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Review

A Comprehensive Review of Nanoparticles Induced Stress and Toxicity in Plants

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Abstract: Increasing demand for Engineered Nanomaterial (ENMs) that have been widely applied in plant systems, for the improvement of quality, development, growth, nutritive value, and gene preservation. The uptake, translocation, biotransformation, and the associated perils of the application of Nanoparticles in crops demand a much deeper understanding of the biochemical, physiological, and molecular mechanisms of the florae concerning nanoparticles (NPs). Interaction between different plant parts and NPs resulted in various changes in physiology, morphology, and genotoxicity, indicating positive as well as negative feedback by (Nanoparticles) NPs over the various mechanisms of the plants and their species. With the ultimate goal of enhancing plant defence and/or stimulating plant growth and development and, eventually, crop output, NPs may create new and safer options for the smart delivery of biomolecules and novel tactics in plant genetic engineering. This study provides an overview of the state-of-the-art knowledge and research directions for plant-nanoparticle integrations.

***Keywords*:** engineered nanoparticles; nanobiotechnology; nanomaterial; nanosciences; physiological response; plant biotechnology

1. Introduction

Nanobiotechnology is emerging as a promising tool in the frontier of science. As the name suggests, it is a hybrid discipline involving the synergy of Nanosciences and biotechnology equivalently [1]. It is an efficient multifunctional, modular technology with diverse functionalities involving a plethora of disciplines [2]. Compared to bulk particles, nanoparticles (NPs) are more efficient because of their Nano dimension approach (1–100 nm) at the molecular level [3]. It can penetrate the matter at its fundamental level and provides tremendous efficiency due to its large surface area, high adsorption capacity, extraordinary optical and electrical properties, easy functionalization, high stability, and presence of active sites at the surface [4]. With the advancement in technology, this revolutionary science has gained significant importance owing to its profound application in diverse fields of electronic communication, food packaging, healthcare, biomedical, biomarkers, and agriculture [5,6].

Its breathtaking potential in the agriculture sector has substantiated a noteworthy impact, in fulfilling the demands of an ever-growing population and curbing the scarcity of food throughout the world. Nanoparticles have found their prospective in agriculture through their pivotal role in plants [7]. However, their activity differs according to the type of plant and properties (charge, size, shape) of NPs shown in Figure 1. They may be distinguished as natural, engineered, or incidental Nanoparticles (NPs) based on their origin. Amid, engineered nanoscale materials (ENMs) have received considerable attention due to their wide usage in various scientific

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fields impacting the socio-economy [8]. Engineered NMs are further classified as a) Inorganic NPs from metal or metal oxides as silver nanoparticles (Ag-NPs), Gold nanoparticles (AuNPs), Titanium nanoparticles (TiO_2), Zero Valent Iron, b) Carbon NPs such as carbon annotates, fullerenes c) Nanocomposites (the combination of NPs) d) Dendrimers (a network of nanopolymers) [9]. The insertion of these NPs plays an important role in the physiological and biochemical regulations of plants by enhancing their productivity through regulation of growth rate, nutrient management, increased disease resistance, and genetic improvement. Various studies found the role of Zinc oxide nanoparticles (ZnO-NPs) as a plant growth enhancer in cucumbers [10], soybean [11], and peanut [12]. Moreover, the inclusion of these nanoscale materials in the plants provides self-regulated, target-oriented release of biomolecules such as proteins, and nucleotides to specific required sites [13] found the involvement of Ag-NPs in the activation of gene expression in hormone signaling pathways and cell proliferation metabolism in *Arabidopsis thaliana* L. They are also found to play an important role in disease resistance and defence mechanism in plants, which owe them the capacity to remain healthy. In certain plants, these nanoparticles (NPs) are found to regulate the requisite release of fertilizers and pesticides while in some it is found to replace them by developing pathogen-specific resistance realized by the activation of antioxidant machinery in plants by metallic ENMs [14]. ENMs are also found to eradicate microorganisms hampering the growth of a plant in tissue culture media.

In the leaps and bounds of its beneficial progression, this technology has also been observed to have negatively impacted nature and its constituents as plants, soil, and human health. In *Phoenix dactylifera* L., ZnO-NPs were reported to affect the carbon and nitrogen cycle in plants by killing their associated fixing soil microorganisms [2]. Their excessive concentration, accumulation, and transfer within the food chain are also known to be influential on the physiological and biochemical responses adversely [15]. In asparagus lettuce (*Lactuca sativa* L. var. angustana), 500 mg L^{-1} concentration of CeO_2 NPs was reported to inhibit root growth and cell membrane damage due to the induction of lipid peroxidation [16]. Similarly, Rico et al. [17] and Majumdar et al. [18] reported the effect of NPs on the quality of seeds of wheat and common beans respectively.

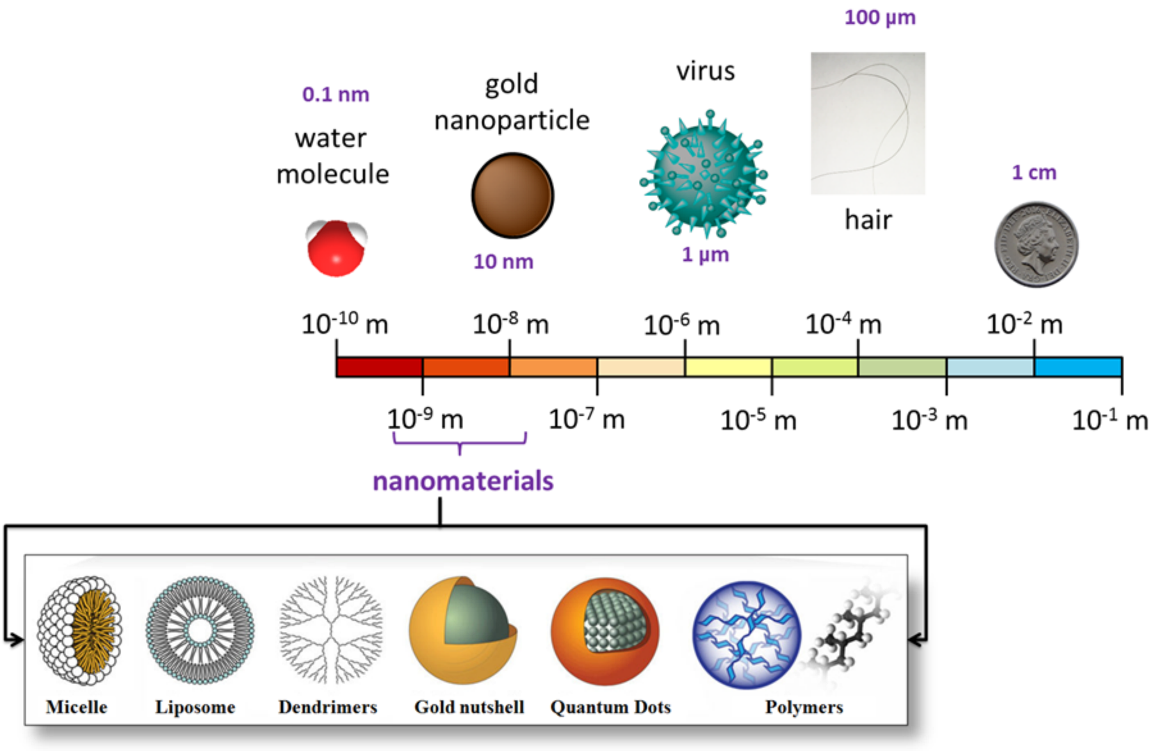

Figure 1. Different types of Nanoparticles in plants and their shapes

A considerate study on the interaction of NPs with air, soil, and plant systems is urgently needed to understand their positive and negative effects [19]. Therefore, possible research on accumulation, absorption, and translocation of NPs from soil to root (lateral roots, cortex, root tips) and shoots (epidermis, bark, stigma), rhizosphere, shoot, leaves (stomata, epidermis) in different plants, their complex molecules and secondary metabolites is to be addressed [20]. Various authors have also evident the role of their shape, size, and properties influencing their rate and pathway of transport and have also inferred the occurrence of bio transformations in NPs during this process [21]. In rice plants, Copper nanoparticles (Cu-NPs) were observed to produce variant Cu species after interaction with various biomolecules in different parts of the plant [22]. In roots, Cu existed as Cu-

NPs, while in leaves it transformed to exist as Cu-citrate, Cu_2O, and Cu-cysteine in similar proportion [23]. Hence forth, dynamic research is prevailing in finding models that can study the kinetics of various pathways involved in the translocation of NPs and their association in plants [24]. NPs can improve plant growth and development, through their use in herbicides, nano pesticides, and nano-fertilizers that can efficiently release their content in requisite amounts to target plant cellular organelles [25].

Plants' growth and development depend on the number of nutrients absorbed and the prevailing external environmental conditions. The addition of NPs to these plants can cause significant positive or negative changes in their physiological and biochemical activities [26]. Beneficially, these NPs can cause enhancement of growth rate and germination in plants which results in the development of healthy leaves, early flowering, an increase in root and shoot length, and many more. Detrimentally, NPs toxicity results in varying anatomical and genetic changes in plants such as the production of reactive oxygen species (ROS), degradation of seed quality, and various indirect side effects as well [27]. The other characteristics of NPs such as their concentration and size also help in studying their positive and negative impacts. This review gives an idea comprehensive review of studies involving the impact of various metal NPs on the growth of plants and depicts the advantages and disadvantages associated with NPs over plant development and growth.

2. Effects of Nanoparticles on Plants

2.1 Effects of Iron Nanoparticles (Fe-NPs)

Plant growth is fundamentally a natural process and is significantly connected with external environmental conditions. It gets impacted positively and negatively both ways depending upon the environment, a plant living in. The very first factor which plays a vital role is the availability of nutrients in the soil. Plants rooted in soil rich in nutrient values feed and grow healthily. On the contrary, soil having very low nutrients or polluted with unwanted metallic/nonmetallic particles potentially force the plants into malnutrition and lead to decay eventually. Recently a plethora of research has been conducted to study the relationship between NPs used and cultivated crops. Agathokleous et al. [28] detailed studies around Ferric Oxide nanoparticles (Fe_3O_4-NPs) have revealed their positive impact on plant germination, growth, and dry biomass along with chlorophyll amount enrichment in *Triticum aestivum* L. It enhances the enzyme activity in hydroponic cultivation within 5 days [14]. Moreover, facts confirmed no adverse impact on existing chlorophyll quantity and also plant growth. For example, in wheatgrass, no lipid peroxidation, no alteration of oxide radicals, and no additional H_2O_2 accumulation occurred [14]. Furthermore, exposure resulted in augmenting chlorophyll content in Quercus macdougallii L. [29].

The introduction of higher fractions of Fe_3O_4-NPs led to brown spots on leaves. Excess exposure generates oxidative stress, affects photosynthesis, and reduces the metabolic process. To get around this, NPs are given a coating that offers them a broad adsorption surface and biocompatible qualities. For instance, the presence of carbon-coated Fe_3O_4 at certain concentrations within particular cells and in extracellular space reduces the concerns for plant tissues and the number of chemicals released into the environment in the Cucurbita pepo L. (pumpkin plant). Magnetic means were deployed on various parts of the beans plant such as dried roots, shoots, and leaves to know the projected number of Fe_3O_4-NPs and discovered the hike in count 2 to 3 folds. This measurement confirmed zero levels of toxicity as well [30]. Empirical studies and explorations concerning Fe_2O_3-NPs postulated some dose-related artifacts and stated the impact of Fe-NPs on plants as per the concentration injected. For example, under hydroponic conditions, 20 mg L^{-1} of Fe NPs for corn plants promoted root extension, whereas 50 and 100 mg L^{-1} of Fe NPs adversely reduced the length of the root [31]. The process of elongation of the root is catalyzed by inducing OH• radical which results in the induced cell wall loosening using nano zero-valent iron Nanoparticle (NZVI)) [32]. On the toxicity front, NZVI gets diluted within 2 to 4 weeks [33]. Comparative evaluation of NZVI and Fe_2O_3-NPs on 'the root hydraulic conductivity of tomato was conducted in the hydroponic experiment by relating the decline in root water uptake with the expected blocking ways in root nutrient uptake by each of them mentioned and magically found that with 100 mg L^{-1} Fe_2O_3 NPs the root hydraulic conductivity gained is 40% resulting Mo and Zn reduction in shoots with NZVI was found to be less harmful [34].

A study of the response of transgenic and conventional rice to γ-Fe_2O_3 NPs has shown that transgenic rice showcased a higher degree of superoxide dismutase (SOD) and peroxidase (POD) activities than that conventional or non-transgenic rice [35]. The ability to take the plants up using fluorescence-labelled γ-Fe_2O_3 NPs was successfully analyzed through watermelon plants [36]. These NPs flow from root to cells hitting the epidermis first followed by the endodermis route. Suitable doses in the appropriate concentration expel iron deficiency chlorosis and strengthen plant growth [37]. The postulated facts about Fe, Zn, Zn, Cu, and Fe oxide NPs on mung bean seedling growth were given by Dhoke et al. [38]. NPs mobility of such metal and its oxides are controlled by symbiotic microenvironments. Arbuscular mycorrhizal fungi help to amplify the metal resistance to exposed roots to a greater extent [39]. The findings of these authors led to the result that various Fe NPs on application to root zones activate adverse effects although Fe NPs are considered to be harmless. Lethal impacts were observed at higher concentrations (1000 mg kg^{-1}) indicating that abnormal plant development and biomass were the results of higher concentrations (above 200 mg L^{-1}) in NZVI and broadleaf cattail along with hybrid poplar [40]. Iron NPs are effective in inducing antioxidant properties and aid in the treatment of chlorosis. Henceforth, the usage of iron NPs at optimum concentration ought to be applied for exploiting the benefits shown in Table1.The methods section is how the study was conducted. Describe in this section any steps or procedures taken to achieve your research goals, including experimental design and data analysis. For the statistical analysis, all details related to the statistical tests are important. These details include preliminary analysis, study sample size, the type of data (mean, median, standard deviation, standards error, and confidence intervals), normalization of your data, statistical methods used, and information for the statistical software program (PASS 2022, NCSS statistical software, Kaysville, UT, USA).

Table 1. Effect of iron nanoparticles on plant growth.

NPs	**Size (nm)**	**Plant**	**Concentration**	**Effect**	**References**
Fe-0	54 ± 1	*Arabidopsis thaliana*	0.5 g kg^{-1}	Increased leaf area	[41]
Fe-0	30 ± 2	*Arabidopsis thaliana*	500 mg kg^{-1}	Increased concentrations of phosphorus, total biomass, and carbohydrates like glucose, sucrose, and starch	[42]
γ-Fe_2O_3	180	Soybean (Glycine *max*)	500 or 1000 ppm	Increased shoot weight, stomatal conductance, intercellular CO_2 concentration, net photosynthetic rate, and transpiration rate	[43]
Fe-0	33.8 ± 3.59 nm	Soybean (*Glycine max*)	20 mg L^{-1}	Increased seedling growth	[43]
Fe_2O_3		Evening primrose (*Oenothera biennis*)	0.2 g L^{-1}	Stimulated germination and seedling growth	[44]
Fe_2O_3	40 nm	Lemon balm (*Melissa officinalis*)	5, 10, 20, 30, and 40 µM	Relief from oxidative stress caused by drought-related stress, greater essential oil content.	[45]
Fe_2O_3	20–40 nm	Wheat (*Triticum aestivum* cv. Cumhuriyet-75)	500 mg L^{-1}	Increased root length, plant height, biomass growth, and chlorophyll content	[46]
Fe-0	35–45 nm	Sunflower (*Helianthus annuus*)	1 or 2%	Alleviation from hexavalent chromium stress, recovered growth	[47]
Fe_3O_4	6.85 ± 1.70 nm	Wheat (*Triticum aestivum*)	2000 mg L^{-1}	Recovered growth of seedlings exposed to heavy metals	[48]
Fe_2O_3	40–100 nm	Tobacco (*Nicotiana benthamiana*)	50 mg L^{-1}	Increased biomass accumulation	[49]
FeS_2	600–700 nm	Spinach (*Spinacia oleracea*)	80 mg mL^{-1}	Bigger leaves, faster biomass growth, and more calcium, manganese, and zinc in the leaves.	[50]

2.2 Impact of Cobalt Nanoparticles

Cobalt is an essential micronutrient required for nitrogen fixation in legumes and other plant growth. It exists as a part of vitamin B12 and is found in an ionic form in plants. The study reveals that cobalt activates different enzymatic activities involved in the process of glycolysis, and oxidizing process, and helps in the transformation of pyruvic acid. Thereupon, the investigation of cobalt NPs' influence on plant growth and development was studied. López-Lopez- Moreno et al. [51] reported the effect of cobalt ferrite ($CoFe_2O_4$) NPs on hydroponically grown tomato plants. Exposure of $CoFe_2O_4$-NPs up to 1000 ppm on tomato plants has no toxic effects but the catalase activity was found to decrease in the leaves and roots of a tomato plant. Because of the inability to pass through the root system and seed coat, $CoFe_2O_4$-NPs show the insignificant result in germination. On the other hand, Faisal et al. [52] reported that treatment of eggplant seeds with Co_3O_4-NPs (1 mg mL^{-1}) resulted in a decrement in the germination of seeds, damaged Deoxyribonucleic acid (DNA) and mitochondria resulting in oxidative stress, thus causing cell death. Based on these studies, it can be determined that Co-NPs have been affected variably based on their chemical nature.

2.3 Impacts of Cerium Oxide Nanoparticles (CeO_2-NPs)

In agriculture, nano-fertilizers are very promising for growth, development, and production but the supply of nano-fertilizers is very limited [53]. Rico et al. [54] demonstrated that soil properties play a crucial role in the distribution of CeO_2 NPs and successive bioavailability of nano-formulations or nano fertilizers is provided to radish tubes. Morales et al. [55] stated that the applications of CeO_2-NPs can transform the nutritional value of coriander plants. In cucumber plants, cerium oxide-based Nano-fertilizers (CeO_2-NPs) analyzed its significant uptake, delivery, and biotransformation by Zhang et al. [56] & Rui et al. [57]. Wang et al. [58] found that extended root hairs formed during second-generation sapling were a result of cured seeds. Rico et al. [59] found some variations in the vital elements and some other nutritive ingredients in the wheat grains during the cultivation of wheat. Corral-Diaz et al. [60] detected that the application of CeO_2 -NPs (0–500 mg kg^{-1}) in soil resulted in retardness of radish seeds, but Cui et al. [16] found that the application of CeO_2-NPs at a concentration of 500 mg L^{-1} or above may induce lipid peroxidation during asparagus lettuce cultured in an agar medium. During radish farming, Zhang et al. [61] significantly analyzed CeO_2-NPs concentration with soil properties. Rico et al. [54] stated that in barley CeO_2-NPs improved plant biomass. The application of CeO_2-NPs and huge CeO_2 particles documented different responses of rape mustard plants [62]. Some amounts of CeO_2-NPs (0.1–1 mg L^{-1}) has been observed to have accumulated in the leaves, shoots, and fruits of tomato plants [63].

The researchers discovered about plant responses to CeO_2 depend on plant growth stages as well as the particle size of the NPs Ma et al. [62] Table 2 illustrates different particle sizes of the NPs CeO_2, uptake, and translocation after coming in contact with the different plant root systems. Ma et al. [62] reported important alterations in the pore size of roots and root hairs of hydroponic cucumber plants.

Barrios et al. [64] discovered from their research that vital components present in the tomato plant were transformed by CeO_2-NPs. Interactions between CeO_2-NPs and biochar influenced CeO_2 accumulation in plants [65]. The sunflower (*Helianthus annuus* L.) was exposed to CeO_2-NPs and its physiological and biochemical responses were investigated [66]. Differences in the physical and chemical interactivity among plant roots and CeO_2 NPs were explained by Ma et al. [62]. Interactions among mesquite, (a desert plant) and CeO_2 NPs with a nutrient suspension (500–4000 mg L^{-1}) of CeO_2-NPs utilizing the plantlets grown for 15 days under hydroponic conditions.

The application of CeO_2-NPs above 2000 mg L^{-1} concentration reported an increment of ascorbate-peroxidase (APOX) activity in the root system. The cortex and epidermis of mesquite plant roots absorb CeO_2-NPs on their uptake by the plant [67]. Exposure of canola plants (*Brassica napus* L.) to CeO_2-NPs, brought about a change in canola plant growth and its physiology [68]. The anti-oxidative stress enzyme activities and macromolecule composition in rice seedlings were affected by the application of CeO_2-NPs [17]. The application of CeO_2-NPs to tomato plants with comparatively lower concentrations (10 mg L^{-1}) influenced seed quality and second-generation sapling growth. The trans-generational effect has also been studied by [58].

Table 2. Uptake and translocation of CeO_2 nanoparticles (NPs) after contact with the diverse plant's root system.

Particle Size (nm)	Plant Species	References
~4	Wheat (*Triticum aestivum* L.)	[69]
231	Wheat (*Triticum aestivum* L.)	[70]
~10	Soyabean (*Glycine max* L.)	[71]
8, 7, 37	Maize (*Zea mays* L.), Cucumber (*Cucumis sativus* L.), Alfalfa (*Medicago sativa* L.), Tomato (*Lycopersicon esculentum* L.)	[72]
8	Wheat (*Triticum aestivum* L.)	[73]
8, 10	Soybean (*Glycine max* L.)	[74]

2.4 Impacts of Copper Nanoparticles (Cu-NPs)

It is essential to employ copper and its compounds as NPs in plant and agricultural systems to increase production and reduce environmental toxicity. The Cu-NPs-treated wheat shoot was studied by Dimkpa et al. [75]. The organ, tissue, and cellular levels of organ, tissue, and cell biotransformation were observed to be limited, as were the potential translocation routes for Cu-NPs [75]. According to Zhao et al. [76], the application of Cu-NPs can cause an increase or reduction in the content of sugars, organic acids, amino acids, and fatty acids in plants. The exogenous gene expression in transgenic crops, especially cotton plants of the gene that codes for Bacillus thuringiensis (Bt) toxin protein in leaves and roots is enhanced due to the low concentration of Cu-NPs [77].

Bt cotton has benefited from the use of Cu-NPs because they provide insect resistance [78]. The cucumber plant's resistance and detoxifying mechanisms were examined under Cu-NPs-induced stress. Cu-NP concentrations of 10 mg L^{-1} and 20 mg L^{-1} caused significant metabolic alterations in cucumber roots and leaves.

Gas chromatography-mass spectrometry (GC-MS) and proton nuclear magnetic resonance (^{1}H-NMR) spectroscopy were used in this investigation [78]. The fusion of different plants and different NPs in environmental management has grabbed the focus of several researchers since some NPs exhibit a significant role in plant seed germination and plant growth. Plenty of literature on the use of NPs has given great outcomes against pathogens yet the actual ground-level applications in agricultural fields are in an exploratory stage. Table 3 shows the effects of NPs on plant growth and development.

Table 3. Effects of nanoparticles on plant growth and development.

NPs	**Plant Species**	**Effects on Plants**	**References**
CeO_2	Soybean (*Glycine max* L.)	Nano CeO_2 effects on the biomass of leaves	[79]
CeO_2	Wheat (*Triticum aestivum* L.)	Nano CeO_2extends the harvest period of Triticum aestivum L. years to a specific degree	[54]
CeO_2	Basil (*Ocimum basilicum* L.)	Effect on the fresh weight	[80]
CeO_2	Tomato (*Lycopersicon esculentum* L.)	Stimulated growth of plants and maturity of fruit at a lower level	[31]
CeO_2	Arabidopsis (*Arabis thaliana* L.)	Declined chlorophyll content at a higher level	[81]
CeO_2	Cucumber (*Cucumis sativus* L.)	No undesirable effect over the entire life cycle of a plant	[82]
Au	Mustard greens (*Brassica juncea* L.)	Increased rate of germination (with 25 ppm AuNPs) and better total growth profile (at 10 ppm Au-NPs)	[83]
MgO	Radish (*Raphanus sativus* L.)	Plants growth is enhanced but also increases the uptake of Pb in plants resulting in Pb toxicity	[84]
NHAP	Ryegrass (Lolium perenne)	Plant biomass increased and soil pH while decreased Pb	[85]
Au	Arabidopsis (*Arabis thaliana* L.)	Retarded length of the root	[86]
SiO_2	Rice (*Oryza sativa* L.)	Enhanced seed germination and sapling growth	[87]

2.5 Impacts of Gold Nanoparticles (Au-NPs)

The absorption, translocation, and dispersion of gold nanoparticles(Au-NPs) depend on the NPs' surface charge and differ for different plant species. In *Arabidopsis thaliana* L., Au-NPs demonstrated a substantial function in seed germination and affected the amounts of mi-RNA expression in plant development, which regulates a variety of morphological, physiological, and metabolic processes [88]. In their analysis of NP translocation and uptake, Koelmel et al. [89] found that rice crops had been exposed to Au-NPs with a core diameter of around 2 nm.

Arora et al. [83] examined Au-NPs application in mustard plants through foliar spray and found significant growth and seed yield in mustard. Zhu et al. [90] suggested that the application of Au-NPs in mustard greens enhances plant growth and yield. The translocation and uptake of Au-NPs with a mean size of 6–10 nm, in pumpkin, radish, rice, and perennial ryegrass were studied by Zhu et al. [90]. He observed that positively charged Au-NPs and negatively charged Au-NPs translocated across the roots and shoots of the plant respectively.

In a study carried out on the rice plants, it was investigated that the bioaccumulation of Au-NPs in the tissues of root and shoot was reliant on the surface charge at a certain concentration done by the treatment and also on the exposure period which was detected with the help of laser-ablation inductively- coupled-plasma mass spectrometry (LA-ICP-MS) [89]. Zhai et al. [91] researched the translocation and uptake of gold nanoparticles across the roots, leafy cells, and cytoplasm of woody poplar (*Liriodendron tulipifera* L.). The uptake and translocation of the Au-NPs to the leaves of the plant Arabidopsis via roots [92].

In a study done on Arabidopsis, it was found that the leaves performed like photochemical mediators by absorbing light energy and raising the surface temperature [92]. The Au-NPs were consumed and translocated by the tomato plant without changing their properties in a study done by Dan et al. [93]. The effect of dose-dependent application of Au-NPs on *Arabidopsis thaliana* L. seedlings was observed on the length of the root and a reported lower dose of Au-NPs to impact root growth [94]. The uptake and translocation of the Au-NPs in the roots and subsequent accumulation in the plant tissues were analyzed by analyzing the materialistic properties [95]. On the application of Au-NPs (100 mg L^{-1}) to the *Arabidopsis thaliana* (L.) which was consumed by it in ionic form, the physiological and genetic responses were studied in the root tissues [86]. Citrate-stabilized Au-NPs (diameter 100–400nm) enhanced the biochemical and physiological stress conditions in *Brassica juncea* L. seedlings [96]. Feichtmeier et al. [97] reported the development in seeds of barley on globular Au-NPs application with a diameter of 2–19 nm. When citrate-coated Au-NPs were applied to onion, it resulted in various aberrations in the chromosome of root tips [98].

2.6 Impact of Zinc Oxide Nanoparticles (ZnO-NPs)

ENMs are the major demands of today's era in this respect ZnO-NPs are one of the most demanded ENMs. Due to its wide applications in different industries (cosmetics, paints, medicine), and biomedical and drug carriers, it becomes very compulsory for researchers to identify its impact on plant growth and development. Enhancement in plant growth and development is reported in cucumber [10], green peas [99], soybean [11], and maize seed [100] when treated with ZnO-NPs. This section deals with such research that explains the impact of ZnO-NPs. Shahhoseini et al. [101] in an experimental investigation tried to observe the impact of ZnO-NPs and $ZnSO_4$ suspension on peanut plants grown in a pod. The experiment varied from much lower concentrations to higher concentrations up to 1000 ppm with an average size of ~25 nm of ZnO-NPs and $ZnSO_4$ chelates. It was found that treatment with high concentration NPs enhanced the rate of seed germination, seedling vigor, increase in chlorophyll content of leaf, and early flowering was also recorded. Similarly, ZnO-NPs inductive effect proves in increasing the rate of root and shoot growth with a 34% increment in growth per pod in comparison to chelated $ZnSO_4$ treated pods. In a similar experiment with a lower concentration of ZnO-NPs and $ZnSO_4$ suspension, the highest peanut yield is found at 29.5% and 26.3% respectively in comparison with the control. In addition, Mukherjee et al. [99] studied that ZnO-NP's physiological impact on the soil helps in developing green peas. The toxic effects were estimated by breaking down different boundaries, for example, plant development, Zn amassing, chlorophyll creation, and movement of stress compounds. An expanded root extension was watched for every examined centralization of ZnO-NPs, though it didn't affect the growth of the shoot. In hay (*Medicago sativa* L.), tomato, and cucumber (*Cucumis sativus* L.), ZnO-NPs and Zn^{2+} particles had an increased effect [27]. On the application of 1600 ppm concentration of ZnO-NPs, the cucumber germination increased by 10%, while tomato germination decreased by 20% and horse feed germination by 40%. Various plants respond to different NPs in their distinct ways and the species of the plant may be a possible reason behind the various responses to the uptake, resistance, as well as toxicity. This examination researched possible biotransformation and featured the phytotoxicity and take-up of ZnO-NPs and Zn^{2+} particles by the plants. Guo et al. [102] developed carboxymethyl cellulose (CMC)-based film packaging that was enhanced with zinc oxide nanoparticles and cinnamaldehyde (CIN) from plant sources (ZnO-NPs). Investigation of CMC-based films, including pristine CMC, CIN/CMC, ZnO-NPs/CMC, and ZnO-NPs/CIN/CMC on physic-mechanical, barrier properties, and antifungal activities were examined. The ZnO-NPs incorporated in film produce Nanocomposites of good flexibility, high mechanical resistance, and low transparency. The addition of CIN to CMC-based film improved the water barrier capacity and antifungal performance improved the water barrier capacity and antifungal performance. In comparison, ZnO/CIN/CMC nanocomposite possesses satisfactory mechanical characterizations, extraordinary barrier capacity against oxygen and water, and shows excellent anti-Aspergillus niger activity. Additionally, this nanocomposite film proved successful in preventing cherry tomato weight loss, maintaining the fruit's firmness, and lowering the fruit's overall acid content during storage. According to the study, cherry tomatoes' quality is improved by this nanocomposite film packaging by reducing the physiological metabolic activities of fruits throughout the postharvest storage period. One of the experiments examined the impact of ZnO-NPs on colored rice (*Oryza sativa* L.). The rice berry plant (*Oryza sativa* L.) was grown and irrigated for 60 days after which plants were exposed to ZnO-NPs. Different doses of NPs (0, 200, 400, and 800 mg L^{-1}) were given to riceberry plants. The low concentration of ZnO-NPs shows high enhancement in plant heights, plant weights, panicles/clump number, antioxidant enzyme activity, and photosynthetic pigment content as compared to other doses and control shown in Table 4. It was also noted that seeds of riceberry show the accumulation of anthocyanin content and reported highest with 200 mg L^{-1} dose. It was suggested that NPs concentrations play a major role in the enhancement of riceberry productivity, plant growth, and metabolite in plants.

Table 4. Effects of ZnO-NPs on plant growth and physiology.

Nano-material	Crop Species	Size	Concentration	Responses	References
ZnO	*Coea arabica*	N.A.	10 mg L^{-1}	Enhanced growth, biomass accumulation, and net photosynthesis	[103]
ZnO	*Triticum aestivum*	N.A.	20 mg L^{-1}	Increased grain yield and biomass accumulation	[19]
ZnO	*Cyamopsis tetragonoloba*	N.A.	10 mg L^{-1}	Improved plant growth, biomass accumulation, and nutrient content	[104]
ZnO	*Nicotiana tabacum*	N.A.	0.2 μM to 1 μM	Positively affected growth physiology, increased metabolites, enzymatic activities, and anatomical properties of plants	[105]
ZnO NPs	Wheat (*Triticum aestivum*)	20 ± 5 nm	2 mg L^{-1}	Increased zinc content in grains, zinc present in form of zinc phosphate	[106]
ZnO NPs	Saffron (*Crocus sativus*)	Size < 30 nm	2 mg L^{-1}	Increased yield of flowers	[107]
ZnO NPs	Sorghum (*Sorghum bicolor* var. 251)	Size of 18 nm	6 mg L^{-1}	Increased grain yield, increased translocation of nitrogen, potassium, and zinc into grains	[108]
ZnO NPs	Lemon balm (*Melissa officinalis*) seedlings	10–30 nm	5 or 15 mg L^{-1}	More developed lateral roots increased leaf fresh mass.	[109]
ZnO-NPs	Mung bean (*Vigna radiata*)	22.4 ± 1.8 nm	10 or 25 mg L^{-1}	Longer stems and larger root volume	[110]
ZnO-NPs	Wheat (*Triticum aestivum*)	20–30 nm	25, 50, 75, 100 mg L^{-1}	Increased growth and yield in soil contaminated with aged cadmium	[111]
ZnO-NPs	Foxtail millet (*Setaria italica*)	Shape, size < 20 nm spherical shape	2.6 mg L^{-1}	Increased oil and nitrogen content in grains	[112]
ZnO-NPs,	Lupine (*Lupinus termis*)	21.3 nm	20, 40 mg L^{-1}	In normal conditions, mitigated the negative effect of 150 mM NaCl	[113]
ZnO-NPs	Winter wheat (*Triticum aestivum* var. Dyna-Gro 9522)	18 nm	1.7, 3.5 mg L^{-1}	Modulation of drought stress	[114]

Not Applicable: N.A.

2.7 Impact of Silver Nanoparticles (Ag-NPs)

Silver is one of the most common metals due to its wide use in different industrial applications, and antibacterial and medicinal values. The broad use of silver increases the risk of humans, plants, animals, and the environment getting exposed. Several researchers have studied the uptake, phytotoxic, and translocation effects of Ag-NPs on plants. Hence, this section deals with the study of the effect of Ag-NPs on plants.

Shams et al. [115] utilized Ag-NPs of 500–3000 ppm size to accelerate seedling growth and seed germination of *Boswellia ovalifoliolata* L. Soil-cultivated cucumber experienced a remarkable impact on agronomic traits over the application of Ag-NPs foliar spray, resulting in an enhanced yield of fruits and weight to 26% in comparison to control. Radish, lettuce, and grain (*Hordeum vulgare* L.) obtained from the nursery were used as a reference for studying the effect of Ag-NPs (10 nm) on root stretching under the soil and hydroponic conditions [116]. Root extension showed positive results in grains with low Ag-NPs concentration under hydroponic conditions, while a critical decrease in the length of the root was observed on the application of elevated concentration levels of Ag-NPs. In lettuce, a discount in the rooting period turned discovered, and for radish, no sizeable variant had been mentioned on remedy. No poor consequences had been visible on remedy with Ag-NPs for the foundation period of the entire 3 flora uncovered to the soil. The boom parameters of not unusual place bean (*Phaseolus vulgaris* L.) and maize (*Zea mays* L.) had been studied with ninety-eight Nair [117] exceptional concentrations of Ag-NPs wherein more desirable boom turned into discovered at low concentrations and inhibitory consequences with better concentrations of NPs [118]. The phytotoxicity of Ag-NPs (29 nm) over cucumber (*Curcumin sativus* L.) and lettuce (*Lactuca sativa* L.) was concentrated with seed germination tests, and a diminished impact on the germination file was accounted for cucumber seeds [119]. The germination data for lettuce seeds appeared to be practically identical to the controls. The grain showed positive feedback in root extension with low Ag-NPs concentration under hydroponics conditions, while high Ag-NPs concentration showed a decline in the length of the root. For lettuce, a discount in the rooting period turned into discovered, and for radish, no sizeable variant had been mentioned on remedy. No poor consequences had been visible on remedy with Ag-NPs for the foundation period of the entire 3 flora uncovered to the soil. The main parameters of usual bean (*Phaseolus vulgaris* L.) and maize (*Zea mays* L.) have been studied with ninety-eight. Nair [117] exceptional concentrations of Ag-NPs wherein more desirable boom turned into discovered at low concentrations and inhibitory consequences with better concentrations of NPs [118]. Increased chlorophyll content, root, and shoot period were seen to be a cure with 60 ppm Ag-NPs and then declined boom criterion and content of chlorophyll for better concentrations. Syu et al. [13] studied the effect of distinct morphological shapes (triangular, spherical, and decahedral) and sizes (8 to 47 nm)

Ag-NPs on A. thaliana resulted in increased root growth. Vannini et al. [120] investigated the phytotoxicity and genotoxicity of Ag-NPs over germinating seedlings of wheat. Variations in morphology in a cell of the root tip and reduced growth of seedlings were seen as a result of higher Ag-NPs concentration. The result also revealed that the toxicity of Ag-NPs is due to the release of Ag ions from Ag-NPs. No sign of DNA polymorphism was reported with the application of Ag-NPs. It was seen that the proteins that controlled primary metabolism and defence mechanism showed variation in their expression. The effect of Ag-NPs on cellular and morphological modifications of A. thaliana. It was concluded that at a cellular level the signaling of ROS and Ca^{2+} was stimulated by Ag-NPs with much more complex physiological alterations. Tripathi et al. [121] studied the effect of Ag-NPs and Nitric oxide on green peas and found that Ag-NPs caused negative effects on the development of crops. Kumari et al. [122] studied the impact of different Ag-NPs concentrations on seed germination, and shoot and root elongation of mung beans. The results indicated that on elevating the Ag-NPs concentration (100 mg L^{-1}) besides the declination in elongation of shoot and root, there was a decline in seed germination. The impact of Ag-NPs on the germination rate of ryegrass, barley, and flax (*Linum usitatissimum* L.) had been studied with three low concentrations ranging from 1 to 100 ppm and sizes between 1 to 20 nm. The result revealed that the different sizes of NPs affected different plant species. The inhibitory effect was observed on ryegrass with low concentration and small-size nanoparticles. Barely shows the high inhibitory effect with high concentration and intermediate size, whereas intermediate size with low concentration showed no inhibitory effect. Flax seeds had been on no account suffering from any amounts of Ag-NPs [123]. Since exceptional sorts of plant species behaved in a different way to an equal form of NPs of various lengths and awareness, the assessments of germination of seeds cannot be entirely relied upon for the evaluation of the environmental effect of Ag-NPs. Di et al. [124] researched the size-dependent toxicity of Ag-NPs over Italian ryegrass (*Lolium multiflorum* L.). It was observed that shorter roots, shoots, and less biomass are observed with smaller Ag-NPs as compared to larger Ag-NPs of the same concentration. It can be concluded that the total surface area of NPs was affected by their toxicity of NPs. The research was further carried out with gum arabic (GA)-coated Ag-NPs of 40 ppm concentration and found seedlings with failed root hairs, broken root caps, and vacuolated cortical cells. This happened as a result of reduced auxin transport which affected gravitropism in plant growth. In further study effect of Ag-NPs on chlorophyll, epidermal polyphenol contents, nitrogen balance index photochemical efficiency, and phenylalanine ammonia-lyase (PAL) activity in *Prosopis juliflora* (L.). The Ag-NPs were obtained from leaf extract of *Hyptis suaveolens* (L.) of 22 nm particle size with 29.50 mv and 1.394 ms cm^{-1} zeta potential and conductivity respectively. Four different doses (25, 50, 75, and 100 ppm) of Ag-NPs synthesized on *Prosopis juliflora* (L.) were tested. The result showed a positive impact on phenylalanine ammonia-lyase (PAL) activity and a neutral effect on other contents. A high dose (100 ppm) of Ag-NPs was noted with a negative effect on photochemical efficiency. It is suggested that future study is needed to reveal the impact of green Ag-NPs in the reduction of stress oxidative in plants which was induced due to PAL enzymes which act as exogenous inducers. Various researchers are working on identifying the impact (positive and negative) of Ag-NPs on plant growth and development are shown in Table 5. However, it is suggested to majorly identify the toxic impact of Ag-NPs on a plant at the cellular level.

Table 5. Effect of Ag-NPs on plant growth, development, and physiology.

Nanoparticle	Size	Plant	Concentration	Effect	References
Ag NPs	Size 6–36 nm	Rice (*Oryza sativa*)	20 mg L^{-1}	Increased germination rate and faster seedling growth	[125]
Carbon-coated Ag NPs,	10 nm	*Populus deltoides* × nigra)	1 mg L^{-1}	Increased root and stem biomass growth	[126]
PEG-coated Ag NPs	Size 5 or 10 nm; Ag^{+} ions	*Arabidopsis thaliana*	0.01 mg L^{-1}	Increased biomass growth	[126]
Ag NPs	1 to 50 nm	Rice (*Oryza sativa*) callus	5 and 10 mgL^{-1}	Faster regeneration of callus	[127]
Ag NPs capped	16.7 nm, spherical shape; Ag^{+} ions	Common bean (*Phaseolus vulgaris*)	(5–60 ppm)	Increased biomass growth and bean yield	[128]
Ag NPs	approx. 100 atoms	Scots pine (*Pinus sylvestris*) and oak (*Quercus robur*) seedlings	5, 25, and 50 ppm	Stimulation of ectomycorrhizal colonization	[129,130]
Ag NPs	100 nm, surface area 5.0 m^2/g	Two orchids (Lilium cv. Mona Lisa and cv. Little John)	100 ppm	Increased leaf and bulb biomass accumulation increased flower abundance and prolonged flowering period	[131]

2.8 Impacts of Silica Nanoparticles (SiO_2-NPs)

Better growth parameters and seed stability in maize were observed with the use of SiO_2-NPs [132]. The sustainable farming of maize crops observed that the application of SiO_2-NPs at 15 Kg ha^{-1}, in maize significantly increased the organic compounds such as proteins, chlorophyll, and phenols especially compared with bulk silica. It also enhanced the germination of seeds along with the growth of seedlings [133]. Slomberg and Schoenfisch [134] studied that the silica scaffolds turned out to be effective in the consumption and translocation of SiO_2-NPs (14, 50, and 200 nm) within the root system of Arabidopsis. The application of SiO_2-NPs in maize grown under hydroponic conditions remarkably increased the dry weight of the plant. Suriyaprabha et al. [135] also reported an increase in the degree of organic compounds including phenol, chlorophyll, and proteins in maize with the use of SiO_2-NPs. Sun et al. [136] applied the SiO_2-NPs (mean diameter 20 nm) on seed germination in selected plant species. Siddiqui and Al-Whaibi [137] revealed that soil properties and characteristics of seed germination in tomato plants were influenced by the treatment with SiO_2-NPs. Tripathi et al. [138] discovered that the application of SiO_2-NPs as pre-addition or bulk SiO_2 controlled the degree of oxidative tension and the seedlings of wheat were protected from UV-B by shielding photosynthesis. Janmohammadi and Sabaghnia's [139] investigation indicated that the application of SiO_2-NPs regulates stress caused by the presence of salts and improved the germination and seedlings of the lentil. Sunflower and Cucurbita grown under salt stress conditions showed increased germination of seeds under the influence of SiO_2-NPs. Tripathi et al. [15] In their experiment used SiO_2-NPs, to reduce oxidative stress as well as to the enhancement of the antioxidant defense system. Wang et al. [140] found that supplementing the soil with NPs affects the soil as well as the plants; the application of SiO_2-NPs in the form of a suspension significantly improved the growth parameters of plants and regulates the soil properties shown in Table 3.

2.9 Effects of Carbon Nanoparticles

Carbon NPs (CBNs) are a novel class of materials that are being used extensively in biomedical fields covering a huge spectrum including the delivery of therapeutics, biomedical imaging, biosensors, tissue engineering, and cancer therapy. It has gained great attention and visibility due to its unique chemical and physical properties including thermal, mechanical, electrical, optical, and structural diversity. Endowed by such intrinsic properties, various CBNs are used in plant growth. The engineered CBNs have proven to hike in germination rate with increased water uptake experimented on rice seeds [117] yielding healthier plants when compared with the control ones.

2.9.1 Carbon Nanotubes (CNTs)

These are CNBs where molecular-scale structures having carbon atoms arranged in cylindrically formed layers, held together by the virtue of covalent bonds in a pattern of hexagonal tiling, to form a hollow tube having a diameter of the order of hundred nanometers. Three types of CNTs are recognized so far:

a) Single-walled carbon nanotube (SWCNT)

b) Double-walled carbon nanotubes (DWCNT)

c) Multi-walled carbon nanotubes (MWCNT)

Following the studies, CNTs empower a tomato plant to increase its flower and fruit production by 2 times in contrast with the control plants. The phylogenetic analyses established the fact that enhancement in the number of CNTs, results in the relative increase of Bacteroidetes and Firmicutes with a decrease in the Proteobacteria and Verrucomicrobia [141]. SWCNT is a layer of atoms arranged cylindrically forming a single molecule, having a diameter of the order of a nanometer. Its mobility throughout the cell membrane as well as, the cell wall of the plant [142] allows the delivery of DNA along with additional particles to keep the plant cells integrated. Fullerenes adsorption results in the cell wall and membrane disruption which led to complete inhibition of cell growth. The presence of oxidative stress in *Arabidopsis* and rice protoplasts resulted in the programmed death of cells constraining the survival of the cells to be especially dependent on dose [143].

MWCNT in small doses of 10, 20, and 40 mg L^{-1} on Brassica juncea L (Indian mustard, Chinese mustard) and Phaseolus mungo L. [144] and the dose of 40 μg mL^{-1} on tomato (*Solanum lycopersicum* L.) were found much more helpful for seed germination than control plants [145]. Its stimulus has been observed at length with the germination of seed and elongation of seedling root in *Triticum aestivum* L. [37]. Henceforth, accelerated barley and soya bean seed germination and then nourished the plant without any adverse effect [146]. Water has been proven a vital ingredient in channelizing the bulk of protein content for the overall growth and nourishment of plants keeping the seed germination so well into consideration [147]. Villagarcia et al. [148] investigated within tomatoes that numerous groups, including COOH and polyethylene glycol (PEG) triggered MWCNTs that help in the generation of water channel protein-aquaporin (LeAqp1). An improved water delivery system and CNTs stimulate growth. Water-soluble CNTs can enhance the water absorbent and holding capacity of roots to positively influence the growth of C. *arietinum* plants [138]. Jiang et al. [149] found in the study over paddy (*Oryza sativa* L.) that application of CNTs (0–100 μg mL^{-1}) to stem and roots enhanced seedling length. However, a dose of 150 μg mL^{-1} was found to reduce the activity of the root, along with the length of the root and stem. With the positive gains from the MWCNT, it offers a flip side as well as far as seed germination and upbringing of seedlings are taken into account. CNTs exposure to a high degree given ultimately damages the plants which highlight the criticality of the intensity of the dose used while giving the treatment to the experiments.

2.9.2 Carbon Nanoparticles (CNPs)

These are CNPs of pure carbon attributed to increased stability, decreased toxic level, ecologically sound, and better conduction. In the interest of plants, it promotes the absorption of micro and macronutrients as well as a level of accumulation, hence enhancing the effectiveness of the fertilizer. The water-soluble CNPs can release nutrients in a steady regulated manner for enhanced assimilation across a plant, which makes it better than manure and fertilizer. For example, *Nicotiana tabacum* (L.) has showcased increased growth at different stages after its treatment (Liang et al. [150] by augmenting nitrogen and potassium content. Modulation in Phytochrome B (PhyB), pathways dependent on photoperiod can stimulate early flowering in plants.

2.9.3Carbon Nanodots (CNDs) and Fluorescent Carbon Dots (FCDs)

The fluorescence microscopy analysis reveals the water-soluble CNDs entry into roots, and flow throughout the plant leaving its presence in leaves (mesophyll cells) and roots. The wheat (*Triticum aestivum* L.) plant has proven root growth ten times as normal after exposure for ten days with a dose of 150 mg L^{-1} water-soluble CNDs [151]. Lettuce yield can be increased and nitrate level can be decreased with the use of CDs in a small dose (20–30 mg L^{-1}). It was detected in *Vigna radiates* L. sprouts with varying concentrations (0.02–0.12 mg mL^{-1}) of CDs, which resulted not only in increased biomass and carbohydrate level (increase to about 21.9%) but also elongation of root and stem. Further, photosystem activity (RUBISCO and chlorophyll content) can also be increased by stepping up the electron transfer level. All kinds of CDs can potentially invoke defense systems of antioxidants more in the roots than shoots [152]. CDs are used in plant cell and tissue imaging.

2.9.4 Carbon Nanohorns (CNHs)

Just like SWCNT, carbon nanohorns follow the same pattern and are normally called as SWNHs (Single Walled Nanohorns). They do exhibit many useful properties such as porosity, electronic behavior, magnetic behaviour, sensor behavior, gas storage, etc. The property of soil porosity due to the virtue of the hexagonal stacking structure empowers it to have a substantial capacity of micropores and trivial mesoporosity. Hence it has also been observed that they enhance terrestrial plant growth [148].On the exposing the cells of *Nicotiana Tabacum* L., to CNHs (25 and 100 µg mL^{-1}) for about 24 h, trivial impacts were studied at 25 µg mL^{-1}, while cultured cells at 100 µg mL^{-1} had a 78% hike in their growth.

2.9.5 Nanocarbon Sol (NCS)

NCS has revealed its new dimension and proved to be one of the agents that participate in an effect of synergy with fertilizers as they are added to the production process of fertilizers. Crops are exposed or treated with NCS to gain enhanced growth. It allows slow percolation of nutrients to the crops stably yielding an increase in production by 5 to 18%. It is a good contributor to the nitration inhibition rate. All in all, they are a friend of crops and the environment leaving no traces behind after their exhaustion.

2.9.6 Carbon Nanofibers (CNFs)

CNFs are micronutrient carriers in plants providing efficient translocation. These are CNFs, vapour grown carbon fibers (VGCFs), or vapour grown carbon nanofibers (VGCNFs), cylindrical nanostructures with graphene layers arranged as stacked cones, cups, or plates. They are micronutrient carriers in plants providing efficient translocation and controlled release of Cu-NPs. Cu-CNFs, ideally engineered NPs can act as carriers for micronutrients thus stimulating plant growth.

3. Advantage and Disadvantage of Nanoparticles

The advantages of using NPs in the plant and their effect on physiology and biochemistry are explained shown in Table 6. But a brief view of its toxicity is also needed to regulate their adequate usage. NPs at certain concentrations are beneficial to plants but their excess concentration and prolonged exposure are known to cause various adverse effects on their diverse functions.

3.1 Physiological effects

Physiological characteristics such as pore size, hydraulic conductivity, and cell wall affect the accumulation and transport of NPs. Size is an important factor depicting its penetration level thus affecting its metabolic pathway [153].

Table 6. Advantages of using nanoparticles in the growth and development of plants.

NPs	Concentration	Plant	Positive Effect	References
TiO_2	100–300 mg kg^{-1}	Soyabean (Glycine max Merr.)	Improvement in the photosynthetic rate	[154]
Mn	0.05–1 mg L^{-1}	Mung bean (*Vigna radiate* L.)	Increased nitrogen metabolism	[155]
CeO_2	20,40,80,160,320 mg L^{-1}	Cucumber (*Cucumis sativus* L.)	Catalase activity in the roots was increased	[156]
NZVI	0.5 g/L	Soyabean (*Glycine max* Merr.)	Increase germination rate in seeds	[119]
Alginate/ chitosan	1.92×10^{12} nanoparticle mL^{-1}	Wild bean (*Phaseolus vulgaris* L.)	Increased biological activity was observed in plants with NPs as compared to those with free plant growth hormone- gibberellic acid.	[157]
Fe_2O_3	500 and 1000 mg L^{-1}	Soyabean (*Glycine max* Merr.)	Increased root elongation and improved photosynthetic activity	[43]
MWCNTs	50–200 ug mL^{-1}	Tomato (*Solanum lycopersicum* L.)	Increased number of flowers and fruits and height of plants	[141]
Magnetic iron NP	100, 200 kg/ha,	Wheat (*Triticum aestivum* L.)	Phosphorus (P) and nitrogen uptake in wheat shoots were significantly greater at lower concentrations of BMCs (100kg/ha)	[158]
Pristine MWCNTs	20 mg L^{-1}	Maize (*Zea Mays* L.)	Enhanced transfer of nutrients and increased biomass	[159]
Carbon	10–150 mg L^{-1}	Wheat (*Triticum aestivum* L.)	Higher growth rates were observed	[160]
mPEG-PLGA-	-	Wheat (*Triticum aestivum* L.)	Enhanced the overall plant growth	[161]
ZnO	10 mg L^{-1}	Pearl millet (*Pennisetum glaucum* L.)	Enhancement in fresh and dry biomass of plant	[162]
SiO_2	-	Tomato (*Lycopersicum esculentum* Mill.)	Improvement in seed germination was observed	[163]
Graphene oxide	400 and 800 mg L^{-1}	Broad bean (*Vicia faba* L.)	Enhanced Germination in Plants	[164]
ZnO	0,10,100, 500 mg L^{-1}	Safflower (*Carthamus tinctorius* L.)	Increased the production of malondialdehyde enzyme.	[165]
ZVI	10, 20, 40, 80, 160 mg L^{-1}	Rice (*Oriza sativa*)	Seed growth, root, and shoot length are enhanced	[166]

NPs toxicity is reported to affect the germination percentage, biomass, root length, and shoot length in soybean, wheat, maize, and barley [167] shown in Figure 2. Wang et al. [33] found reduced chlorophyll content and seedling growth in rice plants exposed to NZVI concentration of 500–1000 mg L^{-1} due to damaged root tissue at a higher concentration which in turn affected the Fe absorption and chlorophyll production. Le Van et al. [168] conducted a study on conventional and transgenic cotton and found Cu-NPs to have caused toxicity above 200 mg concentration thus affecting its plant height and root length. Prolonged exposure of Cu-NPs to *Oryza sativa* (L.) for 7–14 days affected the shoot and root length [22]. Vernay et al. [169] reported the adverse effects of NPs on flowering, fruiting, senescence, abscission, and dormancy which affected the overall growth and development of plants as shown in Table 6.

They are also known to reduce hydraulic conductivities and transpiration in Zea mays L. [170]. Ma et al. [40] found that Ce NPs reduced chlorophyll assembly by 60–85%. Carbon NPs due to aggregation at the root surface reduce the absorption of nutrients, mediate reduced transpiration rate, and photosynthetic process, and reduction in stress tolerance genes [171]. Dose-dependent effects of multi-walled carbon NPs were found in *Cucurbita pepo* L. resulting in reduced bud length, seed germination, biomass accumulation, root length, and vitality index. Vittori et al. [80] reported adverse effects of 50 mg L^{-1} concentration of NPs on their average biomass, fresh weight, and root elongation. Since the higher concentration and long-time exposure of NPs are known to cause toxic or retarded effects on the complete physiology of plants thus affecting their growth and development, their penetration into the food chain further enhances their toxicity to higher organisms [80]. An increased amount of Au-NPs from 10 to 100 ppm resulted in decreased oxidative load and growth [69].

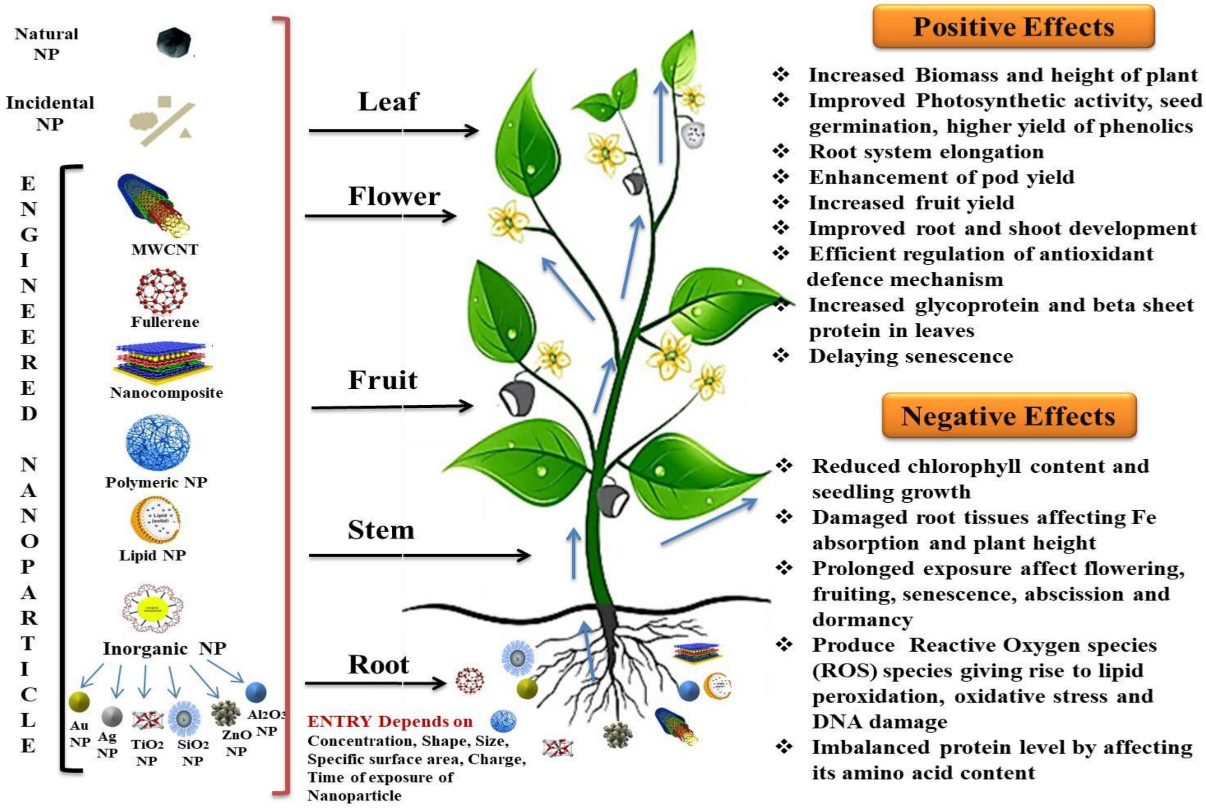

Figure 2. Advantages and disadvantages of nanoparticles on plant growth.

3.2 Biochemical Effects

In certain plants, carbon NPs are known to produce Reactive Oxygen species (ROS) species which induce toxicity in plants giving rise to lipid peroxidation, oxidative stress, and DNA damage. A study by Poborilova et al. [172] found the generation of ROS and lipid peroxidation in Tobacco BY-2 cells, exposed to Al_2O_3 NPs. These NPs can cause damage to plants indirectly by affecting the antioxidant enzymes of the plant, thus affecting its defence mechanism. A decreased trend in catalase (CAT) activity was observed in the root and leaves of *Solanum lycopersicum* (L.) with increasing concentrations of $CoFe_2O_4$ NPs from 0–1000 mgL^{-1} [173]. Oxidative damage in rice plants was observed when they were exposed to a CeO NPs concentration of 62.5 and 500 mg L^{-1} [17]. Mukherjee et al. [99] reported oxidative stress when 500ppm of 10nm Zn NPs were exposed to Pisum sativum L. Imbalance in auxin and ethylene production was reported in Brassica juncea (L.) exposed to Au-NPs. Arora et al. [81] CeO_2 NPs were found to affect the developmental activities in Triticum aestivum (L.) by affecting its amino acid content resulting in an imbalanced protein level [19]. Toxicity in these biochemical pathways further affects the physiological functions of plant and their secondary metabolism Table 7.

Table 7. Disadvantage of using nanoparticles in the growth and development of plants.

NPs	Dose	Plant	Negative Effect	References
AgNPs	25, 50, 75, 100 mg L^{-1}	Rice (*Oryza sativa* L.)	Increasing concentration reduced aflatoxin levels thus significantly affecting plant growth	[174]
Ag (Citrate coated)	73.4 mg L^{-1}	Maize (*Zea mays* L.)	Retarded germination	[175]
AgNPs	0.5 and 3 mg L^{-1}	Thale cress (*Arabidopsis thaliana* L.)	Reduced chlorophyll content due to disruption in the thylakoid membrane structure.	[176]
NZVIs	1000 mg kg^{-1}	Rice (*Oryza sativa* L.)	Negative effect on carotenoids and chlorophyll	[177]
Si NPs	250,1000 mgL^{-1} 1000 mgL^{-1}	Thale cress (*Arabidopsis thaliana* L.) Pumpkin (*Cucurbita pepo* L.)	Reduced stem length and biomass Germination was inhibited	[135,178]
CeO2NPs	-	Wheat(*Triticum aestivum* L.)	The harvest period of ears was prolonged to a specific level.	[54]

CeO2 NPs	20, 40, 80, 160, and 320 mg L^{-1}	Cucumber (*Cucumis sativus* L.)	Ascorbate peroxidase activity was decreased in the leaves	[156]
CuONPs	10,100,500,1000 mg L^{-1}	Raddish (*Raphanus sativus* L.)	The oxidative damage caused to DNA decreased root growth.	[179]
Al2O3 NPs	0.01–0.1 mg L^{-1}	Tobacco BY-2 cells	Reduced oxidoreductase and dehydrogenase activity, impairment of plasma membrane, and reduced cell viability.	[172]
Fe2O3 NPs	0.032,0.32,3.2 mg kg^{-1}	Mycorrhizal Clover	Reduced biomass	[39]
Ag, CeO2, Co, Ni NPs	-	Basil (*Ocimum basilicum* L.)	Affects fresh weight adversely	[80]
Au NPs	48 mg L^{-1}	Tobacco (*Nicotiana tobaccum* L.)	Necrotic lesions observed	[95]
TiO2 NPs	4000 mg L^{-1}	Tomato (*Solanum lycopersicum* L.)	Germination was reduced by 20%	[173]
ZnO NPs	-	Soyabean(Glycine max Merr.)	The deleterious effect on the biomass of leaves	[180]

4. NPs Work in Conjunction with Plants to Remediate Soil Contaminated with Metal and Metalloid

Researchers regularly work in the field of interaction behaviour of plants and NPs and found strong correlative behaviour in Phytoremediation. Fernández et al. [181] Studies on leguminous plants (*Ludwigia peploides* L. and *Limnobium laevigatum* L.) found symbiotic relations between symbiotic relationships of Pb remediation and high adaptability in harsh climatic conditions and decrease Pb concentration by root with time. Similar tolerance behaviour is also shown by other plants such as vetiver and *Targets erecta* L., Ageratum sp., etc. Chand et al. [182] and Cu, Zn, Cd Cr, Pb, and Ni toxicity did not suppress the growth [183,184]. Siddiqi and Husen [184] observed that heavy metal particles assemble in roots, but on exposure to air Pb movement between roots and leaves up to a certain extent of NPs was observed [185]. In turn, Gautam and Agarwal, [183] utilized *Vetiveria zizanioides* (L.) to enhance soil quality by removing dense Cu and Mn to translocate to stems from the roots, and Banerjee et al. [186] also removed the contamination of iron ore and restore soil quality by the use of *Vetiveria zizanioides* (L.). Results from some studies have shown that plant ferns such as Pteridophyta have a higher capacity to prevent As-contamination from soil relative to other hyper-accumulating plants [187].

Table 8. Phytoremediation of metal by plant with the help of nanoparticles.

Plant species	Nanoparticles	Pollutant	References
Soybean (Glycine max Merr.)	NZV-Fe	Cd	[188]
(Ryegrass) (*Lolium perenne* L.)	NZV-Fe	Pb	[189]
Barley (*Hordeum vulgare* L.)	NZV-Fe	As	[190]
Ryegrass (*Lolium perenne* L.)	Nano carbon black and nano-hydroxyapatite	Pb	[150]
Cabbage (*Brassica oleracea* L.)	Biochar supported Nano hydroxyapatite	Pb	[191]
Ryegrass (*Lolium perenne* L.)	Nano hydroxyapatite	Pb	[192]
Sunflower (*Helianthus annuus* L.)	Zeolite and SiO_2	Zn, Pb	[193]
	TiO_2	Cd	[194]

Chand et al. [182] found that on increasing the amount of metal used, in plants maximum was the concentration of the heavy metals which gives a higher translocation rate of metals such as Cr, Ni, and Cd in root shoot but accumulation rate is higher in leaves. Similar results were found by Coelho et al. [195] where the higher the concentration of Cr in the nutrient solution higher the rate of accumulation of levels of Cr in the plant. Choudhury et al. [195] utilized *Brassica* sp. (Indian Mustard) and *Tagetes erecta* L. for a Cr, Pb, Cu, and Zn extraction and found Tagests erecta L more capable of extracting Cr, Cu, and Zn. There are differences in the accumulation rate of different heavy metals in the same plant depending on which type of NM is applied since each metal is having a different binding capacity and the formation of the chelating ability depends on the extent of electronegativity or positivity of the metal thus involved as shown in Table 8.

5. NPs and Their Role in Improving Adaptation of Plants Towards Progressive Changes in Climatic Conditions

Now a day's food security is a challenging issue due to the expansion of urbanization of population growth within the limited resources that cause climate alteration. Climate alteration or change refers to changes in temperatures, water scarcity, salinity, toxic metal, and pollution. But the major concern is accelerating the adaptation of plants to these changes due to climate change without threatening the sensitivity of ecosystems [196]. Numerous efforts are done to improve management practices and the development of technologies toward the overall sustainability of the ecosystem [197]. Utilization of NPs in the agricultural system suggests crop yield increase by Nano-fertilizers in existing adverse environments. Salinity stress is a critical issue because 23% of cultivated land worldwide is affected. The use of Nano- SiO_2 in squash and tomato plant under salt-affected area improve seed germination, chlorophyll content, plant weight, proline accumulation [133,198], and Cd stress in wheat [140]. According to Torabian et al. [199], foliar spray of Nano-$FeSO_4$ on *Helianthus Annus* (L.) shows an affirmative response towards tolerance due to salinity as a result of decreasing the Na^+ absorption from leaves. Recently, Nano-SiO_2 could effectively increase the UV-B stress in wheat [200] and the availability of Nano-zeolite improves nutrient availability which helps in seed germination and growth [201]. In addition, NPs are found to be effective in the detoxification or remediation of harmful pollutants like heavy metals show in Figure 3. Fertilizers containing Si-based NPs are also effective against Cd, Pb, Zn, and Cu because it shows the putative effect on traditional fertilizers in reducing toxicity due to the presence of heavy metals in the soil [202]. Biotic factors influenced pests and diseases of Crops [203]. To minimize crop losses farmers used a huge quantity of inorganic pesticides which adversely affect human health and alter sustainability. Metal oxide NPs of Cu, Zn, and Mg effectively switch many plant diseases [204–206]. Recently in the field of plant protection using Nano-composites for plant protection due to their high effectiveness and eco-friendly nature [207]. NM also helps crop growth under unfavourable conditions by increasing enzymatic activity [208]. Application of Nano-SiO_2 and ZnO increases the accumulation of water uptake, nutrients, and amino acids thereby increasing the activity of catalase enzyme, superoxide dismutase, nitrate reductase, and peroxidases eventually improving the tolerance of plants to extremely harsh climatic conditions [140,209]. In addition, according to Jampílek and Kráľová [210], NPs regulate the expression of stress genes. Therefore, further work is required to identify the cascades for the regulation of genes by specific NPs in different plant species.

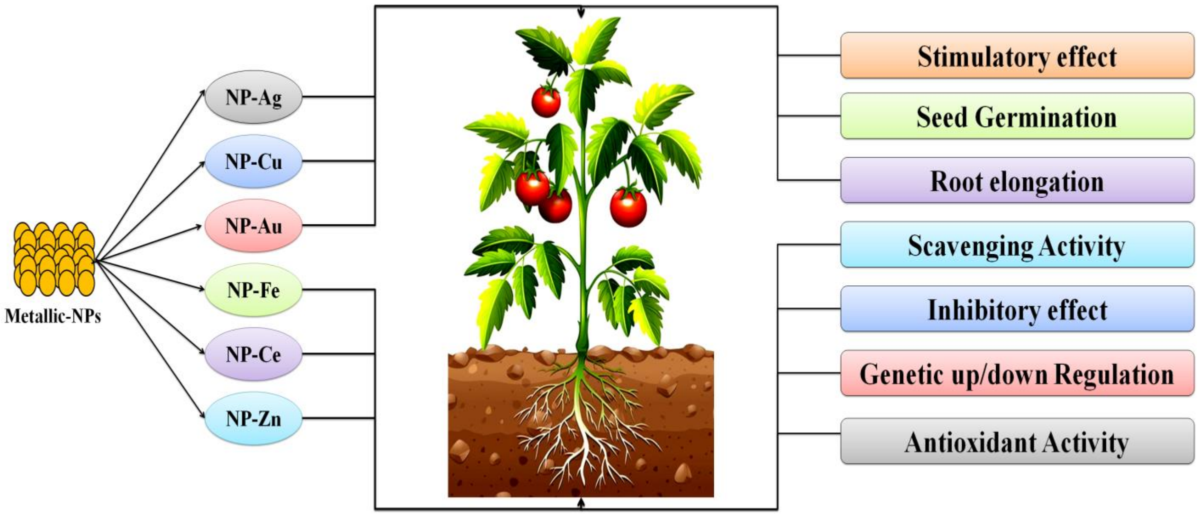

Figure 3. NPs and their role in Improving Adaptation of Plants Towards.

6. Conclusion and Prospects

ENMs play a significant role in the sustainable development of the environment. It is, therefore, necessary to study their toxicity to their surrounding ecology and environment. The study of the use ENMs in plants is related to their behaviour during translocation in plant systems and is dependent upon their surface energy, type, size, and chemical behaviour.

Literature studies have revealed that NPs show both positive and negative effects based on the part of the plant on which it acts. Despite the availability of several studies dealing with the different aspects of working of NPs it is still difficult to predict their behaviour in plants since it is based on several interrelated factors. Some case studies have shown that the NPs improved the process of seed germination and enhanced plant growth parameters. However, many contradictory results are also available. Studies related to the Phytotoxicity of NPs due to their direct exposure have emphasized the need for an ecologically responsible release of NPs containing waste in the environment. The most commonly used metal-based NPs include CuO, Ag, Au, ZnO, CeO_2, and TiO_2. Due to their wide range of applications, NPs have become the materials of choice among technology experts and scientists. Future studies should aim to obtain an enhanced mechanistic role of morphological and chemical behaviour on toxicity uptake and translocation of the NPs in plants and their parts.

Author Contributions

Shamshad Ahmad- Visualization, Writing original draft, review & editing; Atin Kumar Pathak- Writing – review & editing; Rose Pratima Minj- Writing – review & editing; Shalini Chaudhary- Writing – review & editing; Ashis Kumar: Writing – review & editing; Tania Chalotra Writing – review & editing; Neelu Raina Writing – review & editing.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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