health. Agriculture (poľnohospodárstvo) 65(1):16–29. https://doi.org/10.2478/agri-2019-0002

Marchiol L, Mattiello A, Pošćić F et al (2016) Changes in physiological and agronomical parameters of Barley (*Hordeum vulgare*) exposed to cerium and titanium dioxide nanoparticles. Int J Environ Res Public Health 13:332–350

Maswada HF, Djanaguiraman M, Prasad PV (2018) Seed treatment with nano-iron (III) oxide enhances germination, seeding growth and salinity tolerance of sorghum. J Agron Crop Sci 204:577–587. https://doi.org/10.1111/jac.12280

Merghany MM, Shahein MM et al (2019) Effect of nano-fertilizers on cucumber plant growth, fruit yield and it' s quality. Plant Arch 19:165–172

Mutlu F, Yurekli F, Mutlu B et al (2018) Assessment of phytotoxic and genotoxic effects of anatase TiO_2 nanoparticles on maize cultivar by using RAPD analysis. Fresenius Environ Bull 27:436–445

Naing AH, Adedeji OS, Kim CK (2021) Protoplast technology in ornamental plants: current progress and potential applications on genetic improvement. Sci Hortic 283:110043

Nejatzadeh F (2021) Effect of silver nanoparticles on salt tolerance of *Satureja hortensis* l. during in vitro and in vivo germination tests. Heliyon. 7:e05981

Omar RA, Afreen S, Talreja N et al (2019) Impact of nanomaterials in plant systems. In: Prasad R (ed) Plant nanobionics, nanotechnology in the life sciences. Springer Nature, Switzerland, pp 117–135. https://doi.org/10.1007/978-3-030-12496-0_6

Patil SM, Kumari VC, Sumana K, Sujay S, Tejaswini M, Shirahatti PS, Ramu R (2021) Sustainable development of plant tissue culture industry: the Indian scenario. J Appl Biol Biotechnol 9(2):1–7

Pérez-de-Luque A (2017) Interaction of nanomaterials with plants: what do we need for real applications in agriculture? Front Environ Sci 5:12. https://doi.org/10.3389/fenvs.2017.00012

Prasad R, Bhattacharyya A, Nguyen QD (2017) Nanotechnology in sustainable agriculture: recent developments, challenges, and perspectives. Front Microbiol 8:1014. https://doi.org/10.3389/fmicb.2017.01014

Prasad TNV, Sudhakar KVP, Sreenivasulu Y et al (2012) Effect of nanoscale zinc oxide particles on the germination, growth and yield of peanut. J Plant Nutr 35:905–927. https://doi.org/10.1080/01904167.2012.663443

Predoi D, Ghita RV, Iconaru SL et al (2020) Application of nanotechnology solutions in plants fertilization. In: Urban horticulture—necessity of the future. IntechOpen, London, pp 51–74. https://doi.org/10.5772/intechopen.91240

Rahman MS, Chakraborty A, Mazumdar S et al (2020) Effects of poly (vinylpyrrolidone) protected platinum nanoparticles on seed germination and growth performance of *Pisum sativum*. Nano-Struct Nano-Objects 21:100408. https://doi.org/10.1016/j.nanoso.2019.100408

Raj NP, Chandrashekara CP (2019) Nano zinc seed treatment and foliar application on growth, yield and economics of Bt cotton (*Gossypium hirsutum* L.). Int J Curr Microbiol Appl Sci 8:1624–1630. https://doi.org/10.20546/ijcmas.2019.808.192

Raliya R, Tarafdar JC (2013) ZnO nanoparticle biosynthesis and itseffect on phosphorous-mobilizing enzyme secretion and gum contents in cluster bean (*Cyamopsis tetragonoloba* L.). Agric Res 2:48–57. https://doi.org/10.1007/s40003-012-0049-z

Ramesh R, Catherine G, Sundaram SJ et al (2021) Synthesis of Mn_3O_4 nano complex using aqueous extract of *Helianthus annuus* seed cake and its effect on biological growth of Vigna radiata. Mater Today Proc 36:184–191. https://doi.org/10.1016/j.matpr.2020.02.883

Razzaq A, Ammara R, Jhanzab HM et al (2016) A novel nanomaterial to enhance growth and yield of wheat. J Nanosci Technol 2:55–58

Remedios C, Rosario F, Bastos V (2012) Environmental nanoparticles interactions with plants: morphological, physiological, and genotoxic aspects. J Bot 2012:1–8. https://doi.org/10.1155/2012/751686

Reza A, Mahdi B, Mahdi T (2014) Effects of nano fertilizer application and maternal corm weight on flowering of some saffron (*Crocus sativus* L.) Ecotypes Turk J Field Crops 19:158–168. https://doi.org/10.17557/tjfc.46269

Rico CM, Lee SC, Rubenecia R et al (2014) Cerium oxide nanoparticles impact yield and modify nutritional parameters in wheat (*Triticum aestivum* L.). J Agric Food Chem 62:9669–9675. https://doi.org/10.1021/jf503526r

Sabet H, Mortazaeinezhad F (2018) Yield, growth and Fe uptake of cumin (*Cuminum cyminum* L.) affected by Fe-nano, Fe-chelated and Fe-siderophore fertilization in the calcareous soils. J Trace Elem Med Biol 50:154–160. https://doi.org/10.1016/j.jtemb.2018.06.020

Saedpanah P, Mohammadi K, Fayaz F (2016) Agronomic traits of forage maize (*Zea mays* L.) in response to spraying of nanofertilizers, ascorbic and salicylic acid. J Res Ecol 4(2):359–365

Salama Dina M, Osman SA, Abd El-Aziz ME, Abd MSA, Elwahed EAS (2019) Effect of zinc oxide nanoparticles on the growth, genomic DNA, production and the quality of common dry bean (*Phaseolus vulgaris*). Biocatal Agric Biotechnol 18. https://doi.org/10.1016/j.bcab.2019.101083

Sanborn JR, Chen X, Yao YC et al (2018) Carbon nanotube porins in amphiphilic block copolymers as fully synthetic mimics of biological membranes. Adv Mater 30:1803355. https://doi.org/10.1002/adma.201803355

Santos ESD, Graciano DAE, Falco WF et al (2021) Effects of copper oxide nanoparticles on germination of *Sesbania virgata* (FABACEAE) plants. An Acad Bras Cienc 93: e20190739 1–e20190739 14 https://doi.org/10.1590/0001-3765202120190739

Seleiman MF, Alotaibi M, Alhammad BA et al (2020) 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 10:1–21. https://doi.org/10.3390/agronomy10060790

Shafaqat A, Muhammad R, Afzal H et al (2019) Silicon nanoparticles enhanced the growth and reduced the cadmium accumulation in grains of wheat (*Triticum aestivum* L.) Plant Physiol Biochem140:1–8 https://doi.org/10.1016/j.plaphy.2019.04.041

Shafiq I, Hussain S, Raza MA et al (2021) Crop photosynthetic response to light quality and light intensity. J Integr Agric 20:4–23. https://doi.org/10.1016/S2095-3119(20)63227-0

Shang Y, Hasan K, Ahammed GJ (2019) Applications of nanotechnology in plant growth and crop protection: a review. Molecules 24:2558. https://doi.org/10.3390/molecules24142558

Sharifi R, Mohammadi K, Rokhzadi A (2016) Effect of seed priming and foliar application with micronutrients on quality of forage corn 68 (*Zea mays* L.). Environ Exp Biol 14:151–156. https://doi.org/10.22364/eeb.14.21

Sheykhbaglou R, Sedghi M, Shishevan MT, Sharifi RS (2010) Effects of nano-iron oxide particles on agronomic traits of soybean. Not Sci Biol 2:112–113. https://doi.org/10.15835/nsb224667

Shinde S, Paralikar P, Ingle AP, Rai M (2020) Promotion of seed germination and seedling growth of *Zea mays* by magnesium hydroxide nanoparticles synthesized by the filtrate from Aspergillus niger. Arab J Chem 13:3172–3182. https://doi.org/10.1016/j.arabjc.2018.10.001

Siddiqui H, Ahmed KBM, Sami F, Hayat S (2020) Silicon nanoparticles and plants: current knowledge and future perspectives. In: Hayat S et al (eds) *Sustainable agriculture reviews 41*. Springer Nature, Switzerland pp 129–142. https://doi.org/10.1007/978-3-030-33996-8_7

Singh A, Singh NB, Hussaina I et al (2015) Plant-nanoparticle interaction: an approach to improve agricultural practices and plant productivity. Int J Pharm Sci Invent 4:25–40

Sohrab D, Ali Gholamhossein T et al (2016) Effects of foliar applications of zinc and boron nanofertilizers on pomegranate (*Punica granatum* cv. Ardestani) fruit yield and quality. Sci Hortic 210:57–64. https://doi.org/10.1016/j.scienta.2016.07.003

Tahmasbi D, Zarghami R, Azghandi AV, Chaichi M (2011) Effects of nanosilver and nitroxin biofertilizer on yield and yield components of potato mini tubers. Int J Agric Biol 13:986–990

Tarafdar JC, Raliya R, Mahawar H, Rathore I (2014) Development of zinc nanofertilizer to enhance crop production in pearl millet (*Pennisetum americanum*). Agric Res 3:257–262. https://doi.org/10.1007/s40003-014-0113-y

Tovar GI, Briceño S, Suarez J et al (2020) Biogenic synthesis of iron oxide nanoparticles using *Moringa oleifera* and chitosan and its evaluation on corn germination. Environ Nanotechnol Monit Manag 14:100350. https://doi.org/10.1016/j.enmm.2020.100350

Usman M, Farooq M, Wakeel A et al (2020) Nanotechnology in agriculture: current status, challenges and future opportunities. Sci Total Environ 721:137778. https://doi.org/10.1016/j.scitotenv.2020.137778

Uzu G, Sobanska S, Sarret G et al (2010) Foliar lead uptake by lettuce exposed to atmospheric fallouts. Environ Sci Technol 44:1036–1042. https://doi.org/10.1021/es902190u

Velasco EAP, Galindo RB, Aguilar LAV et al (2020) Effects of the morphology, surface modification and application methods of ZNO-NPS on the growth and biomass of tomato plants. Molecules 25:1282. https://doi.org/10.3390/molecules25061282

Yan A, Chen Z (2019) Impacts of silver nanoparticles on plants: a focus on the phytotoxicity and underlying mechanism. Int J Mol Sci 20:1003. https://doi.org/10.3390/ijms20051003

Younes NA, Dawood MFA, Wardany AA (2019) Biosafety assessment of graphene nanosheets on leaf ultrastructure, physiological and yield traits of *Capsicum annuum* L. and *Solanum melongena* L. Chemosphere 228:318–327. https://doi.org/10.1016/j.chemosphere.2019.04.097

Younes NA, Nassef DMT (2016) Effect of silver nanoparticles on salt tolerancy of tomato transplants (*Solanum lycopersicom*, L. Mill.). Assiut J Agric Sci 46:76–85