Review Article

A DETAILED ANALYSIS OF THE CONSEQUENCES OF VARIOUS NANOPARTICLES ON GROWTH, DEVELOPMENT, AND PHYSIOLOGICAL RESPONSES IN PLANTS UNDER CHANGING ENVIRONMENTS

ABSTRACT:

Enhancing plant nutrition without changing soil texture and protecting it from microbial diseases, nano-fertilizers, nano-pesticides, and nano-herbicides are some examples of how nanotechnology is being used in agriculture. So, nanotechnology keeps the soil healthy, which in turn keeps the plant healthy. Nanoparticles (NPs) increase agricultural productivity and production while decreasing chemical runoff and nutrient loss. Concentrations, physiochemical characteristics, and plant species all have a role in how NPs affect plants. There are a number of NPs that affect plant physiology, which in turn increases biomass production and germination rate. By influencing gene expression, NPs also modify the molecular pathways in plants. Ag, Au, ZnO, Fe2O3, TiO2, SiO2, Al2O3, Se, carbon nanotubes, quantum dots, and non-metal oxides of NPs (NPs) play a crucial role in stress amelioration and plant development and growth.

Meanwhile, the function of NPs in growth suppression, inhibition of chlorophyll, and photosynthetic efficiency has been extensively studied. We aimed to summarize research that has investigated NP effects, translocation, and interactions with plants in order to fill this review. Also discussed are methods for phytoremediation of polluted soil that make use of NPs in conjunction with one another to promote environmentally responsible farming.

Keywords: gene expression, nanotechnology, photosynthetic efficiency, phytoremediation, quantum dots

1. INTRODUCTION:

During the techno-science period, nanotechnology was at the forefront of innovation, drawing interest from many fields and industries that are directly related to human well-being, such as plant and agricultural sciences, energy, materials science, nanomedicine, and environmental science. The most effective strategy to revamp contemporary farming methods is the controlled synthesis of current nano-materials—a process that is simple, safe, and economically viable (Rai et al., 2018). Precision agriculture is the latest innovation in modern farming, made possible by state-of-the-art nanomaterials that may be found in nature in plants and soil. Natural resource depletion, pest disease outbreaks, and changing weather patterns are only a few of the major threats to agricultural output (Kah et al., 2019; Lowry et al., 2019; De La Torre-Roche et al., 2020).

Food and Agriculture Organization projections put the global population at 9–10 billion by 2050, meaning food production has to increase by 25–70% from where it is now (Scott et al., 2018). Therefore, new technology must be used in the agricultural sector to guarantee sustainability and production in order to feed the growing population. By introducing a nano-based smart delivery system that revamps agriculture and associated industries, nanotechnology might play a role in the new technology-based agricultural revolution (Lowry et al., 2019; Camara et al., 2019; Shakiba et al., 2020; Batsmanova et al., 2013). According to what is known, NPs of different sizes, shapes, and kinds may improve stance varieties, pesticide Nano formulation, plant disease diagnostics, and more (Hao et al., 2016).

A plethora of NPs with ever-improving capabilities and applications are unveiled annually. The biological responses to NPs are determined by their physicochemical features, which include their size, zeta potential, and concentration (Pérez-de-Luque, 2017; Acharya et al., 2019).. The plant productivity could be improved with the help of NPs because of their many potential uses, including as germination enhancers, in the creation of nanofertilizers, as herbicide delivery systems, as nanosensors for pest detection, and as nanoporous zeolites for slow release and efficient water and fertilizer dosage (Scrinis and Lyons, 2007; Scott, 2007). However, some NPs exhibit phytotoxic effects, meaning they hinder seed germination or are toxic to seedlings (Rajput et al., 2018; Falco et al., 2020; Hayes et al., 2020).

Leaching, hydrolysis, degradation by photolysis, and decomposition make certain fertilizers inaccessible to plants, despite the fact that they are an essential source for plant growth and development. Nanopesticides and nanofertilizers are only two examples of the many novel NP solutions developed in recent years with the goal of lowering food waste and raising crop yields (Kah et al., 2019; Camara et al., 2019; Zhao et al., 2020).

Nanofertilizers and nano encapsulated nutrients control the release of chemical fertilizers that enhance the target plant activity (DeRosa et al., 2010; Nair et al., 2010). Multiple NPs are being evaluated for their ability to protect plants from different environmental stresses and to support plant growth (Rajput et al., 2021). In plant biotechnology, this field of study opens up new possibilities for influencing gene expression as well as cellular and cellular organelle properties. In addition to their many uses in agriculture and environmental remediation, NPs have a wide range of biosensor applications (Khan et al., 2019).

Despite their usefulness in agriculture, NPs have been shown to cause phytotoxicity and serious environmental problems. Anthropogenic activities release them into the environment, where they enter the food chain and produce biomagnification (Rizwan et al., 2017). Nanoparticles (NPs) have a significant impact on plant uptake and translocation due to their size, concentration, types, toxicity, surface charge, pore sizes, reactivity, and other properties (Palocci et al., 2017; Hu et al., 2020). There is a potential for NPs to alter their characteristics, reactivity, and bioavailability to live organisms when they penetrate treated surfaces (Singh et al., 2021 a). The purpose of this review is to provide a balanced account of the pros and cons of using nanoscale materials in farming.

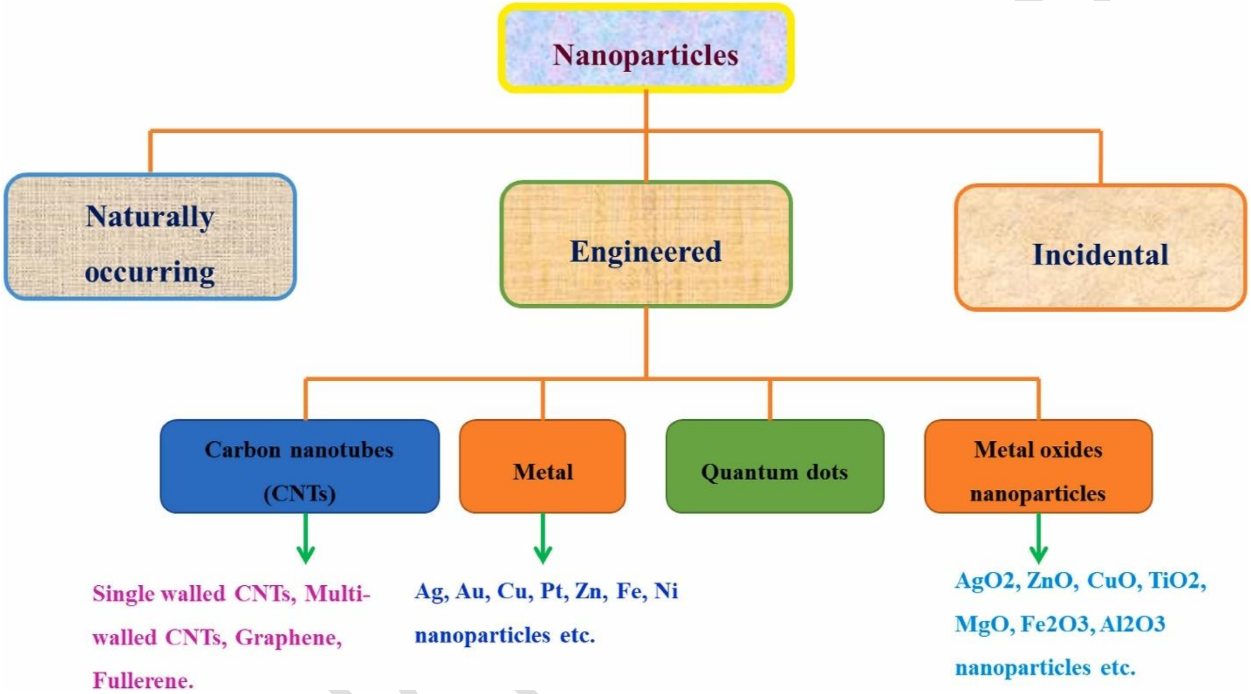

Figure 1. Nanoparticles and their types

2. PLANT ABSORPTION OF NANOPARTICLES

In order to prevent the entrance of any foreign material, including NPs, the cell walls of plants include a variety of functional groups, including as carboxylate, hydroxyl, phosphate, and many more. These groups combine to form biomolecules, such as protein, polysaccharides, and cellulose (Vinopal et al., 2007). The plant species is the primary determinant of NP uptake and translocation. Therefore, NPs enter plants by a process involving the whole system, including roots, stems, and leaves, which interact with soil, water, and other environmental variables. Additionally, NPs in soil may cause root system interactions that result in cellular absorption (Rico et al., 2011a; Tripathi et al., 2017a, b). Only NPs with a diameter similar to that of the cell wall may pass through its sieving capabilities and reach the plasma membrane. The cell wall diameter ranges from 5 to 20 nm. Following a complicated chain reaction, the NPs cross the root cell membrane, enter the plant's vascular system, and eventually make their way to the leaves (Tripathi et al., 2017 c). Nanoparticles (NPs) of a certain size may diffuse across lipid bilayers and enter cells by endocytosis via pore creation, binding to ion channels and aquaporins, and so on (Schmidt, 2015).

There are two pathways that NPs may take after they enter a plant cell: the apoplastic and the symplastic transport systems **(Figure 2)**. The size of the pore determines how NPs enter the cell wall; hence, smaller NPs move more freely (Fleischer et al., 1999), but bigger particles pass via stomata, hydathodes, and the stigma of the flower (Hossain et al., 2016). Although there are many stomata that can open and close, only a small fraction of them really can. Nanoparticles (NPs) larger than 40 nm are able to cross the plant's stomata and hydathodes on their way to the surface of the leaf, where they translocate via the leaf phloem and palisade parenchyma (Tripathi et al., 2017c). The seed coat has parenchymatous intercellular gaps that the NPs may penetrate (Lee et al., 2010). On the other hand, aquaporins have a role in controlling NP entrance in the seed coat by reassembling the AQP-1 and Galphai-3 regulatory complex (Abu-Hamdah et al., 2004).

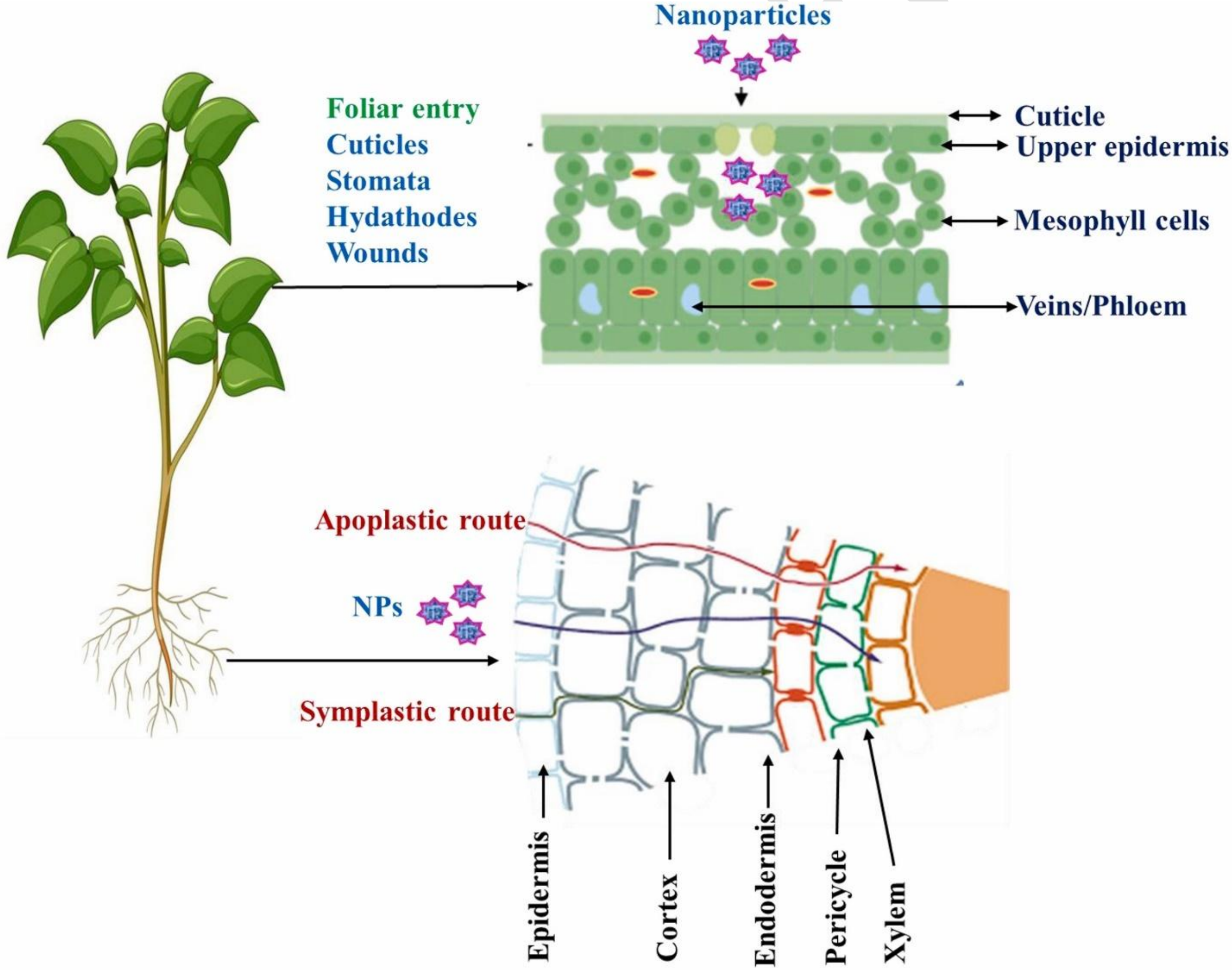

Figure 2. An organized display of NPs absorption and translocation into various plant tissues via apoplastic and symplastic pathways, respectively, according to the plant's entrance point (leaves and roots).

3. NANOPARTICLES INFLUENCE ON PLANTS

Figure 3 explains how NPs change plant shape by interfering with plant metabolism via several pathways, providing micronutrients, and regulating genes. Many different types of pathogens may infect crops, causing illnesses and reducing crop yields and economic output. The non-phytotoxicity, wide availability, and low cost of NPs make them useful in many agricultural contexts. Numerous plant species benefit from the application of NPs at pre-optimized rates, which enhance seed germination, stand establishment, growth, and yield production. Plants build defence mechanisms by regulating molecular, biochemical, and physiological pathways in response to the many stresses they encounter during their life cycle. Plants address these challenges by adjusting gene expression in specific ways, which they call molecular pathways. Table 1 shows the results of many research that show the impact of NPs on plant growth and development is concentration dependent. NPs increase the activity of antioxidant enzymes such as peroxidase (POD), superoxide dismutase (SOD), and catalase (CAT) (Das & Das, 2019).

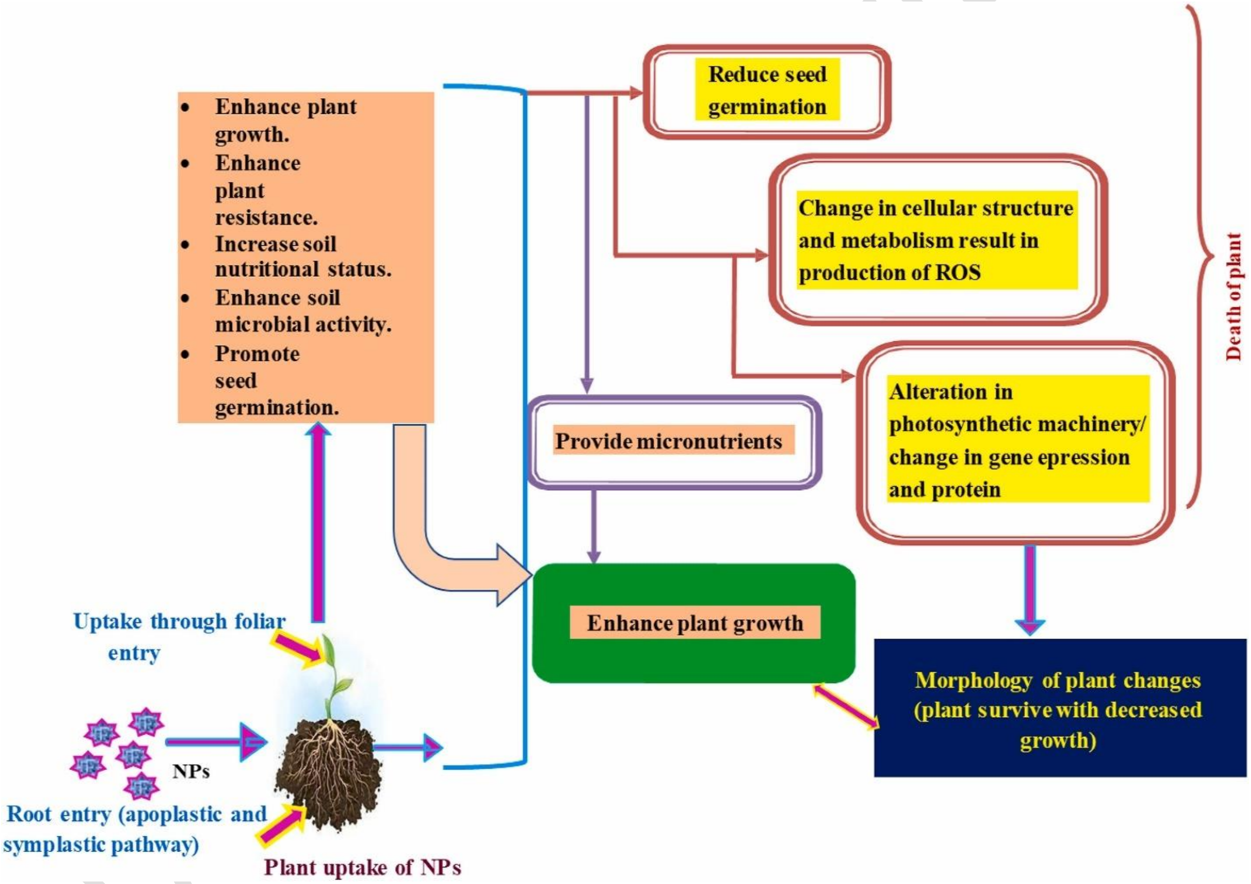

Figure 3. There are a number of ways in which NPs might interact with plant metabolism or disrupt various oxidative processes in plants.

4. IMPACT OF DIFFERENT NPS ON THE PHYSIOLOGICAL PROCESSES INVOLVED IN PLANT DEVELOPMENT, GROWTH, AND MATURATION

4.1. COPPER NANOPARTICLES

Various plant species were shown to have their germination, biomass, shoot development, and other processes significantly impacted by CuO NP exposure (Lee et al., 2008b; Adhikari et al., 2012b; Rajput et al., 2017). There was no effect on seed germination caused by CuO NP toxicity in maize plants.

The NPs were translocated to the shoots by xylem and then returned to the roots via phloem (Wang et al., 2012). According to Rahmani et al. (2016), seedlings of B. napus were grown in MS media with CuO NPs (0, 10, 100, and 1000 mg L−1) for 10 days. The highest dosage of 10 mg L−1 resulted in an induction of growth, whereas higher concentrations (100 and 1000 mg L−1) resulted in a reduction in root dry weight and shoot elongation.

The release of Cu2+ in the culture medium hindered the development of Lemna minor at lower concentrations compared to higher concentrations of CuO (Song et al., 2016). The effect on the Mentha longifoila plant was a 45-48.4% rise in height and growth, a 29.4-33.9% increase in internodes, a 55.6-26.2% increase in shoots, and a 30-40% increase in reproduction coefficient when a colloidal solution of CuNP (0.5 mg L−1) and CoNP (0.8 mg L−1) and MS media were applied to the plant (Talankova-Sereda et al., 2016). Copper nanoparticles, which are biosynthesized from tea extract, had positive impacts on the development of seedlings and nitric oxide signalling when exposed to Lactuca sativa at a concentration of 20 µg mL−1 or less (Pelegrino et al., 2020).

4.2. IRON OXIDE NANOPARTICLES

When applied to plants, iron oxide (Fe2O3) NPs significantly improve their development, stress tolerance, and nutritional status. In a study conducted by Yasmeen et al. (2015), it was found that soaking wheat (T. aestivum) in distilled water and then incubating it in a solution containing iron nanoparticles improved the germination percentage. However, when the roots were soaked in distilled water without the NPs, root growth was reduced, but when the roots were soaked in distilled water with the NPs suspension, root growth was enhanced. At concentrations of 3 and 25 mg L−1, the physiology of A. thaliana was impacted by both the positive and negative charged ions of iron oxide. The seedling and root length were unaffected by a dose of 3 mg L−1, but they were severely decreased at 25 mg L−1 (Bombin et al., 2015).

Iron oxide and chelated iron EDTA treatments of Acinetobacter hypogaea increase peanut plant biomass, germination, and growth via increasing enzyme antioxidant activities and phytohormone levels. According to Rui et al. (2016), applying Fe2O3 to plants increased their availability of iron, and the author even advised using it as a fertilizer. Root elongation in L. sativa seedlings was found to be improved by 12-26% when exposed to Fe2O3 NP (5-20 ppm), as reported by Liu et al. (2016). A study conducted that when Fe3O4 was accumulated in Hordeum vulgare, plant growth and photosynthetic efficiency were both improved (Tombuloglu et al., 2019).

4.3. SILVER NANOPARTICLES

The antibacterial properties of silver (Ag) have led to its increased exposure to both plants and people as a result of its widespread usage in industry and medicine. Ag NPs have many beneficial effects on plant growth and development, and their use in agriculture has shown encouraging results (Almutairi, 2016). Overuse of silver nanoparticles boosted the production and activity of antioxidants such as proline and carotenoids, as well as peroxidases and catalases. Also, it decreased the root length of V. radiata and Sorghum bicolor and improved seed germination and development in Lolium multiflorum and Eruca sativa at higher doses (Krishnaraj et al., 2012; Vannini et al., 2013). Separately, Iqbal et al. (2019) revealed that Ag NPs alleviated heat stress symptoms in T. aestivum. Plants treated with Ag NPs had improvements in many biochemical parameters, including leaf area, root and shoot length, carbohydrate and protein contents, and activity of antioxidant enzymes. These plants were B. juncea, maize, and common bean (Salama, 2012).

4.4. CARBON NANOTUBES

The diagnostic, biomedical, and agricultural communities are showing increasing interest in carbon nanotubes (CNTs) due to their diverse physiochemical characteristics. Carbon nanotubes (CNTs) have unique physicochemical characteristics that make them excellent plant growth regulators, water-absorbing agents, and nutritional supplementers (Mathew et al., 2020). In light of this, there are a number of scientific applications for carbon-containing NPs, such as SWCNTs, MWCNTs, and C60. SWCNTs enhance water intake and accelerate germination rate in rice seedlings via modulating gene expression (Zhang et al., 2017).

CNTs, in comparison to a control group, increased the rate of germination and development of tomato seedlings (Solanum lycopersicum) and helped them absorb water via piercing their protective outer layer (Khodakovskaya et al., 2009). B. juncea may be effectively treated with multi-walled carbon nanotubes (~30 nm) using a reduced concentration of oxidized MWCNT (Mondal et al., 2011). MWCNTs hasten the germination of seeds in G. max and H. vulgare without negatively impacting the plants' subsequent development (Lahiani et al., 2013). Additionally, compared to control seeds, treated seeds showed an increase in genes encoding water channel protein. Water delivery in Z. mays plants was enhanced by using a lower concentration of MWCNTs (Tiwari et al., 2014).

According to other researchers (Mondal et al., 2011; Tripathi et al., 2011f), the same outcomes have been shown for B. napus and C. arietinum plants. In addition, under NaCl challenged circumstances, MWCNTs were shown to improve aquaporin transduction by altering the lipid content, stiffness, and permeability of the root plasma membrane (Martinez-Ballesta et al., 2020).

5. THE STRUCTURE AND FUNCTION OF PLANTS' PHOTOSYNTHETIC SYSTEM ARE AFFECTED BY NANOPARTICLES

The process of converting solar energy into chemical energy is carried out by both plants and algae. Just 2-4% of the energy is transformed by plants throughout their life cycle (Kirschbaum, 2011). Plants play a crucial role in the oxygen cycle, translocate minerals and other vital nutrients to other parts of the food web, and carry out photosynthetic activities. Plants may take in both necessary and non-essential nutrients, but there is a threshold concentration beyond which they become poisonous (Ke et al., 2007). Scientists are able to enhance plants' photosynthetic apparatus and efficiency via gene editing and the use of nanotechnology. Translocation of NPs and the acceleration of plant biotechnology are both impacted by the inevitable interaction between plants and NPs.

Toxic NPs, such as CuO and Ag, disrupt photosynthetic apparatus structure and function. Reduced photosynthetic pigment concentration (especially chlorophyll), grana disruption, and other chloroplast abnormalities are all effects of the NPs. Photosynthesis and photosystem II are both made less efficient by NPs. Despite the fact that NPs of CeO2 and TiO2 enhanced electron transport between PS II and I and Rubisco activity, they did not eliminate all negative effects (Tighe-Neira et al., 2018). The use of SWCNTs tripled the photosynthetic activity and electron transport rate in chloroplasts. Increased photosynthetic carbon absorption is facilitated by nano TiO2 induced carboxylation via Rubisco activation (Gao et al., 2006). SiO2 NPs accelerated photosynthesis via changing the activity of carbonic anhydrase and photosynthetic pigments (Xie et al., 2012; Siddiqui and Al-Whaibi, 2014c). **Table 1** displays the impact of several NPs on the photosynthetic apparatus organization.

NPs	**Plants Species**	**Concentration**	**Effect**	**References**
CuO	*Lemna gibba*	1.1–0.4 g L^{-1}	Photosynthetic pigment reduces.	(Perreault et al., 2010a)
	Elodea densa	1 mg L^{-1}	Broken thylakoid membrane and chloroplast water oxidizing complex.	(Nekrasova et al., 2011)
	Elsholtzia splendens	100 mg L^{-1}	Fewer photosynthetic pigments.	(Shi et al., 2014)
	Oryza sativa	10 mg L^{-1}	Reduced photosynthetic pigments and thylakoid quantity per granum.	(Da Costa and Sharma, 2016)
Ag, NP	*Chlamydomonas reinhardtii*	2 μM	Reduced electron transit and increased QB non-reducing centers.	(Matorin et al., 2013)
	Skeletonemacostatum	5 mg L^{-1}	Photosynthesis inhibition and chl a reduction.	(Huang et al., 2016)
	Spirodelapolyrhiza	25 mg L^{-1}	Plastoquinone and chl a fluorescence decrease.	(Shabnam et al., 2016)
	Wolffia globosa	10 mg L^{-1}	Reductions in chlorophyll a (chl a) of 77.7 percent, carotenoids of 66.2 percent, and soluble proteins of 72.9 percent were observed.	(Zou et al., 2016)
TiO_2	*Spinacia oleracea*	0.25%	Total chlorophyll increased.	(Yang et al., 2007c)
	Chlorella sp	1 mg L^{-1}	Less chlorophyll and changes to the chloroplast, plasma membrane, and nucleus.	(Iswarya et al., 2015)
CeO_2	*Zea mays*	400 mg kg^{-1}	Chlorophyll *a* content become reduced	(Zhao et al., 2015c)
	Solanum lycopersicum	250 mg kg^{-1}	Chlorophyll a and b content increase.	(Barrios et al., 2016)
	Phaseolus vulgaris	250 mg kg^{-1}	Decrease content of chlorophyll and carotenoid.	(Majumdar et al., 2016)
ZnS	*Brassica juncea*	25 mg kg^{-1}	Decline the presence of Chlorophyll *a and b* content.	(Nayan et al., 2016)

6. NANOPARTICLES AND DEFENSE MECHANISM

It has been shown that NP exposure may trigger oxidative damage, ROS generation, and antioxidant defense system activation (Rico et al., 2015). Enzymatic antioxidants like glutathione reductase (GR), glutathione, ascorbate, thiols, and phenolics are part of the antioxidant defense, along with enzymatic antioxidants like APOX, CAT, SOD, GPOX, and GR (Rico et al., 2015b; Singh and Lee, 2016d; Kaur et al., 2019). Superoxide dismutase (SOD) catalyses the conversion of superoxide ions into hydrogen peroxide, whereas peroxy radicals and reactive oxygen species (ROS) are stifled by CAT and GPOX, respectively (Rico et al., 2015). Direct reduction of H2O2 into H2O occurs during the formation of ROS by NPs via APOX (Rico et al., 2015; Mittler, 2016).To combat the oxidative stress caused by NPs, Wei and Wang (2013) examined the plants that showed promise as anti-oxidants. The anti-oxidant enzyme capabilities of several NPs have been studied by Tripathi et al. (2017c). For example, nFe2O4, nCeO2, and nCo3O4 stimulate catalase, nFe3O4, nCeO2, nMnO2, nCuO, and nAu promote GPOX, and nCeO2 and fullerene produce SOD.

Although many nanophytotoxicity studies have shown that plants exposed to NPs have enzyme activity disturbances, no evidence has been found to link these disturbances to the chemical properties of NPs or to prove that the enzyme interactions with the NPs were the cause of these changes. Indeed, research revealed that NPs had varying impacts on enzyme activity. While nTiO2 increased the activities of GPOX, SOD, and CAT in Lemna minor (Song et al., 2012) and SOD, CAT, APOX, and CAT in spinach (Lei et al., 2008), it lowered the activities of GR and APOX in Vicia faba (Foltete et al., 2011). Because of this, it is not easy to determine which NPs have an effect on particular enzymes.

7. CONCLUSION

Nanotechnology is a relatively new method that has found applications in several scientific disciplines. Nanoparticles (NPs) are a potential new material for food security and cutting-edge farming techniques. Incorporating NPs into farming practices boosts the world economy in several ways. Toxic effects of NPs are not yet understood because of a lack of adequate information, while NPs-plant interaction is sensitive to NP size and may have both beneficial and detrimental effects. Their effects may change depending on the plant's development stage, exposure duration, uptake rate, and physiochemical characteristics. In comparison to more conventional resources, the advent of NPs has increased efficacy and agronomic efficiency. When it comes to detecting diseases on-site, the interactions between plants and NPs provide genuine promise for achieving sustainable agriculture. There has been research into the potential of nano-based formulations, including as herbicides, insecticides, fertilizers, fungicides, and sensors, for improved plant management and controlled release to safeguard the environment. However, environmental contamination is a major worry due to the growing usage of NPs in agriculture and related industries, thus proactive steps should be made to prevent their accumulation. Food security is a major concern for agricultural scientists due to the increasing human population. Not only will the nano revolution help with food security and environmental preservation, but it is also predicted to bring about a paradigm change in the sustainability of agriculture. To lessen the phytotoxic effects and increase agricultural output for human welfare, molecular science research into the interactions between plants and NPs is urgently required.

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