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Review Article

Positive and negative effects of nanoparticles on plants and their applications in agriculture

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Abstract

Nanotechnology is the promising field with its wide applications in biotechnology, pharmaceutical science, drug targeting, nano-medicine and other research areas. This review highlights the positive and negative impact of nanoparticles on plants and its wide applications in agricultural sciences. Effect of NPs in terms of seed germination, growth promotion and enhancement of metabolic rate has been evaluated by several scientific researches. However, NPs also exert their negative effects such as suppression of plant growth, inhibition of chlorophyll synthesis, photosynthetic efficiency etc. Effects of NPs can be either positive or negative it depending upon the plant species and type of nanoparticles used & its concentration. Modern nano-biotechnological tools have a great potential to increase food quality, global food production, plant protection, detection of plant and animal diseases, monitoring of plant growth nano-fertilizers, nano-pesticide, nano-herbicides and nano-fungicides.

Keywords: Nanoparticles; Agro-waste; Nano-application; plant protection; biogenic nanoparticles.

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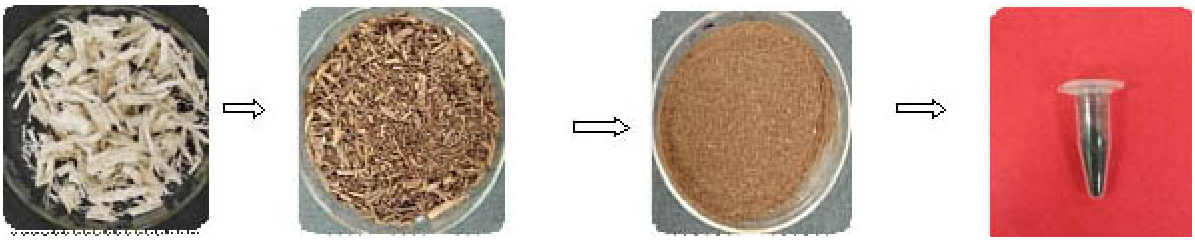
Introduction

Nanoscience is a developing concept in the agricultural area. In recent times, rapid progress in nanotechnology has made it possible to synthesize engineered nanoparticles (ENPs) with multiple types, sizes, and morphologies (1). Nanoparticles (NPs) are characterized by unique physical and chemical features like, surface area, pore size, particle morphology, and reactivity. Another name of NPs is “magic bullets” due to their intensive applications in agricultural field. Nanoparticles can be used as nanofertilizers, nano-pesticides and herbicides which are useful to increase crops productivity, to control excessive uses of chemicals fertilizers and also increase survivability against biotic stress. They regulate plant development and increase metabolic activity (2-4). NPs may affect on the plant growth species either positively or negatively depending on its type and concentration used. It is important to consider the interaction and impact of NPs in agricultural, for example Zn which expresses toxic effects whereas silicon is detected as valuable for flora (5). Several investigators



(a) Sugarcane bagasse (b) combusted bagasse (c) Ashes of bagasse (d) Silica powder

Fig. 1. Synthesis of silicon nanoparticles from agro-waste (Sugarcane bagasse)

depicted that NPs have potential to improve the germination rate, growth and productivity. Higher amount of NPs occur in the soil rather than water and air (6). The influence of NPs on agronomic, atmosphere or society can be both progressive and destructive.

Synthesis of Nanoparticles

Nanoparticles can be synthesized in three ways: physical, chemical, and biological. Commonly physical and chemical methods used for the synthesis of nanoparticles. Due to aforesaid reasons, biological synthesis pathway prefer over the physical and chemical methods for the synthesis of NPs.

Major disadvantage of Physical and chemical methods is that physical methods needs a more time to achieve thermal stability, consuming a lot of energy, occupying large space in case of furnance. In case of chemical synthesis of NPs employs harsh reducing agent like sodium borohydride, sodium citrate and organic solvents etc. These chemical reagents pose toxicity issues along with environment issues. Due to toxic impacts of the physical and chemical methods, biological method prefer for the synthesis of NPs. Production of NPs involves use of bacteria, fungi, algae, plant and agro-waste. Agronomy is a backbone of our economy but now agricultural sector facing many problems like environmental issue, urbanization, sustainable uses of resources, climate changes. NPs can be synthesized through green technology by using algae, plant extract and agricultural waste. It would be a cost-effective, ecofriendly and easy to handle as compare to physical and chemical methods (7,8). So, these materials can be used for improvement of crop productivity and minimize agronomy problems. Plants and agro-waste tender a superior option for the biogenic NPs as the protocols involving plant source are free from toxicants. The various NPs can be synthesized through plant extract like *Aloe vera, Allium sativum, Chenopodium album, Azadirachta indica, Citrus sinensis, Eclipta prostrata, Vitex negundo, Mangifera indica, Glycine max* and from algae such as *Sargassum muticum, Chlamydomonas spp., Euglena gracillis, Chlorella vulgaris* and from agriculture waste, sugarcane bagasse (Fig. 1), Egg shell, rice husk, mango peel, corn cob bamboo leaves etc. (Table 1 and 2).

Interaction and Translocation of Nanoparticles in plants

Interaction and uptake of NPs by the plant system based upon the nature of NPs (Size, shape and concentration). The NPs lies in size (40-50 nm), can penetrate the plant tissues. NPs interact with plant roots system with different methods, which are specialized in absorption of nutrient and water. NPs of 2 nm size can be applied exogenously through leaves and will cross cuticular pore and stomata (29,30). The presence of symbiotic bacteria, fungi, algae also influences the uptake of NPs into plant system (31,32). Here are certain processes and carriers by which NPs can enter into the plant system and cross the plasma membrane such as endocytosis, pore-formation, carrier proteins, Plasmodesmata and ion channels. Endocytosis is most suitable way for NPs to enter into plant cell. The interaction and translocation of NPs depend upon the size, shape, concentration and plant variety. The response of NPs depends upon the plant species, age and internal and external conditions. NPs can damage the cell wall and plasma membranes through penetration into the cell (33). Cell wall is first barrier as a molecular sieve which permits only minor NPs to enter into the cell. Small sized NPs move into the cell by root system and large sized NPs enter through flower stigma and stomata with the help of endocytosis and symplast (34,35). After penetrating the cell, NPs can move only by two ways such as the apoplast and the symplast (Fig. 2).

Phytotoxicity and survival mechanism induced by NPs

NPs enter into the cell and interrupt Electron transport system (ETS) cycle of chloroplast and mitochondria and triggered oxidative burst due to increase of reactive oxygen species (ROS) concentration (36, 37). ROS have both hydroxyl radical and superoxide free radical and non-radical singlet like oxygen and hydrogen peroxidase (37). It work as an transporter molecule, excess level of ROS cause adversative impacts in cell known as oxidative stress (38-42). When cells are exposed to excess levels of ROS induce destruction of DNA, oxidation of protein, lipid peroxidation and membrane damage finally caused programmed cell death (43). So, metal and metal based NPs can induce oxidative stress in many plant species. ROS lead to oxidative destruction in chloroplast and mitochondrial DNA damage and DNA molecule causes change in the encoded protein that result in malfunction and entire inactivation of the determined proteins (44). Various study showed that *Ricinus communis* seed under the treatment of AgNPs increase ROS production which involved in antioxidant defense mechanism (Superoxide dismutase enzyme (SOD), peroxidase (POD) activity and phenolic acids). Production of phenol increase defense against pathogen. Due to ROS generation, increase root length up to a certain level (45-48).

Table 1. Nanoparticles synthesized from different plants species

Plant	Type of Nanoparticles	References
Aloe vera	Au, Ag, Cu, ZnO	(10,20)
Allium sativum	Ag	(11)
Anacardium occidentale	Au/Ag bimetallic	(12)
Azadirachta indica	Au/Ag bimetallic	(13)
Chenopodium album	Ag, Au	(14)
Citrus sinensis	Ag	(15)
Eclipta prostrata	Ag	(16)
Terminalia catappa	Au	(17)
Vitex negundo		(18)
Mangifera indica		(19)
Lycopersicum esculentum	Zn	(21)
Glycine max	Pd	(22)

Table 2. NPs from Agro waste of wild growing plants

Agro waste	NPs	References
Tea leaf extract (*Camellia sinensis)*	Ag	(23)
Egg shell	Au	(24)
Banana peel extract	Au	(25)
Papaya fruit extract	Ag	(26)
Sugarcane bagasse, Cassava periderm, Maize stalk	Si	(9)
Grape waste	Au	(27)
Tea waste	Fe	(28)

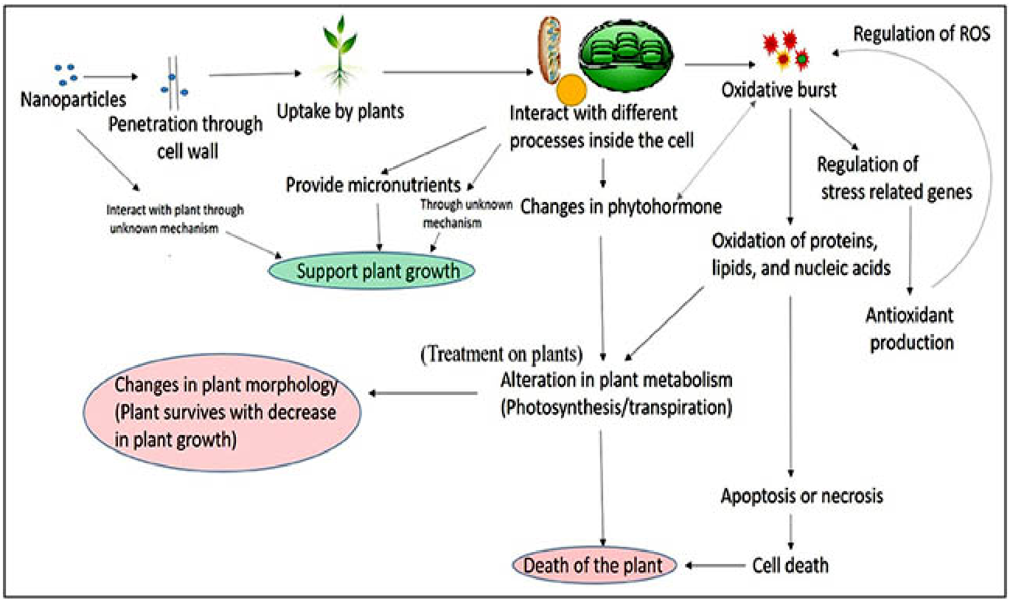


Fig. 2. Interaction, translocation and mechanism induced by nanoparticles in plants, from Kurpea (33)

Table 3. Positive and negative effect of different nanoparticles on various plant species

Nanoparticles	Plant species	Effects	References
AgNPs		**Positive effect**	
	Lolium multifolium, Eruca sativa	Enhance plant growth	(50)
	Zea mays	**Negative effect**	
		At low concentration root and shoot length increase but at high concentration decrease the length	(51)
	Sorghum bicolor		
		Reduced root growth, root length and biomass	
	Lolium multiform		(50)
		Broken epidermis and root cap	
	Baccopa monnieri		(52)
		Different concentration affected the seed germination	
	Vigna radiata		(53)
		Decrease shoot weight and increase biomass. Reduction in growth	
	Triticum aestivum		
ZnNPs		**Positive effect**	
	Cucumis sativa	Increase micronutrients	
	Cicer arientum	Increase dry shoot weight	(70)
	Cyamopsis tetragonoloba	Increase biomass, root and shoot length	(84)
	Vigna radiata	Increase germination, root and shoot growth	101)
	Arachis hypogaea	Increase seed germination at low concentration but decrease at high concentration	(67)
		Negative effect	
ZnO			
		Inhibited root growth	
	Cucumis sativa		(70)
	Triticum aestivum	Inhibition of chlorophyll synthesis leading to reduce photosynthetic efficiency	(68)
	Brassica napus	Reduced germination and simultaneously inhibit root growth	(102)
		Positive effect	
SiO_2	*Lycopersicum esculentum*	At low concentration enhance seed germination of tomato	(63)
	Glycine max	Promoter effect on germination	(64)
Si	*Ocimum basilicum*	Increase dry and fresh weight of leaf	(66)
TiO_2	*Vigna radiata, Arabidopsis thaliana, Foenticum vulgare, Lemna minor, Triticum aestivum*	**Positive effect**	
		enhance germination, plant growth chlorophyll content	(82)
AlO		**Positive effect**	
	Triticum aestivum	Significantly improved elongation	(83)
		Negative effect	
	Nicotiana tabacum	Decrease plant growth and development	(83)
Cu		**Positive effect**	
	Triticum aestivum	Increase in germination percentage	(57)
Fe		**Positive effect**	
	Triticum aestivum	Reduction in root length	(57)
FeO		**Negative effect**	
	Arabidopsis thaliana	Inhibitory effects on development	(52)
CNTs		**Positive effect**	
	Hordium vulgare, Glycine max, Zea mays	Increase seed germination	(62)
MWCNTs	*Lycopersicum esculentum,* *Nicotiana tabacum*	Increase plant growth, height, flower number	(61)

Positive and Negative Effects of various NPs on Plant Growth and Seed Germination

The main objective of nanomaterials in agronomy is to promote plant protection, productivity and reduce nutrient losses (7). They can also be used to reduce the toxicity of metals and increase crop productivity without high cost of energy (8). The extensive uses of NPs promote seed germination, plant development and can ange its morphology with abiotic stress shown in (Table 3).

Silver (Ag) NPs

AgNPs shows both progressive and destructive influence on plants growth and development. The extensive use of AgNPs leads to an enhancement in peroxidase, catalase activities and synthesis of antioxidants complexes like carotenoids and proline. It also enhance plant growth and seed germination in *Lolium multifolium* and *Eruca sativa* (50) but in *Vigna radiata, Sorghum bicolor,* inhibit the root length at high concentration and increase at low concentration (51,52*).* In *Triticum aestivum,* AgNPs decrease shoots weight and increase biomass. Green synthesized AgNPs increase the rate of germination of *Boswellia ovaliofoliolata*, improved growth rate (root and shoot length, leaf area) and enhanced biochemical traits (enzymes, protein content antioxidant, carbohydrates, chlorophyll) in *Brassica juncea*, *Phaseolus vulgaris* and *Zea mays*. The seeds of *Oryza sativa* treated with 20 nm $AgNO_3$ which shows minor negative effects on seed germination (Fig. 3). The silver NPs synthesized by green route also shows significant impact on *Trigonella foenum-graecum* seedlings (53).

Fig. 3. Effect of Silver nanoparticles on *Oryza sativa*, Thuesombat (49)

Carbon Nanotubes (CNTs)

Carbon-based nanomaterials have gained high attention due to its unique properties. CNTs are classified into two categories *i.e.* single-walled carbon nanotubes (SWNT) and multi-walled carbon nanotubes (MWNTs). CNTs have the tendency to penetrate the wall of cell and deliver to cells. Single-walled-CNTs (SWCNTs) act as transporters for transmit DNA fragments. Numerous studied shows that multi-walled-CNTs (MWCNTs) have tendency to improved development of plant and uptake efficiency of essential nutrients (54-56). MWCNTs regulated genes expression in *Hordeum vulgare*. CNTs show the progressive role in growth and germination rate, but have negative influence in various floras (57). MWCNTs improved peroxidase, dehydrogenase activity, gene expression (58,59) and increase the rate of germination in *Oryza sativa*, *Glycine max*, *Brassica juncea*, *Phaseolus mungo* and *Lycopersicum esculentum.* Water soluble CNTs influence the *Triticum aestivum* development in sunny and shady environments (60-62).

Silicon Dioxide (SiO_2) NPs

NPs influence the plant growth and seed germination and it depends upon the concentration. Nano-SiO_2 increase sprouting in *Lycopersicum esculentum* at low concentration (63). Nano-SiO_2 and nano-titanium dioxide (nano-TiO_2) enhanced seed sprouting of *Glycine max* through increasing nitrate reductase (64) which improved the ability of seed to absorb water and nutrients. Due to Nano-$SiO_{2,}$ plant can grow despite in environment stress and the use of nano-SiO_2 enhance leaves weight, accumulation of proline, amino acids, nutrients, chlorophyll, and action of enzymes (65). SiO_2NPs also enhance the growth of plant, rate of photosynthesis, PSII potential activity, photochemical efficiency, stomata conductance, transpiration rate, ETS. Leaf dry and fresh weight, chlorophyll and proline content of *Ocimum basilicum* increased by silica NPs (66).

Zinc Oxide (ZnO) NPs

ZnO NPs show positive impact on *Arachis hypogaea*, *Glycine max*, *T. aestivum* and *Allium cepa* at low concentration (67-69). Only *Cucumis sativus* germination was increase when different concentrations of ZnO NPs were applied on different plant species like *Cucumis sativus*, *Medicago sativa* and *Lycopersicum esculentum* (70). In *Cymopsistetra gonoloba,* ZnO NPs promoted an important enhancement like improve plant biomass, plant growth, chlorophyll content, synthesis of protein (71). Nano ZnO added in MS media promoted embryogenesis, plantlets regeneration, plant development and some enzymes (proline, superoxide dismutase, catalase, and peroxidase) which are promote to survive in biotic stress (72). ZnO NPs show positive effect on *Fagopyrum esculentum* (Fig. 4). The presence of ZnO NPs improved the antioxidant properties, photosynthetic efficiency and enhanced proline accumulation that provides stability to plants (74).

Gold (Au) NPs

AuNPs increase the amount of leaves, plant height, and chlorophyll content and promoted the photochemical reaction, increase NADPH + H^+ and ATP to convey CO_2 fixation, increases sugar amount in treated seedling (75,76). Cellular and physiological process (lipid metabolic rate, glycolysis, transport system, DNA transcription, synthesis of protein, photosynthesis rate) increased due to treatment of AuNPs. Green synthesized AuNPs from *Tiliacora sp.* show minimum toxicity in rice seedlings (Fig. 5) which can be potentially used as nanocarriers in agriculture.

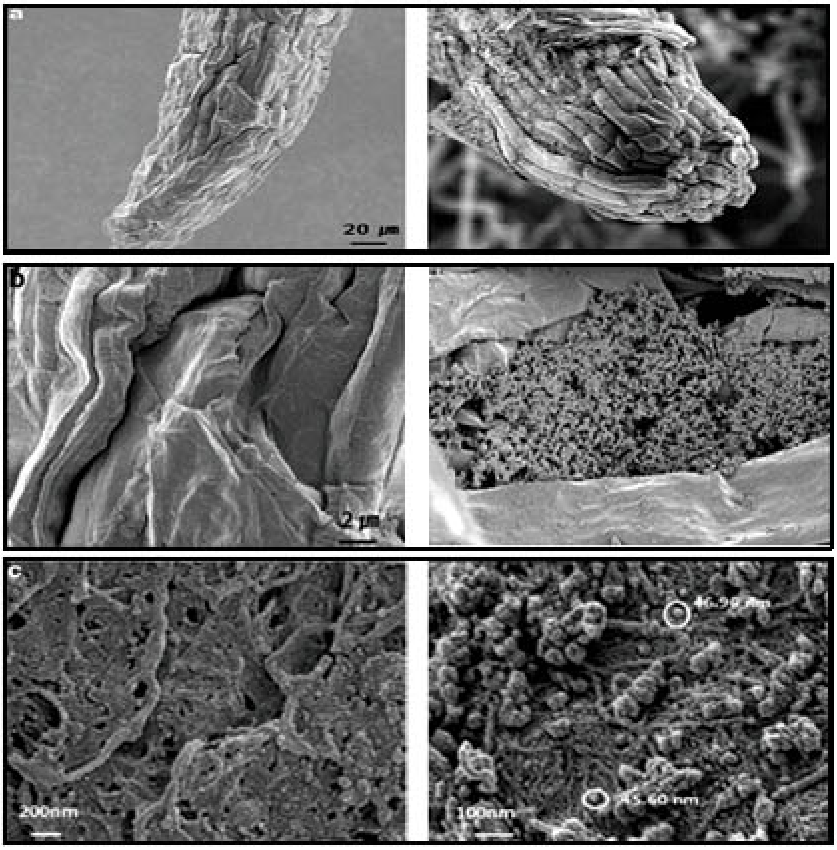


Fig. 4. Scanning electron microscope images of Buckwheat (*Fagopyrum esculentum*) root surface under control (left) and treatment (right) with ZnO nanoparticles (1,000 mgL^{-1}) at a magnification of ×1,000 (a), ×5,000 (b), and ×150,000 (c); Lee (73)

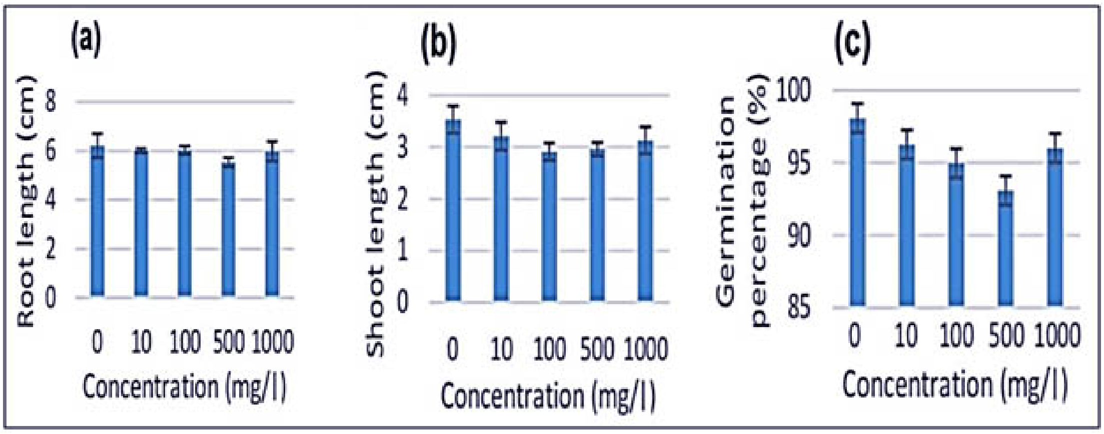


Fig. 5. Effect of different concentration of gold nanoparticles on *Oryza sativa;* Ndeh (77)

Titanium Dioxide (TiO_2) NPs

TiO_2 NPs initiate progressive growth, development and productivity of crop under abiotic pressure in *Triticum aestivum* plant. Various studies of TiO_2NPs were done on bacteria, algae, planktons, fish, mice, but remain incomplete on plant. Enzymes activity (glutamine synthase, glutamate dehydrogenase, glutamate-pyruvate transaminase and nitrate reductase), which are involve in nitrogen metabolism was direct regulated by TiO_2NPs. Conversion of Inorganic nitrogen to organic nitrogen in the form of protein and chlorophyll and enhancement weight of plant was also done with the help of titanium oxide (78,79). TiO_2NPs protect the chloroplast from extreme light through activity of peroxidase, superoxide dismutase catalase, antioxidant enzymes (80,81). TiO_2NPs act as a photo substance which is used in pigment production, photosynthesis rate enhancer etc. and also increase germination rate and plumule growth in *Brassica napus* (Fig. 6).

Aluminium (Al_2O_3) NPs

In *Nicotiana tabacum*, Al_2O_3NPs show negative impacts like decrease root length and seedling growth at higher concentration while in *Triticum* *aestivum* did not show any toxicity (83). In *Oryza sativa* and *Sorghum bicolor*, excess Al induce iron (Fe) deficiency symptoms (84) and it does not affect the seed germination but helps in new root development and seedling establishment (85). After 2-3 days the initiation of seed germination the root growth inhibition was detected (86). Nano-scale alumina did not have any significant effect on inhibition or increment of shoot length and dry biomass.

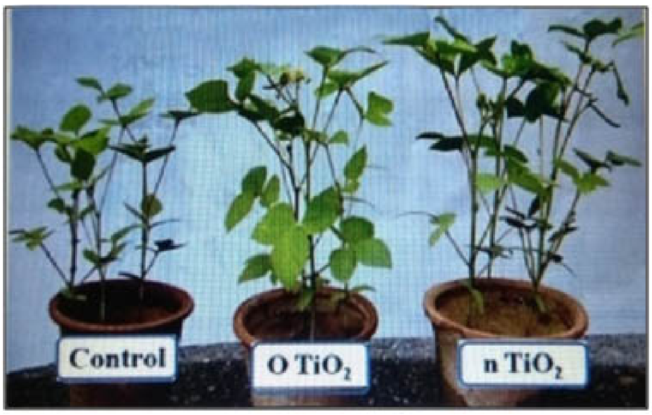


Fig. 6. Titanium oxide effect on *Brassica napus* seedlings, Farooqui (3)

Iron oxide (Fe_3O_4) NPs

Uptake and translocation of Fe_3O_4NPs in *Hordeum vulgare* plant which promoted the plant growth probably due to enhancement in photosynthetic efficiency. No phytotoxic effects were recorded at high dose (87). Iron oxide NPs show significant effect on root elongation of *Lactuca sativa* seedlings. FeNPs could be used as a fertilizer (88, 89). The Iron oxide NPs shows positive and negative effects on *Arabidopsis thaliana*. These NPs did not show any effects at the lower concentration but at higher concentration reduce the shoot and root length in plants.

Nanoparticles influence on molecular level in plants

Seedlings of *Oryza sativa* were exposed to various concentrations of AgNPs which increase hydrogen peroxidase formation, lipid peroxidation, proline accumulation and decrease sugar content in shoot and root. High dose of AgNPs increase reactive oxygen species generation which cause cytotoxicity and decrease mitochondrial membrane potential (90). In *Triticum aestivum*, high concentration of AgNPs induced the metallothionein gene (MT) while did not show any expression of the MT gene at low concentration. ZnO NPs up regulated 660 genes and down regulated 826 genes in *Arabidopsis thaliana* which are related to different stress, cell organization. TiO_2NPs showed mild changes in genes as compared to ZnONPs (91,92). In *Arabidopsis thaliana*, genes which are related to oxidative stress, sulfur assimilation, glutathione and proline biosynthesis (ATPS, APR, CS, GCL, P5CS1, and P5GS2) were up regulated by high concentrations of CuONPs (93). Reduced the hydrogen peroxidase content and expression of photosynthetic genes (petA and psaA) were increased at high concentration of Fe_3O_4NPs. Receptor molecules sense the occurrence of exterior or interior particles and modify its own confirmation then message transferred to the receptor molecules which bind to DNA and leads to change in the transcription and control the gene expression. Thus, nanoparticles have good potential to change the cell signaling pathways. Different proteins translate via different RNA and these proteins are directly associated with metabolic processes by accessing of the RNA expression. When plants are exposed to various nanoparticles several reports have shown an up regulation or down regulation of genes which are related to plant stress (94). Other reports depicted that plant DNA can be damaged under the presence of nanoparticles which may result in a low level of RNA expression and ultimately the death of the organism. NPs used as a carrier for transport of genetic material into the plant cell.

Application of nanoparticles on sustainable agriculture

Nanoparticles has the ability to transform the agricultural and food industry through various innovative tools for the disease management, disease detection and enhancing the capacity of plants to absorb nutrients (7). The main objective of NPs is to increase crop efficiency with low input of fertilizers, pesticides, and herbicides among others chemical compounds with same salts. NPs also called as “magic bullets” which aims to target particular cellular organelles in plant to pass their content (8) and also contain nano-pesticide, nano-fertilizers and herbicides properties to control plant diseases and promote plant growth.

NPs as fertilizers

Uses of Nano-fertilizers can improve crop yield. Contented and reactivity of phytohormones are main index of plant physiology. CeO_2 NPs improve the biochemical aspects like amino acids, non-reducing sugar, fatty acids, and phenolic complex in numerous plants. Nano-fertilizers increase nutrient productivity and provide the nutrient according to the need of crops. Many studies depicted that chemical fertilizers are less efficient compare to nano fertilizers (7,8,87).

Nano-herbicides

Nano-herbicides used to eradicate weeds and their propagation. Very minor amount of nanoparticles is capable to amalgam with loam and eliminate weeds from nature without any toxicity and avoid the development of unwanted plant (87).

Nano-Pesticides

Porous hollow silica NPs (PHSNs) with validamycin (pesticide) as an effective transport structure of water–soluble pesticide to control many diseases.

Nano-emulsions were valuable to constructions of pesticides then it might be active in contradiction of the numerous pests in agronomy (95). Likewise, oil-loaded NPs were more beneficial on behalf of preparations of nano-pesticides (96). Nano silica can be effectively used as a nano pesticide.

Nano insecticide

Encapsulation of nano is presently the greatest skill used for defense host plant in contradiction of pest. Nanosilicon can be used as insect repellent. After applied the silicon on the surface of plant cause insects death by physical mean. Insect repellent activity of Poly- ethylene glycol-coated NPs used as insecticide against adult *Tribolium castaneum* insect. SiNPs loaded with validamycin (pesticide) can be used as efficient pesticide (96).

NPs as a Plant diseases control

Ag and SiNPs have potential to control the many plant diseases. Silver nanaoparticles (AgNPs) can be used as antimicrobial negotiator which prevents the action to microbes (97,98). These nanoparticles has countless prospective in the controlling of plant syndromes comparatively to artificial fungicides (99,100). ZnO and MgO NPs are active antibacterial agents. Therefore, usage of NPs has been measured an alternative and operative method which is environmentally friendly and cost effective for the control of pathogenic microorganism.

Conclusion

Nanotechnology have huge prospective and profits in the field of agronomy and biotechnology. As discussed in the present review the possibility of negative impact of nanoparticles on plants along with positive implications, it is necessary to carefully examine the concentration of nanoparticles and its interaction with plants. Such knowledge is important before the use of nanoparticles in future research work in plant sciences. The size of NPs also plays an important role in the interaction and accumulation inside the plants. Although there are new approaches for plants improvement using NPs has shown the successful effect even though NPs has shown many lethal effects on plant growth and survivability rate. Therefore, the research on NPs especially related to interaction with plants and their impacts on physiological, biochemical and molecular impacts need to be carried out.

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Authors' contribution

JM conceived the idea of writing the review and designed the content. PG and SY collected the literature and prepared the article. All authors contributed to the content of the manuscript and approved the final version.

Competing Interest

The authors declare that they have no competing interest.

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