Review

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Impact of Nanoparticles on Plant Growth, Development and Physiological Processes: A Comprehensive Review

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Review

Impact of Nanoparticles on Plant Growth, Development and Physiological Processes: A Comprehensive Review

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Abstract: Nanotechnology is being used in agriculture to improve plant nutrition while maintaining soil texture and safeguarding it against microbial illnesses. Examples of such applications include the utilization of nano-fertilizers, nano-pesticides, and nano-herbicides. Nanotechnology plays a crucial role in maintaining soil health, hence promoting the overall well-being of plants. Nanoparticles have been shown to enhance agricultural productivity and output, mitigate the opposing effects of chemical runoff and nutrient loss. Several factors, including concentrations, physiochemical properties, and plant species, influence the impact of nanoparticles on plants. Several nanoparticles have been shown to impact plant physiology, leading to enhanced biomass output and germination rate. Nanoparticles have the ability to alter molecular pathways in plants via their impact on gene expression. The presence of quantum dots, carbon nanotubes, ZnO, Ag, Fe_2O_3, Se, Au, TiO_2, Al_2O_3, SiO_2, and non-metal oxides of nanoparticles is of significant importance in the promotion of plant development and growth. Extensive research has been conducted on the role of NPs in the reduction of growth, inhibition of chlorophyll, and enhancement of photosynthetic efficiency. The main purpose of this study was to offer a comprehensive overview of studies that have examined the impacts, translocation, and interactions of nanoparticles with plants.

Keywords: Nanotechnology; microbial illness; pathway; productivity; translocation; interactions

1. Introduction

In 2050, the world's population will reach 9.8 billion, which is a one third increase over the current population, by a report of Food and Agriculture Organization (FAO) (van Dijk et al. 2021). To fulfil the nutritional requirements of this population, agricultural output must be increased and food security must be enhanced. Pollution, among other environmental factors, and biotic and abiotic stressors experienced by certain soils are preventing agricultural output from keeping pace with population growth (Godoy et al. 2021). There is a lot of pressure to find new ways to make food production better, safer, more efficient, and less harmful to the environment because to the enormous demand for high-quality agricultural goods (van Dijk et al. 2021).

Nanotechnology, which has found several uses in areas including materials science, medicine, physics, and chemistry, has also been effectively used in farming in the last few decades (Omanović-Mikličanin and Maksimović 2016). The utilization of nanoparticles in various applications has hastened the transformation of traditional farming and food production due to the fast expansion of nanotechnology **(Figure 1)** (Chaud et al. 2021). These particles can serve as nanosensors, antimicrobial, nanofungicides, nanoherbicides, and nanofertilizing agents (Fatima et al. 2021), and as stimulants for plant growth, enhancing resistance to adverse conditions like abiotic stress due to contamination of heavy metal in the soil (Rodríguez-Seijo et al. 2022). To keep agricultural systems viable in the long run, it is important to minimize the negative impacts that might come from employing nanoparticles (Ali et al. 2021).

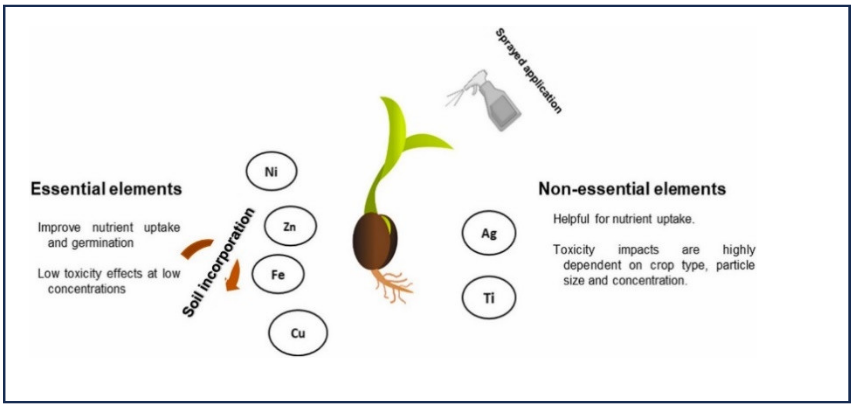

Figure 1. Effects of spraying essential and non-essential elements.

This manuscript specifically examines the use of inorganic nanoparticles in crop germination, with a focus on both the potential negative and positive effects (Ashraf et al. 2021). Understanding the process of germination is crucial for the survival and conservation of plant species. It helps in improving growth and yield of crops, which is essential for modern agriculture. Therefore, any factor that impacts germination will inevitably impact the subsequent plant development (Khan et al. 2022).

Understanding germination is crucial for restoring degraded soils and promoting vegetation growth. It also plays a dynamic role in food production, as it directly impacts the productivity of crops (Arnott et al. 2021). Germination is typically assessed using two parameters. The first is the germination percentage (GP), which calculates the proportion of seeds that have successfully germinated out of the total number of seeds. The second parameter is the seedling vigour index (SVI), which considers factors such as root and leaf weight or length. Various methods can be used to calculate the SVI (González-Feijoo et al. 2023).

Every year, a multitude of new NPs are introduced, each with enhanced capabilities and a wide range of applications. Biological responses to NPs are influenced by their physicochemical characteristics, like size, zeta potential concentration (Acharya et al. 2019). Biologists have discovered that NPs have an extensive range of potential that can greatly enhance plant productivity. These include acting as germination enhancers, creating nanofertilizers, delivering herbicides, detecting pests through nanosensors, and using nanoporous zeolites for controlled water and fertilizer release. Nevertheless, certain NPs can have negative effects on plants, inhibiting seed germination or being toxic to young seedlings (Hayes et al. 2020).

Various processes such as leaching, hydrolysis, photolysis, and decomposition can render certain fertilizers unavailable to plants, even though they are crucial for plant development and growth (Kah et al. 2019). There have been numerous innovative solutions developed in recent years to address the issue of food waste and improve crop yields. Nanopesticides and nanofertilizers are just a couple of examples of these novel solutions (Omara et al. 2019).

Biologists have discovered that nanofertilizers and nano encapsulated nutrients have the ability to regulate the release of chemical fertilizers, which in turn boost the activity of the desired plants (Iqbal et al. 2019). Various NPs are currently under investigation to determine their effectiveness in shielding plants from various environmental pressures and promoting plant growth (Rajput et al. 2021). Plant biotechnology offers exciting opportunities to manipulate gene expression and cellular properties, expanding our understanding of plant biology. Aside from their significant contributions to agriculture and environmental remediation, NPs also have a diverse array of applications in biosensors (Khan et al. 2019).

Plant uptake and translocation are influenced by various factors, such as the size, types, concentration, reactivity, toxicity, pore sizes, surface charge, and other properties of nanoparticles (Hu et al. 2020). When nanoparticles enter treated surfaces, they have the ability to modify their

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characteristics, reactivity, and bioavailability to living organisms (Singh et al. 2022). As a biologist, our aim is to present a comprehensive analysis of the advantages and disadvantages associated with the utilization of nanoscale materials in agriculture **(Figure 2)**.

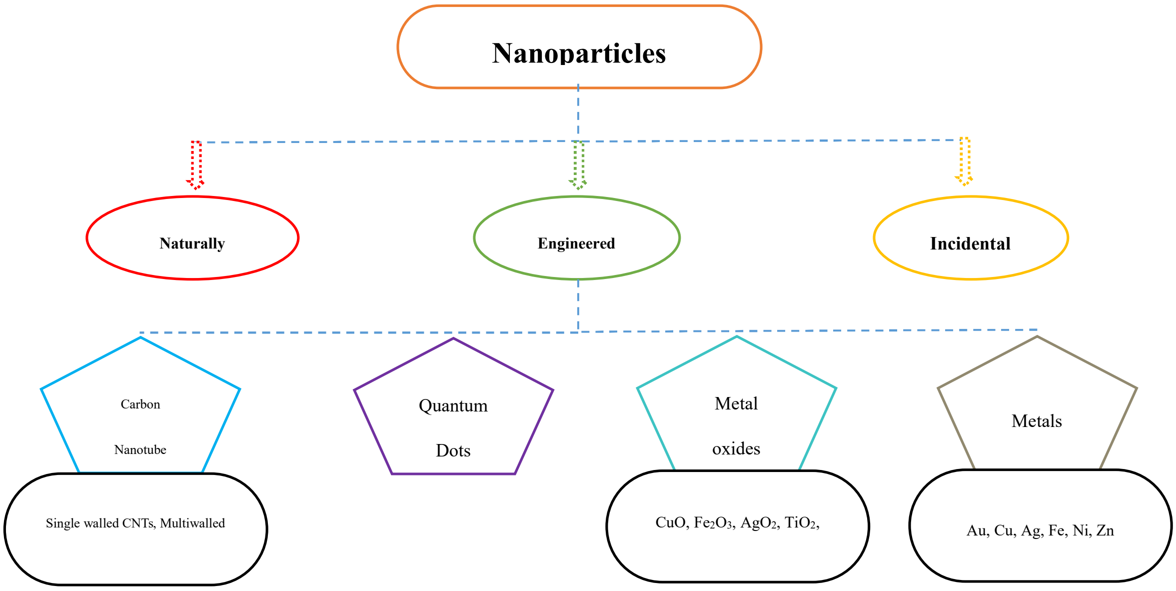

Figure 2. Nanoparticles and its types.

Micronutrients such as Zn, Mn, Mo, Fe, Cu, B, etc. are widely recognized as crucial for the process of growth and development. The implementation of the green revolution and innovative agricultural methods has led to a substantial rise in crop productivity, but at the expense of soil micronutrients such as Zn, Mo, and Fe (Dhaliwal et al. 2021). The use of nanotechnology (NT) has the potential to enhance the accessibility of micronutrients for plants. The enhancement of soil health and vitality may be achieved by the use of nano-formulations of micronutrients, which can be administered to plants through spraying or incorporated into the soil for root absorption (Peteu et al. 2010).

Zinc is crucial for plant metabolism when present at levels below the threshold, but it becomes harmful when present in quantities that exceed the optimal range (Natasha et al. 2022). Zn deficiency is a disorder that has been extensively studied and documented. Zn insufficiency is often seen in semi-arid/arid regions due to reduced solubility and heightened fixation (Younas et al. 2023). Hence, the amount of Zn available in dry soils varies from 0.1 to 2.0 mg/kg, which is inadequate to satisfy the plant's minimum micronutrient requirement of 60 mg/kg. Therefore, additional Zn treatments are necessary to optimize plant productivity. As to the World Health Organization (WHO), around 50% of the global population is affected by this deficiency, which makes Zn one of the micronutrients with the lowest recommended consumption (Beal et al. 2017).

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2. Plants Growth

Physiological reactions are the first notable modifications that transpire upon plant exposure to diverse environmental factors. The physiological reactions of plants to nanoparticles may exhibit both positive and negative effects, which are contingent upon the quantities of NPs and the specific plant species (Gupta et al. 2018). Research has consistently shown that the use of nanoparticles at lower concentrations promotes plant growth and facilitates the production of secondary metabolites (Karimi et al. 2018).

Zn (Zn) plays a vital role as a microelement in several biochemical processes inside plants, such as development and reproduction (Veena & Puthur, 2022). Multiple studies (Choukri et al. 2022) have provided evidence of the advantageous impacts of ZnO NPs on plant development.

To mitigate the ingress of extraneous substances, such as nanoparticles, the cellular walls of plants include a diverse array of functional groups, such as carboxylate, hydroxyl, phosphate, and many others. Biomolecules, such as proteins, polysaccharides, and cellulose, are formed by the combination of these groups (Vinopal et al. 2007). The key factor influencing absorption and transport of nanoparticles is the plant species. Therefore, a comprehensive mechanism that includes the entire system—roots, stems, and leaves—introduces nanoparticles into plants through interactions with soil, water, and several other environmental factors. Furthermore, the presence of nanoparticles in soil might lead to interactions with the root system, ultimately resulting in cellular absorption (Tripathi et al. 2017). Nanoparticles that possess a diameter comparable to that of the cell wall are capable of traversing its sieving mechanisms and ultimately reaching the plasma membrane. The diameter of the cell wall varies between 5 and 20 nm. Refer to **Table 1.**

Table 1. Applications of different NPs on plants to observe the effects in different concentration.

NPs Application	Size (nm)	Plants	Concentration	Effect	References
Soaking	20 to 45	Methi	20 to 30 mg/L	Promoted fresh and dry weights of plant	Elsherif et al. 2023
Adding to soil	20 to 60	Wheat	7mg/kg	Promoted plant height and tillers number	Mazhar et al. 2023
Adding to soil	20 to 60	Rice	10 mg/kg	Enhanced the number of tillers and height of plants	Mazhar et al. 2023
In Petri dishes	31	Barley	1 to 4 mg/L	Improved elongation of root, shoot and germination of seed	Plaksenkova et al. 2021
To soil	More than 100	Carrot	1 to 100 mg/kg	Biomass of the plant is increased	Song and Kim, 2020
To soil	More than 100	Lettuce	1 to 100 mg/kg	Biomass of the plant is increased	Song and Kim, 2020

Studies examined the physiological alterations that led to the growth-promoting effects of ZnO nanoparticles. These changes included the modulation of plant pigments associated with biomass accumulation, such as chlorophyll and carotenoids (Faizan et al. 2018), an enhancement in nutrient uptake efficiency (Chanu and Upadhyaya 2019), and an elevation in antioxidant metabolism (Venkatachalam et al. 2017).

3. Nanoparticle Absorption by Plants

NPs breach the root cell membrane, enter the plant's vascular system, and reach the leaves via a complex chain reaction (Tripathi et al. 2017). Certain nanoparticles may diffuse across lipid bilayers and enter cells via endocytosis by creating pores, binding to ion channels and aquaporins, etc. (Schmidt, 2015).

NPs may enter plant cells via the apoplastic and symplastic transport mechanisms. Smaller NPs penetrate the cell wall more readily, while larger ones pass via stomata, hydathodes, and the flower stigma (Hossain et al. 2016). Stomata can open and shut, despite their abundance. Nanoparticles bigger than 40 nm may pass the plant's stomata and hydathodes to reach the leaf's spongy and palisade parenchyma (Tripathi et al. 2017). NPs may enter the seed coat via parenchymatous intercellular spaces (Banerjee et al. 2019). However, aquaporins reassemble the AQP-1 and Galphai-3 regulatory complex to limit seed coat NP entry (Abu-Hamdah et al. 2004).

3.1. Foliar Uptake and Translocation of Nanoparticles

Foliar NPs penetrate plants via leaf epidermis or stomata. After absorption, they enter vascular tissue via apoplastic or symplastic pahways. NPs are largely deposited in vacuoles and cell walls, although vascular tissue (xylem and phloem) transports them upward and downward (Su et al., 2019). Plant physiological traits, atmospheric abiotic variables (humidity, light, and temperature), and NP attributes (size, shape, and charge) all influence NP penetration, transfer, and accumulation. *Cucumis sativus* exhibits foliar uptake of 8 ± 1 nm CeO2 NPs (Hong et al. 2014) and *Lactuca sativa* uptake of 50-100 nm Cu(OH)2 NPs (Zhao et al. 2016). **Figure 3** shows that foliar spraying NPs is more effective and environmentally favourable than root or soil exposure (Fan et al. 2020).

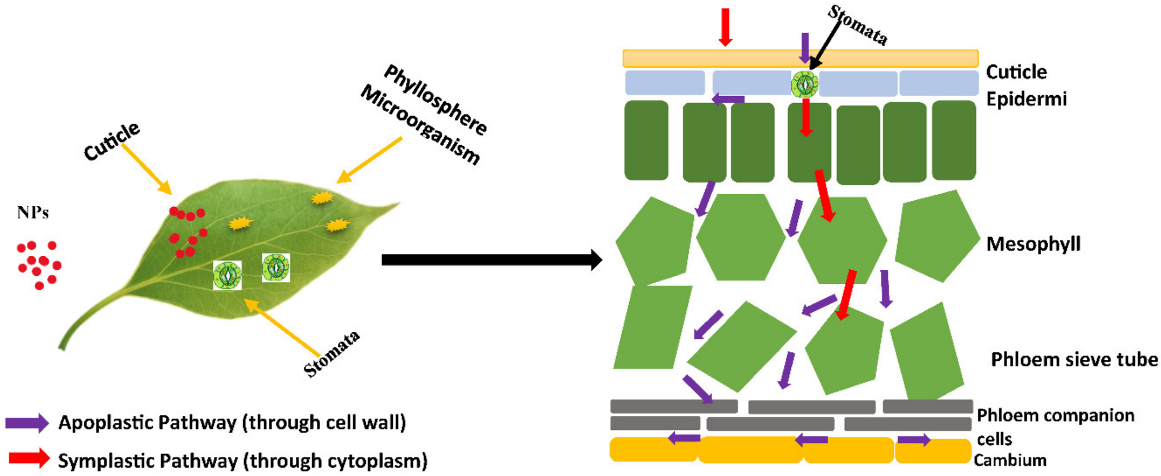

Figure 3. Foliar applications of NPs and transport via apoplastic and symplastic pathway.

3.2. Transformation and Uptake of Nanoparticles by Root

Roots have the ability to directly absorb nanoparticles from the soil and then transfer them to plant parts. For example, the roots of *Arabidopsis thaliana* can absorb Au NPs ranging in size from 7 to 108 nm (Taylor et al. 2014). Similarly, the roots of Arabidopsis thaliana can take up SiO2 NPs with sizes up to 200 nm (Slomberg and Schoenfisch, 2012). Wheat root has the ability to absorb TiO2 nanoparticles ranging in size from 36 to 140 nm (Larue et al. 2012). According to Larue et al. (2012), nanoparticles with a size smaller than 36 nm were able to enter the roots of plants and subsequently spread to other parts of the plant without undergoing any transformation. However, NPs ranging in size from 36 to 140 nm did not migrate to the shoots and instead accumulated in the root parenchyma. Furthermore, NPs larger than 140 nm did not accumulate in the root. **Figure 4** illustrates the transportation of nanoparticles in plants via the apoplastic and symplastic pathways (Avellan et al. 2021).

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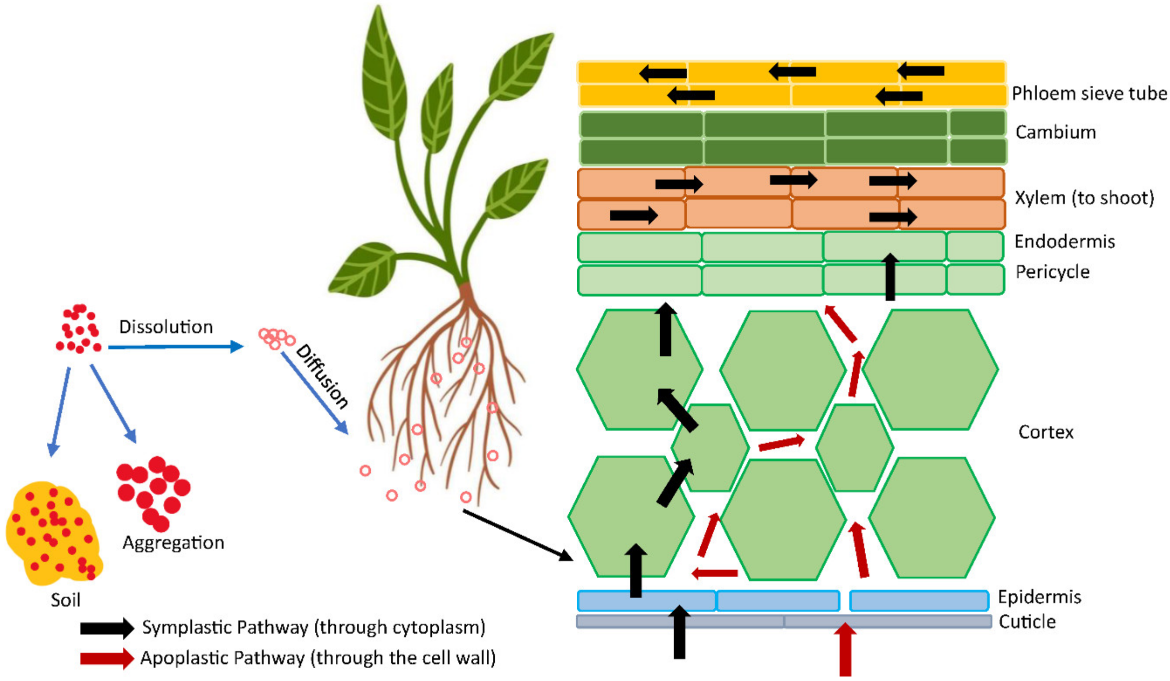

Figure 4. Root application of NPs and their transport via symplastic and apoplastic pathway.

The **apoplastic route** involves NPs passing via epidermis and cortex to endodermis, where casparian strip is formed in radial and transverse walls to inhibit NP and macromolecule access into the vascular system. The casparian strip is detached at the lateral root junction or underdeveloped at the root tip, so NPs may bypass it and enter the vascular system (Schymura et al. 2017). In the **symplastic route**, NPs reach the cytoplasm or plasmodesmata of neighboring cells via plasma membrane (PM). Transmission Electron Microscope (TEM) showed that Arabidopsis thaliana root tips subjected to 20, 40, and 80 nm Ag NPs accumulated Ag NPs in root cell plasmodesmata and middle lamella. Au NPs were found in poplar root cell cytoplasm, plasmodesmata, mitochondria, plastids, and cell walls using TEM subjected to 15, 25, and 50 nm Au NPs (Zhai et al. 2014).

4. Transformation of Nanoparticles

The conversion of nanoparticles takes place at several plant sites, including the root, leaf surface, and internal tissues (Mia et al. 2021). This study provides a concise overview of the sites where nanoparticles undergo transformation, the variables that influence NPs transformation, and the processes of absorption and translocation of changed NPs in plants.

4.1. Transformation in Soil

The presence of inorganic and organic components, as well as soil texture, can have an impact on the transformation of NPs in soil. Clay soil, with its limited pore space for air, creates a reducing environment that can result in a decrease in NPs. This decrease can occur through various mechanisms, including:

- **Leaching:** NPs being washed away by water, potentially entering groundwater or nearby water sources.
- **Dissolution:** NPs breaking down into smaller species or ions, losing their nanoparticle properties.
- **Adsorption:** NPs adhering to surfaces, such as soil particles or plant cell walls, reducing their availability.
- **Degradation:** NPs being broken down by chemical or biological processes, such as oxidation or enzymatic activity.

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- **Uptake and internalization:** NPs being taken up by plants or microorganisms, reducing their external concentration.
- **Sedimentation:** NPs settling out of solution due to gravity, reducing their concentration in the surrounding medium.
  - ➢ When dealing with sandy soil, it's worth noting that NPs tend to undergo oxidation due to the higher oxygen content. For instance, the presence of an Ag2O layer around Ag NPs can lead to the dissolution and subsequent release of Ag+ (Li et al. 2017).
  - ➢ The weathering process can have a significant impact on the availability of copper nanoparticles in soil, as well as its uptake and movement within lettuce plants (Servin et al. 2017).

4.2. Plant-Mediated Transformation of NPs

- ➢ A complicated process produces differences in organic matter, mineral components, soil pH, and microbial community that alter the transformations of NPs during their dissolution and transformation in the rhizosphere. Many chemical reactions, including dissolution, accompany the change of metal-based NPs, which may also include sulfidation, phosphorylation, chelation, or reduction (Zhang et al. 2020).
- ➢ The chemical modification of NPs at the Phyllosphere via interactions with the epiphytes (bacteria, fungus, and yeast) on the surface of the leaf might alter the aggregation state (Zhang et al. 2020).
- ➢ Depending on the species of plant, the kind and degree of NP transformation may differ. As an example, the root exudates of cucumbers (Cucumis sativus) are firmly bound to by CuO NPs (~40 nm), which causes the transformation of CuO NPs to Cu(I) and Cu (II) and decreases the absorption and buildup of Cu (Huang et al. 2017).

5. Physiological Effects of Nanoparticles in Plants

Figure 5 shows the positive and negative impacts of NPs on morphophysiological traits, plant growth, and agricultural crop output. Factors influencing NPs' effects include plant species, developmental stage, application technique, dosage, and supplementing level. In order to increase crop yields and plant development, many agricultural products nowadays are generated from nanotechnology (Awasthi et al. 2020). These goods are superior to traditional farming methods and pesticides because to their many desirable qualities, including their compact size, low toxicity, ease of handling, extended storage life, and high efficacy (Hong et al. 2021).

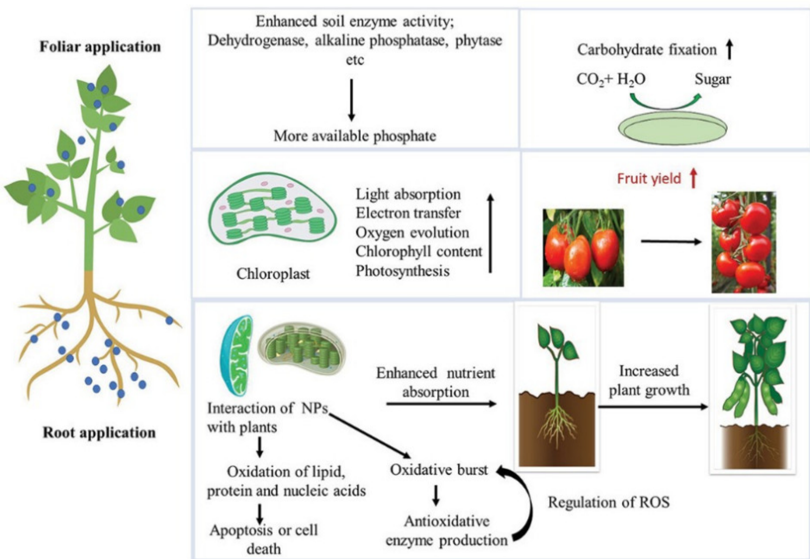

Figure 5. Effect of foliar and root application of NPs on the growth and yield of plants.

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6. Impression of Different NPs on the Physiological Processes for Plant Development, Growth, and Maturation

6.1. Copper Nanoparticles

CuO NP exposure had a substantial influence on the germination, biomass, shoot development, and other processes of many plant species (Rajput et al. 2018). The toxicity of CuO nanoparticles did not have any impact on seed germination in maize plants. The nanoparticles were transported to the shoots via the xylem and then transported back to the roots via the phloem. *Brassica napus* seedlings were cultivated in MS medium supplemented with CuO NPs (0, 10, 100, and 1000 mg L^{-1}) for a duration of 10 days (Wang et al. 2012). The administration of a maximum dose of 10 mg L^{-1} led to the initiation of growth, whereas higher concentrations (100 and 1000 mg L^{-1}) caused a decrease in root dry weight and an increase in shoot elongation (Rahmani et al. 2016).

The growth of *Lemna minor* was impeded by the presence of Cu^{2+} in the culture medium at lower concentrations, in contrast to greater concentrations of CuO (Song et al. 2016). Applying a colloidal solution of CuNP (0.5 mg L^{-1}) and CoNP (0.8 mg L^{-1}) along with MS media to the *Mentha longifoila* plant resulted in a significant increase in height and growth, as well as a 29.4-33.9 % increase in internodes, a 55.6-26.2 % increase in shoots, and a 30-40 % increase in reproduction coefficient (TalankovaSereda et al. 2016). Copper nanoparticles, produced from tea extract, had beneficial effects on the growth of seedlings and the signalling of nitric oxide when exposed to Lactuca sativa at a concentration of 20 μg mL^{-1} or lower (Pelegrino et al., 2020).

6.2. Iron Oxide Nanoparticles

Applying iron oxide (Fe_2O_3) nanoparticles to plants greatly enhances their growth, ability to withstand stress, and nutritional condition. According to Yasmeen et al. (2015), the germination percentage of wheat (*Triticum aestivum*) was enhanced by immersing it in distilled water and thereafter subjecting it to incubation in a solution containing iron nanoparticles. Nevertheless, the absence of NPs in the distilled water resulted in a decrease in root development, while the presence of NPs in the distilled water led to an increase in root growth. Both the positively and negatively charged ions of iron oxide at concentrations of 3 and 25 mg L^{-1} influenced the physiology of *A. thaliana*. According to Bombin et al. (2015), the seedling and root length remained unchanged when exposed to a dosage of 3 mg L^{-1}. However, these lengths significantly reduced when exposed to a dose of 25 mg L^{-1}.

Researchers have shown that applying iron oxide and chelated iron EDTA to Acinetobacter hypogaea enhances the biomass, germination, and development of peanut plants by increasing enzyme antioxidant activities and phytohormone levels. According to Rui et al. (2016), the application of Fe_2O_3 to plants resulted in enhanced iron availability, making it a viable option for fertilization purposes. Liu et al. (2016) revealed that the exposure of L. sativa seedlings to Fe_2O_3 NP (5-20 ppm) resulted in a 12-26 % improvement in root elongation. According to research done by Tombuloglu et al. (2019), the accumulation of Fe_3O_4 in *Hordeum vulgare* resulted in enhanced plant growth and higher photosynthetic efficiency.

6.3. Silver Nanoparticles

Because of its antimicrobial characteristics, silver (Ag) has found extensive use in industry and medicine, exposing it to more plants and humans than ever before. The usage of Ag NPs in agriculture has shown promising results due to their many favorable impacts on plant growth and development (Almutairi 2016). When silver nanoparticles were used excessively, they increased the synthesis and activity of antioxidants such carotenoids and proline, as well as peroxidases and catalases. Additionally, at higher dosages, it enhanced seed germination and development in *Lolium multiflorum* and *Eruca sativa*, while it reduced root length in *V. radiata* and *Sorghum bicolor* (Aqeel et al. 2022). The effects of heat stress in *T. aestivum* were mitigated by Ag NPs (Iqbal et al. 2019). Numerous biochemical indicators, such as leaf area, root and shoot length, carbohydrate and protein

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contents, and antioxidant enzyme activity, were enhanced in plants that were exposed to Ag NPs. These plants included *B. juncea*, common bean, and maize (Salama 2012).

6.4. Carbon Nanotubes

Carbon nanotubes (CNTs) are gaining attention in the diagnostic, biomedical, and agricultural fields because of their varied physiochemical properties (Patel et al. 2020). Thanks to their one-of-a-kind physicochemical properties, CNTs are great for regulating plant development, absorbing water, and supplementing nutrients (Achari et al. 2020). Nanoparticles containing carbon, such as C60, SWCNTs, and MWCNTs, have many uses in the scientific community. By influencing gene expression, SWCNTs improve rice seedlings' water intake and speed up the germination process (Zhang et al. 2017).

Tomato seedlings (*Solanum lycopersicum*) were shown to germinate and grow more rapidly when exposed to CNTs as compared to a control group. Additionally, the CNTs facilitated water absorption by penetrating the plants' outer layer (epidermis) (Fincheira et al. 2020). According to Rahmani et al. (2020), a lower concentration of oxidized multi-walled carbon nanotubes (~30 nm) might be an effective treatment for *B. juncea* effect are:

- Enhanced growth and biomass production (e.g., TiO2 NPs)
- Improved photosynthesis and light absorption (e.g., ZnO NPs)
- Increased water uses efficiency and drought tolerance (e.g., SiO2 NPs)
- Enhanced nutrient uptake and transport (e.g., Fe3O4 NPs)
- Altered hormone regulation and signaling (e.g., Au NPs)
- Increased stress tolerance and antioxidant activity (e.g., CeO2 NPs)
- Modified cell wall composition and structure (e.g., Ag NPs)
- Changed gene expression and regulation (e.g., CuO NPs)

The use of MWCNTs has been shown to hasten seed germination in *G. max* and *H. vulgare* plants, with no detrimental effects on the plants' future growth (Samadi et al. 2020). Water channel protein-encoding genes were more abundant in treated seeds compared to control seeds. Using a lower dose of MWCNTs improved water delivery in *Z. mays* plants (Tiwari et al. 2014).

The same results have been shown for *B. napus* and *C. arietinum* plants. Also, via influencing changes in root plasma membrane lipid content, stiffness, and permeability, MWCNTs enhance aquaporin transduction in NaCl-challenged conditions (Martinez-Ballesta et al. 2020).

7. Nanoparticles Influence the Structure and Function of Plants' Photosynthetic Systems

Plants and algae both use photosynthesis to transform the energy from the sun into chemical energy. The amount of energy that plants are able to shift over their life cycle is a meagre 2-4% (Kirschbaum 2011). Photosynthesis, mineral and nutrient translocation, and the oxygen cycle are all processes in which plants play an essential role. The nutrients that plants take in may be either essential or non-essential; nonetheless, there is a concentration at which they start to become toxic (Mitra 2017). By using gene editing and nanotechnology, scientists can improve the photosynthetic system and efficiency of plants. The interaction between plants and NPs will inevitably have an effect on translocation as well as the acceleration of plant biotechnology.

Toxic NPs like CuO and Ag disrupt the structure and function of the photosynthetic apparatus.

Inhibitory Effects:

- Ag NPs (silver nanoparticles)
- CuO NPs (copper oxide nanoparticles)
- ZnO NPs (zinc oxide nanoparticles)

can inhibit photosynthesis by:

- Damaging chloroplasts and disrupting electron transport chains
- Reducing light absorption and pigment content
- Altering stomatal aperture and gas exchange
- Inducing oxidative stress and antioxidant defenses

On the other hand, NPs like:

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- TiO_2 NPs (titanium dioxide nanoparticles)
- SiO_2 NPs (silicon dioxide nanoparticles)
- Fe_3O_4 NPs (iron oxide nanoparticles)

can enhance photosynthesis by:

- Increasing light absorption and scattering
- Improving electron transport and ATP production
- Enhancing stomatal conductance and CO_2 uptake
- Reducing oxidative stress and promoting antioxidant activity

NPs cause chloroplast anomalies such as reduced photosynthetic pigment concentration (particularly chlorophyll) and grana disruption. Nones are inefficient in photosynthesis and photosystem II. A number of undesirable effects persisted even after the introduction of CeO_2 and TiO_2 NPs improved electron transport between PS II and I and Rubisco activity (Tighe-Neira et al. 2018). The use of SWCNTs resulted in a tripling of chloroplast electron transport rate and photosynthetic activity. Nano TiO_2-induced carboxylation by Rubisco activation enhances photosynthetic carbon absorption (Ali et al. 2021). SiO_2 NPs enhanced photosynthesis by influencing carbonic anhydrase and photosynthetic pigment activity (Poddar 2020).

8. Nanoparticles and Antioxidant Capacity

Exposure to NPs has the potential to activate antioxidant defence mechanisms, cause oxidative damage, and generate reactive oxygen species (ROS) (Rico et al. 2015). An integral aspect of the antioxidant defence system are enzymatic antioxidants such as glutathione reductase (GR), glutathione, as well as chloramphenicol acetyltransferase (CAT), superoxide dismutase (SOD), glutathione peroxidase (GPOX), and glutathione reductase (GR) (Kaur et al. 2019). As per Rico et al. (2015), SOD is responsible for converting superoxide ions into hydrogen peroxide, whereas CAT and GPOX are responsible for stifling peroxy radicals and reactive oxygen species, respectively. The generation of reactive oxygen species (ROS) by NPs via APOX involves the direct reduction of hydrogen peroxide into water (Mittler 2016). The anti-oxidant enzyme activities of several NPs. A few examples are the following: nFe_2O_4, $nCeO_2$, and nCo_3O_4 improve catalase activity; nFe_3O_4, $nCeO_2$, $nMnO_2$, nCuO, and nAu enhance GPOX activity; and $nCeO_2$ and fullerene generate superoxide dismutase (Tripathi et al. 2017).

There is a lack of evidence connecting the enzyme activity disruptions seen in plants exposed to NPs to the chemical features of NPs or to the enzyme interactions with these NPs as the origin of these changes, despite the fact that several nanophytotoxicity studies have proven this. It turned out that NPs affected enzyme activity in different ways, for sure. While $nTiO_2$ enhanced the GPOX, SOD, and CAT activities in *Lemna minor* and spinach, respectively, it decreased the GR and APOX activities in *Vicia faba* (Lei et al. 2008). This makes it difficult to isolate the NPs that affect certain enzymes.

9. Conclusion

Nanotechnology, a novel approach, has several scientific uses. Nanoparticles may lead to food security and innovative farming. NPs in farming improve the global economy in various ways. Due to a paucity of data, NPs' toxic effects are unknown, however NP-plant interaction is sensitive to NP size and may be useful or harmful. They affect plants differently according on their growth stage, exposure duration, the absorption rate, and physiochemical traits. NPs outperform traditional resources in effectiveness and agronomy. Interactions between plants and NPs may identify illnesses on-site, promising sustainable agriculture. Nano-based herbicides, insecticides, fertilizers, fungicides, and sensors have been studied for plant management and controlled release to protect the environment. However, the expanding use of NPs in agriculture and related sectors raises concerns about environmental pollution, thus proactive measures should be taken to avoid their buildup. Due of population growth, agricultural experts worry about food security. Nano-revolution will improve food security, the ecology, and farm sustainability. Molecular science research on plant-NP interactions is critically needed to reduce phytotoxicity and boost agricultural yield for human welfare.

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Data availability statement: Not applicable

Conflict of interest: We declare that current article is original and has not been submitted for publication, in part or in whole, to any other national or international journal.

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