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Recent Advances of Nanotechnology in Agro-Production by Mitigating Abiotic Stress, Boosting Fertilizer and Pesticide Efficacy: A Review

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Abstract: *This paper explores the role of nanotechnology in modern agriculture, particularly in addressing abiotic stress and improving the effectiveness of fertilizers and pesticides. Nanotechnology involves the creation and use of materials with nanoscale dimensions (<100 nm). It has applications in agriculture, biotechnology, and plant sciences, offering innovative tools to improve plant growth and productivity. Nanoparticles (NPs) can enhance plant metabolism, improve stress tolerance, and boost yields. They can be used in nanoformulations, nanosensors, and genetic modification techniques for crop improvement. NPs help plants withstand extreme environmental conditions such as drought, salinity, and temperature fluctuations. Certain nanoparticles aid in nutrient absorption and water retention, thereby improving plant resilience. Nano-based fertilizers ensure a slow and controlled release of nutrients, minimizing waste and environmental pollution. Nanopesticides improve pest control by enhancing the efficacy of active ingredients and reducing harmful side effects. NPs exist naturally (e.g., volcanic ash, dust storms, ocean spray, and microbial activity). They can also be artificially synthesized using physical, chemical, and biological methods. Nanotechnology has significant potential to revolutionize agricultural production by improving plant health, increasing crop yields, and reducing environmental impact. Further research is needed to fully understand the interactions between nanoparticles and plants, as well as to ensure their safe and sustainable use in agriculture*

Keywords: Nanoparticles, Nanofertilizer, Nanopesticides

I. INTRODUCTION

Every person is exposed to nanometer-sized foreign particles; we inhale them with every breath we take and drink them with every drink we drink. In fact, every organism on Earth constantly encounters nanometer sized-entities. Most cause little damage and go unnoticed, but sometimes the invader causes serious damage to the organism. Among the poisonous invaders, the most advanced are viruses, which consist of nucleic acid and proteins that allow them not only to disrupt biological systems, but also to make excellent use of cellular processes for their own reproduction. The most benign viruses cause common symptoms in humans, such as the common cold or flu, which are obvious manifestations of biochemical competition between these foreign invaders and our immune system, whose nanometer-sized particles (chemicals and proteins) normally destroy and eliminate viral invaders. According to Scott and Chen (2003) and Joseph and Morrison (2006), new nanomaterials and nanodevices are being developed as a result of advances in nanotechnology. According to the Royal Society (2004), nanotechnology includes the development, manufacture, analysis, and use of systems and structures with dimensions less than one nanometer. Since the last century, nanotechnology has been a well-known area of study. Since Nobel laureate Richard P. Feynman introduced the concept of "nanotechnology" in his well-known 1959 lecture "There's Plenty of Room at the Bottom" (Feynman, 1960), there have been a number of ground-breaking advancements in the subject. Materials of numerous types were created at the nanoscale thanks to nanotechnology. Nanoparticles (NPs) are a broad category of materials that include particulate compounds with at least one dimension smaller than 100 nm. These materials can be 0D, 1D, 2D, or 3D depending on the overall shape. Agriculture and plant biotechnology may benefit from the development of nanodevices and

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nanomaterials. Nanoformulations, which are devices that help to detect biotic or abiotic stresses before they can affect production, nanosensors, or new techniques for genetic manipulation that allow higher efficiency during plant breeding programs are some examples of how nanotechnology can benefit agriculture (Fraceto et al., 2016). We will concentrate on applications for the synthesis in this paper because the subject is so vast. According to Cossins (2014), nanotechnology has a great deal of potential to give plant scientists and researchers in other domains the chance to create new techniques for incorporating nanoparticles into plants that might enhance already-existing functions and add new ones. Different physical, chemical and biological processes can be used to create NPs and they can interact with plants in a variety of ways. The use of nanobiotechnology tools in agriculture has expanded since NPs aid in enhancing plant growth, development, and productivity as well as overcoming abiotic and biotic stress. While Wang et al. (2001) demonstrated that plants naturally produce NPs under normal growth conditions. Giraldo et al. (2014) highlighted the potential of NPs to enhance plant metabolism.

Source of Nanoparticles

Nanoparticles are present everywhere in the environment. They are of natural and anthropogenic origin (Sadik 2013). Natural nanoparticles occur in nature, ie. ocean sprays, forest fires, dust storms, volcanic ashes, and biological life such as in bacteria and fungi (Buzea et al., 2007). Humans have long been exposed to naturally occurring nanoparticles that resulted from combustion. The human body is well adapted against these potentially harmful invaders (Badawy et al., 2010). Anthropogenic nanoparticles are the result of unintentional human exposure. These man-made nanoparticles can be classified into the first category as having no predetermined size, and these include combustion particles, diesel exhaust, welding fumes, and coal fly ash. Another category of man-made nanoparticles, engineered nanoparticles (ENPs), have a characteristic size of 1-100 nm. Pure materials with controllable surfaces include fullerenes, carbon nanotubes, dendrimers, quantum dots, TiO_2, gold, and silver nanoparticles, for instance. Nature is full of nanoparticles. They are created by plants as well as by a variety of natural processes, such as photochemical reactions, volcanic eruptions, forest fires, and straightforward erosion.

Nano-plant interaction

It has been observed that the germination percentage, root elongation, biomass, and leaf number are the primary physiological indicators of NPs' harmful effects on plants. NPs can have significant adverse consequences, including suppressing plant elongation and seed germination, and even killing plants. A number of previous studies on plant nanotoxicity found that exposure to NPs (MWCNTs, single-wall carbon nanotubes, ZnO NPs, Ag NPs, and Fe NPs) inhibited the growth of various plant species, including soybean, maize, wheat (*Triticum aestivum*), ryegrass, and barley. These studies found that several aspects of plant growth were impacted, including seed germination, shoot length, biomass, and gene expression. *Bacillus thuringiensis* (Bt)-transgenic cotton treated to SiO_2 NPs showed growth suppression (Le Van et al. 2014). CuO NPs reduced the growth of wheat plants when they were planted in a sand matrix and altered the structure of the roots (Dimkpa et al. 2012). CuO NPs dramatically decreased the fresh weights and root length of Arabidopsis seedlings, as well as the germination rate and biomass of rice seeds, according to research by Shaw and Hossain (2013). It has been discovered that high concentrations of the rare earth oxide nanoparticles (CeO_2, La_2O_3, Gd_2O_3, and Yb_2O_3) had a negative impact on the growth of plants in radish, tomato, rape, lettuce, wheat, cabbage, cucumber and corn.

Impact of Nanoparticles on Mitigation of Abiotic Stresses

With a wide range of possible applications, nanotechnology has developed as a multidisciplinary subject. One such application is in agriculture, where nanoparticles (NPs) are making an impact by enhancing the effectiveness of fertilizers and pesticides. Although the primary goal of using nanoparticles is to promote crop development and productivity, recent investigations have shown that NPs can have both good and negative effects on plants. According to some accounts, NPs can cause phytotoxicity and negatively affect a plant's overall metabolism, but they can also be used to enhance crop performance according to their unique features. However, unexplained NP release into the ecosystem has sparked widespread worry about their possible phytotoxic consequences, which must be resolved before

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NPs can be used commercially and on a broad scale to improve crop output. One of the main negative effects of NPs released into the environment is the induction of oxidative stress. Oxidative stress is a complex physiological, biochemical, and molecular phenomenon that occurs in higher plants in response to almost all biotic and abiotic stresses and results from the overproduction and accumulation of reactive oxygen species (ROS). It has been observed that NPs of varied compositions, sizes, concentrations, and physical/chemical characteristics affect the growth and development of diverse plant species in both favorable and unfavorable ways. Multi-walled carbon nanotubes have been shown to significantly affect tomato seed germination and seedling growth by upregulating stress-related gene expression. In comparison to silicon oxide, iron oxide, and zinc oxide nanoparticles in Arabidopsis, Al_2O_3-NPs were found to be the least hazardous. The harmful effects of NPs on algae were previously studied [*Arouja et al 2009*]. NPs such titanium oxide, zinc oxide, cerium oxide, and silver NPs were deposited in the organelles and on the surface of the cell, causing the cell to experience oxidative stress by way of the activation of oxidative stress signaling [*Buzea et al 2007*]. The effects of silver, copper (Cu), zinc oxide, and silicon nanoparticles on the plant *Cucurbita pepo* showed that the germination of seeds was unaffected by these NPs and their bulk counterparts. However, Cu nanoparticles shortened roots compared to plants with control and those given bulk Cu powder [*Stampoulis et al 2009*]. In early growth phases of rice, ZnO NPs, but not titanium oxide, have detrimental impacts on the root length [*Boonyanitipong et al 2011*]. Similar research on *Hordeum vulgare*'s nano-CuO-modulated photosynthetic performance and antioxidant defense system revealed restriction in root and shoot growth along with a lower photosynthetic performance index (*Shaw et al 2014*). Radish (*Raphanus sativus*) and ryegrass (*Lolium perenne* and *Lolium rigidum*) have both been found to exhibit DNA damage by nano-CuO as well as restricted plant growth (*Atha et al 2012*). On exposure to very high concentrations of cerium oxide NPs, changes in enzyme activity, ascorbate and free thiol levels leading to increased membrane damage and photosynthetic stress have been seen in shoots of developing rice seedlings [*Rico et al 2013*]. It has been suggested that the toxicity of Ag and ZnO-NPs is mostly produced by both the particulates and ionic forms by the generation of ROS, reactive oxygen species, reactive nitrogen species, and H_2O_2 during exposure to the Ag and ZnO manufactured NPs on the duckweed (*Spirodela punctuta*) (*Thwala et al 2013*). Due to its distinctive physiochemical and biological characteristics in comparison to the enormous bulk material, Ag-NP has received the most attention among the numerous metal NPs (*Sharma et al 2009*). Because of their bactericidal and fungicidal qualities, Ag-NPs have a wide range of uses as a crucial component in various products such as home, food, industries etc (*Tran et al 2013*). Ag-NPs are said to be more hazardous to bacteria, fungi, and viruses than silver-based compounds because they have more surface area accessible for microbial contact. Similar to other metal ions, Ag-NPs can cause oxidative stress in higher plants, microbes, animals, and algae (*Jiang et al 2012*). However, the effects of Ag-NPs on plants are greatly influenced by a number of variables, including plant species, stage of growth, nanoparticle composition and concentration, and the experimental setup (temperature, treatment duration, media composition, exposure mode, etc.). One of the NPs whose toxicity has been investigated in a variety of crops is nano-Ag (*Stampoulis et al 2009*, *Jiang et al 2012*, and *Kumari et al 2009*). Despite the fact that exposure to Ag-NPs is thought to be harmful for plant growth, several research have shown that Ag-NPs can actually promote it in plants including *Brassica juncea* (*Sharma et al 2012*), *Eruca sativa*, marsh plants, *Zea mays* and *Phaseolus vulgaris* (*Salama et al 2012*). According to research by Kumari et al. [2009], Ag-NPs had chromotoxic effects on mitotic cell division in *Allium cepa* root-tip cells. Additionally, Ag-NPs engage signaling pathways that stop cell proliferation by interacting with membrane proteins [*Roh et al 2012*, *Gopinath et al 2010*]. Silicon (Si) is most plentiful in soil and the Earth's crust. Its significance in plant defense and plant growth and development is widely known and established. Several studies have identified its enormous potential to effectively counteract varied abiotic stresses such as drought, salinity, cold stress, and other heavy metal toxicities. However, there is little knowledge on the precise mechanisms of Si-mediated abiotic stress reduction in plants [*Riahi-Madvar et al 2012*, *Shaw et al 2013*, *Shaw et al 2014*]. A wide variety of tailored nanomaterials are presently produced using silver nanoparticles for use in a variety of commercial items. Since the development of nanotechnology, silver nanoparticles have been successfully used in a variety of applications, including insecticides, coatings for household items, and food packaging. Their (silver nanoparticles) uses in electronics, drug delivery and biological labelled medicine have been widely accepted [*Landa et al 2012*].

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Nanofertilizers for Plant Growth

Due to the rising global demand for food, fertilizers continue to be utilized extensively in food production. Typically, plants absorb nutrients provided inefficiently, which sharply raises farmers' costs. In order to boost plant development and fulfill the future food demand, nanotechnology has opened up a wide range of unique applications in the field of plant nutrition. Its goal is to increase the effectiveness with which present fertilizers are used, either by improving the efficiency of nutrient delivery to plants or by reducing nutrient loss to the environment. Nanofertilizers can be applied to plants' leaves or roots. Additionally, they are designed to be target-oriented, increasing the efficiency with which nutrients are utilized, lowering the rate at which nutrients are fixed, and minimizing nutrients loss. Generally speaking, we categorize the nanofertilizers into four broad groups depending on the function of the nanomaterials and the nutrients being used: 1) Nanofertilizers containing macronutrients, 2) those containing micronutrients, 3) nanomaterials loaded nanofertilizers, and 4) additional types of nanofertilizers. The first two types of nanomaterials serve themselves as nutrients, allowing plants to absorb them more efficiently. The third type of nanomaterial contains no vital plant nutrients and is frequently employed as a nanocarrier for slow release nutrients. The final type of nanomaterial is not nutritionally necessary by plants, but it has been shown to have a good impact on plant development and production.

1. Nanofertilizers containing macronutrients

Macronutrient nano-fertilizers are made up of one or more macronutrient elements (for example, nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and sulfur (S)) that supply huge amounts of nutrients to plants. By 2050, there will likely be a 263 Mt global need for macronutrients. In particular, N fertilizer has led to a 40% rise in per capita food output over the previous 50 years. But eventually, enormous amounts of these fertilizers—N, P, and K—are carried into surface and groundwater, seriously harming aquatic ecosystems. Therefore, in order to achieve sustainable food production based on preserving the ecological environment, it is required to develop highly effective and environmentally safe macronutrient nano-fertilizers. Three essential nutrients for plant growth and development are N, P, and K. Anhydrous ammonia, urea, ammonium, and nitrate are among the solid or liquid forms of N that the soil needs. Table 1 provides a list of various N, P, and K nanofertilizers, their methods of application, and growth-enhancing properties, such as N-doped carbon dots, apatite nanoparticles (NPs), and monopotassium phosphate. These nanofertilizers have a very small diameter (20 nm) and good water solubility.

Table 1. Currently reported macronutrient nanofertilizers

Nano material	Comparison	Plant	Concentration	Fertilization method	Growth enhancements	Ref.
N-CDs	Pure water and urea	Mung bean	0.2 mg L^{-1}	Nutrient solution	The growth rate of mung bean improved by 200% (average length of shoots and roots).	[Wanget al 2019]
Apatite NPs	$Ca(H_2PO_4)_2$	Soybean	21.8 mg L^{-1}	Soil	The growth rate and seed yield increased by 32.6% and 20.4%, and the biomass production was enhanced by 18.2% for the above-ground and 41.2% for the below-ground.	[Liu et al 2014]
MKP	Nothing treated	Tomato	3 g L^{-1}	Foliar and soil	The growth parameters of tomatoes under salt stress were improved.	[Sassine et al 2020]
CaO NPs	Bulk CaO and $CaNO_3$	Groundnut	500 mg L^{-1}	Foliar	The germination and growth rate of groundnut increased.	[Deepa et al 2015]
S NPs	Nothing treated	*Cucurbita pepo*	100–400 mg L^{-1}	Soil	The number of leaves and branches, height per plant, stem diameter, and healthy plant increased.	[Salem et al 2015]

S NPs	Nothing treated	Tomato	300 mg L^{-1}	Soil	The root and shoot growth rate increased and the effect was concentration dependent.	[Salem et al 2016]

They are blended with nutritional solution or water and applied to foliar or soil, which has considerably accelerated plant growth. Furthermore, composite nanofertilizers that can offer diverse nutrients (e.g., monopotassium-phosphate that can provide N, P, and K nutrients) help plants cope with abiotic stress (e.g., salt stress). In addition to the three basic nutrients listed above, Ca and S are significant macronutrients. Sulphur and calcium oxide nanoparticles (S and CaO, respectively) have been combined with water and then applied to soil and foliage. However, compared to the N, P, and K nanofertilizers, these nanofertilizers have wide and irregular widths (20-80 nm), and they are utilized in substantially higher amounts (Table 1). It should be emphasized, however, that although these various nanofertilizers only contain a some harmless elements (i.e., C, O, N, K, P, Ca, and S), more extensive research is still required to guarantee their safety for extensive and long-term agricultural usage.

2. Nanofertilizers containing micronutrients

Micronutrients give plants relatively tiny amounts of critical nutrients (10 mg kg^{-1} of soil) compared to macronutrients. They are essential components for triggering enzymes and creating biomolecules necessary for plant defense. Furthermore, eating meals poor in micronutrients might have a negative impact on one's health, resulting in anemia, slowed growth, and cognitive decline. Thus, in addition to applying macronutrient nanofertilizers to plants, it is also important to do so with micronutrient nanofertilizers, such as Zn, Cu, Iron (Fe), Manganese (Mn), and Molybdenum (Mo).

Table 2. Currently reported micronutrient nanofertilizers

Nanomaterial	**Comparison with**	**Plant**	**Concentration**	**Fertilization method**	**Growth enhancements**	**Ref.**
ZnO NPs	Nothing treated	Rice (PR-121)	5 g L^{-1}	Foliar	The growth, yield, yield-attributing characters, microbial counts, and the dehydrogenase enzyme activity improved.	[Bala *et. al.* 2019]
ZnO NPs	$ZnSO_4$ and untreated group	Coffee (*Coffea arabica* L)	10 mg L^{-1}	Foliar	The fresh weight (roots: 37%, leaves: 95%), dry weight (roots: 28%, leaves: 85%), and the net photosynthetic rate (55%) increased.	[Rossi *et. al.* 2019]
Fe_2O_3 NPs	$FeCl_3$	*Brassica napus*	2 mg mL^{-1}	Soil	The H_2O_2 content reduced to 83 μM g^{-1}, the malondialdehyde formation reduced to 26 mm g^{-1}, growth rate of leaves enhanced to 50%, and chlorophyll content increased to 52.	[Palmqvist *et. al.* 2017]
nZVI	mZVI and Fe^{2+}	Rice	100 mg kg^{-1}	Soil	The grain yield increased (47.1–55.0%), the grain PCP content decreased (83.6–86.2%), and the soil	[Liu *et. al.* 2021]

					PCP removal rate increased (49.9–89.0%) after the addition of three different nZVI.	
Cu-based NPs (CuO, CuS, and $Cu(OH)_2$)	Nothing treated	Wheat (*Triticum aestivum*)	1 mg mL^{-1}	Root	High-solubility $Cu(OH)_2$ NPs provided more uptake of Cu, while low-solubility materials (CuO and CuS) were more persistent on the roots and continued to transport Cu to plant leaves during the 48 h depuration period.	[Spielman-Sun *et. al.* 2018]
CuO NPs	Nothing treated	Maize (*Zea mays* L.)	8 mg L^{-1}	Foliar	The plant growth grate improved by 51%.	[Adhikari *et. al.*1916]
Mn NPs	$MnSO_4$	Mung bean (*Vigna radiata*)	0.05 mg L^{-1}	Foliar	The root and shoot length increased by 52% and 38%, respectively, and the fresh and dry weight enhanced.	[Saheli et. al. 2013]
Mo NPs	Water treated	Chickpea (*Cicer arietinum* L.)	8 mg L^{-1}	Seed	The microbial activity and seed growth improved.	[Yu et. al. 2014]

Zn is a necessary micronutrient for humans, animals, and plants. ZnO NPs, which were bought from various companies, were utilized as nanofertilizers in two investigations. Their particle diameters are approximately 50 and 70 nm, respectively. These ZnO NPs dissolve fairly slowly in water. However, the diameter of these ZnO NPs or their aggregates is still smaller than the stomatal pore size, demonstrating their capacity to enter and travel through plant tissues. Zn^{2+} may constantly release after the NPs were bonded to the leaf surfaces, offering a long-term source of Zn that plants can absorb through stomatal pores. Therefore, the application of ZnO NPs enhanced the development and yield of several plants. Fe is a crucial nutrient that is involved in the manufacture of chlorophyll and the electron transfer system. A shortage in Fe can damage a plant's normal physiological function and lower the nutritional value of the plant. Maghemite (γ-Fe_2O_3) NPs were created by Palmqvist and colleagues to serve as nanofertilizers. The outcomes demonstrated that the plants' drought endurance had significantly improved. In addition, the amount of H_2O_2 was lowered and chlorophyll content increased and the pace of leaf growth was accelerated. Even so, γ-Fe2O3 NPs dissolve slowly and NPs aggregate to a hydrodynamic size of up to 500 nm. This is also helpful for plants to continuously absorb iron (Fe^{3+}) over a lengthy period of time. In a different study, Liu and colleagues used nanoscale zero-valent iron (nZVI) to achieve soil remediation which enhanced rice yield. They discovered that nZVI with larger size (100 nm) and lower coercivity (35.17 Oe) may significantly increase grain production and the pace at which pollutants were removed from the soil. Another crucial micronutrient for the growth of microbes and plants is copper (Cu). Various Cu-based NPs have been sprayed on the roots and leaves of various plants, including copper oxide (CuO), copper sulfide (CuS), and copper hydroxide (Cu(OH)2) (Table 2). The spindle-shaped Cu(OH)2) NPs among them have better dispersibility than spherical CuO and CuS NPs, allowing plants to absorb more copper.

3. Nanomaterials-Loaded Nanofertilizers

Although nanomaterials-loaded nanofertilizers can enhance plant development to some extent, these nanoparticles are not well absorbed by plants. They are utilized as nanocarriers for long-term nutrient delivery, enhancing plant uptake efficiency and decreasing the negative impacts of standard fertilizers. Chitosan NPs and nano-zeolite are two common examples of this class. Chitosan NPs combine the properties of chitosan and NPs, such as surface and interface effect, good physicochemical properties, high water solubility, and environmental friendliness, as well as bioactivity. As a result, chitosan NPs are frequently utilized as nanocarriers for loading NPK fertilizers in order to achieve gradual release of NPK fertilizers. According to published findings, chitosan molecules in solution are cationic polyelectrolytes that can easily form particular nanostructures by electrostatic interaction with methacrylic acid (MAA). Because of this, the majority of chitosan NPs employed as nanocarriers are produced when MAA is polymerized in chitosan solution (i.e., CS-PMMA NPs). For instance, Abdelaziz et al. examined the effects of applying CS-PMMA NPs loaded with NPK fertilizers through foliar application to wheat crops. When compared to typical fertilizers, they discovered that the overall saccharide, K, and P concentrations in the wheat grains were much higher. The same nanomaterial was utilized by Khailfa and colleagues to load NPK fertilizers and assess their impact on garden pea plants (Pisum sativum var. Master B). They discovered that, in comparison to other groups, the synthesized nanofertilizer could trigger mitosis and also elevated the expression of a few key proteins in plants. The CS-PMMA NPs have an average diameter of about 23 nm. The dispersion of NPs after loading NPK is homogeneous, free of agglomeration, and exhibits good stability across a range of pH gradients.

4. **Other Nanofertilizers**

Other nanoparticles not considered to be plant nutrients also have beneficial effects on plants, in addition to the three categories of nanofertilizers already described. Although these nanomaterials are not themselves nutrients that plants need, they can nonetheless support plant growth and development. These nanomaterials include CNTs NPs, ceric dioxide NPs (CeO_2 NPs) and titanium dioxide NPs (TiO_2 NPs). Ti is not typically regarded as a crucial plant nutrient. However, some research suggested that by boosting photosynthesis, TiO_2 NPs could promote plant development. In one study, the influence of synthetic TiO_2 NPs (12–15 nm) on the growth of mung beans was assessed. Significant increases in shoot and root length, chlorophyll content, and total soluble leaf protein were seen after the foliar application. The stomatal holes on plant leaves may allow the TiO_2 NPs to adsorb and be taken up. The TiO_2 NPs may improve the activity of phytase and phosphatase enzymes after being absorbed by plants, aiding in the mobilization of native phosphorous nutrients in the rhizosphere and improving plant metabolic activities. Plant cell walls and membranes can be penetrated by CNTs, according to some studies. CNTs can promote plant growth and seed germination, usually at small dosages. Joshi et al. evaluated the impact of multi-walled carbon nanotubes (MWCNT; 35 nm in diameter; 200–300 nm in length) on oat growth and yield. They discovered that these MWCNT traveled through the cells using the seed-priming technique, accelerating xylem cell growth, increasing chlorophyll content, and boosting photosynthetic activity.

Plant Protection using Nanopesticides

Achieving high agricultural production requires effective pest management. However, it is believed that around 90% of the chemical pesticides used are lost either during or after application owing to volatilization, degradation, and photolysis, which has detrimental impacts on the food chain and health of individuals. Furthermore, increasing pesticide use has resulted in increased pesticide resistance in weeds, insects, and diseases. As a result, pesticide use should be controlled in an efficient and environmentally friendly manner, and pesticides should be properly administered to targeted places. Since nanotechnology has been shown in numerous studies to promote plant growth and nutrient utilization efficiency, its potential in protecting plants from pests, infections, weeds etc is also attracting greater attention. Nanopesticides, which are pesticide formulations that contain nanomaterials with biocidal characteristics, have received a lot of attention. In general, nanomaterials can be employed as pesticides directly, as well as to protect pesticides and improve their transport to the site of action. As a result, in this section, we divide nanopesticides into two groups: 1) Nanomaterials that are directly employed as nanopesticides, and 2) nanomaterials that are used as pesticide nanocarriers.

II. CONCLUSION AND POSSIBILITIES FOR THE FUTURE

With a thorough understanding of "plant nanoscience," these nanotechnologies have numerous unanticipated benefits. However, many challenges remain in the future, such as a uniform international standard, fragmented regulation, nanosafety issues, grower health, social perception and acceptability, "real-life" application, and so on. As was already said, there are more and more papers and patents involving nanotechnology in agriculture. Large-scale scientific research and the use of commercial products are still not feasible for a variety of reasons, such as inconsistent national legal frameworks, insufficient regulation, a dearth of public licensing programs, etc. Predicting the direct, indirect, and cumulative effects of nanomaterials is challenging due to the physical, chemical, and biological characteristics of nanomaterials, which differ greatly from single atoms, molecules, or bulk materials in many ways. However, it is still unclear how nanomaterials are affecting the environment, living things, and people. The development of globally harmonized rules and laws is significantly hampered by these issues. However, it is still unclear how nanomaterials are affecting the environment, living things, and people. The development of globally harmonized rules and laws is significantly hampered by these issues. Therefore, coordination between international and national organizations is essential, and a significant amount of study and field work must be done right away. The successful use of nanotechnologies in agriculture can only be possible if everyone works together to solve the hurdles provided by fragmented rules and regulations. NPs in the field, ecotoxicological risk factors, and the influence of NPs on the metabolome, proteome, metagenome, and transcriptome of plant and soil systems is urgently needed. The establishment of industrial sectors is necessary to scale up nanoproduct production, educate farmers about the use of nanoformulation, create application processes, and control the regulatory environment. Additionally, future research should focus on developing NPs that are inexpensive, nontoxic, self-degradable, and eco-friendly using green methods. We believe that this review will be helpful in the development of efficient nano-enabled agricultural strategies to address the worldwide issue of food security brought on by various abiotic pressures. Due to changes in the environment, soil types, plants that need to be treated, and most crucially, the physicochemical properties of the new metallic/nonmetallic substances, the field use of many of the created new chemicals is still very limited. Toxicity and NP buildup in agricultural plants are two restrictions related to field applications. To enable outdoor uses of nanotechnology, future research on evaluating the toxicological effects on model microbes, vegetation, and animals is essential. However, more investigation is required to identify the pertinent pathways. Abiotic stress tolerance in plants has also been made possible by nanotechnology, albeit this has primarily just recently been proved at the laboratory scale. To encourage the adoption of abiotic stress tolerance provided by nanotechnology in agricultural production, we urgently need to discuss and establish rules and regulations that are universally accepted. Additionally, more research is required to examine how source-sink control may apply to how nanomaterials may impact plants under abiotic stressors. The impact of foliar spraying nanomaterials on the ability of plants to act as sinks should be investigated. Overall, we think that nanotechnology will be extremely important in ensuring a community of sustainable farmers.

REFERENCES

[1]. Adhikari T., Sarkar D., Mashayekhi H., Xing B. (2016) *J. Plant Nutr*: 39, 99.

[2]. *Arouja V., Dubourguier H.C., Kasemets K., Kahru A. (2009) Toxicity of nanoparticles of CuO, ZnO, and TiO2 to microalgae Pseudokirchneriella subcapitata. Sci. Total Environ: 407: 1461–1468.*

[3]. *Atha D.H., Wang H., Petersen E.J., Cleveland D., Holbrook R.D., Jaruga P., Dizdaroglu M., Xing B., Nelson B.C. (2012) Copper oxide nanoparticle mediated DNA damage in terrestrial plant models. Environ. Sci. Technol: 46: 1819–1827.*

[4]. Bala R., Kalia A., Dhaliwal S. S. (2019) *J. Soil Sci. Plant Nutr*: 19, 379.

[5]. *Boonyanitipong P., Kositsup B., Kumar P., Baruah S., Dutta J. (2011) Toxicity of ZnO and TiO2 nanoparticles on germinating rice seed Oryza sativa L. Int. J. Biosci. Biochem. Bioninform:1: 282–285.*

[6]. *Buzea C., Pacheco I.I., Robbie K. (2007) Nanomaterials and nanoparticles: sources and toxicity. Biointerphases. 2:17–71.*

[7]. Buzea Cristina, Ivan I. Pacheco, Kevin Robbie (2007) Nanomaterials and nanoparticles: Sources and toxicity. *Biointerphases* 1: 2 (4): 17–71

[8]. Cossins D. (2014) Next generation: nanoparticles augment plant functions. The incorporation of synthetic nanoparticles into plants can enhance photosynthesis and transform leaves into biochemical sensors. The scientist, news & opinion.

[9]. Deepa M., Sudhakar P., Nagamadhuri K. V., Reddy K. B., Krishna T. G. (2015) *Appl. Nanosci.* : 5, 545.

[10]. Dimkpa CO, McLean JE, Latta DE, Manangon E, Britt DW, Johnson WP, Boyanov MI and Anderson AJ (2012). CuO and ZnO nanoparticles phytotoxicity, metal speciation and induction of oxidative stress in sand-grown wheat. J. Nanopart. Res. 14:1125

[11]. El Badawy AM, Luxton TP, Silva RG, Scheckel KG, Suidan MT, Tolaymat TM. (2010) Impact of environmental conditions (pH, ionic strength, and electrolyte type) on the surface charge and aggregation of silver nanoparticles suspensions. Environ Sci Technol. 15; 44(4): 1260-6.

[12]. Feynman R. P (1960). There's plenty of room at the bottom, a talk given by Dr. Feynman on December 29, 1959 at the annual meeting of the American Physical Society at Caltech. Engineering and Science.

[13]. Fraceto LF, Grillo R, de Medeiros GA, Scognamiglio V, Rea G and Bartolucci C (2016) Nanotechnology in Agriculture: Which Innovation Potential Does It Have? Front. Environ. Sci. 4:20.

[14]. Giraldo JP, Landry MP, Faltermeier SM, McNicholas TP, Iverson NM, Boghossian AA, Reuel NF, Hilmer AJ, Sen F, Brew JA, Strano MS. (2014) Plant nanobionics approach to augment photosynthesis and biochemical sensing. Nat Mater.

[15]. *Gopinath P., Gogoi S.K., Sanpui P., Paul A., Chattopadhyay A., Ghosh S.S. (2010) Signaling gene cascade in silver nanoparticle induced apoptosis. Colloids Surf. B: 77: 240–245.*

[16]. *Jiang H.S., Li M., Chang F.Y., Li W., Yin L.Y. (2012) Physiological analysis of silver nanoparticles and AgNO3 toxicity to Spirodela polyrrhiza. Environ.Toxicol. Chem. 31: 1880–1886.*

[17]. Joseph T, Morrison M (2006). Nanotechnology in Agriculture and Food. Institute of Nanotechnology, Nanoforum Organization. Available: http://www.nanoforum.org.

[18]. *Kumari M., Mukherjee A., Chandrasekaran N. (2009) Genotoxicity of silver nanoparticles in Allium cepa. Sci. Total Environ. 407: 5243–5246.*

[19]. *Landa P., Vankova R., Andrlova J., Hodek J., Marsik P., Storchova H., White J.C., Vanek T. (2012) Nanoparticle-specific changes in Arabidopsis thaliana gene expression after exposure to ZnO, TiO2, and fullerene soot. J. Hazard. Mater. 241–242: 55–62.*

[20]. Laware S.L. and Raskar S. (2014) Influence of Zinc Oxide Nanoparticles on Growth, Flowering and Seed Productivity in Onion Int.J.Curr.Microbiol.App.Sci 3(7) 874-881

[21]. Laware, S.L. and Raskar, S. (2014) Influence of Zinc Oxide Nanoparticles on Growth, Flowering and Seed Productivity in Onion. International Journal of Current Microbiology and Applied Sciences, 3, 874-881.

[22]. Le, V.N., Rui, Y., Gui, X. (2014) Uptake, transport, distribution and Bio-effects of SiO_2 nanoparticles in Bt-transgenic cotton. *J Nanobiotechnol* 12: 50

[23]. Lee CW, Mahendra S, Zodrow K, Li D, Tsai YC, Braam J, Alvarez PJ. (2010) Developmental phytotoxicity of metal oxide nanoparticles to Arabidopsis thaliana. Environ Toxicol Chem. 29: 669–675

[24]. Liu R., Lal R. (2014), *Sci. Rep.* 4, 5686.

[25]. Liu Y., Wu T., White J. C., Lin D., *Nat. Nanotechnol.* 2021, 16, 197.

[26]. Palmqvist N. G. M., Seisenbaeva G. A., Svedlindh P., Kessler V. G. (2017) *Nanoscale Res. Lett.* 12, 631.

[27]. *Riahi-Madvar A., Rezaee F., Jalili V. (2012) Effects of alumina nanoparticles on morphological properties and antioxidant system of Triticum aestivum. Iran. J. Plant Physiol: 3: 595–603.*

[28]. *Rico C.M., Hong J., Morales M.I., Zhao L., Barrios A.C., Zhang J.Y., Peralta-Videa J.R., Gardea-Torresdey J.L. (2013) Effect of cerium oxide nanoparticles on rice: A study involving the antioxidant defense system and in vivo fluorescence imaging. Environ. Sci. Technol: 47: 5635–5642.*

[29]. *Roh J.Y., Eom H.J., Choi J. (2012) Involvement of Caenorhabditis elegans MAPK signaling pathways in oxidative stress response induced by silver nanoparticles exposure. Toxicol. Res. 28: 19–24.*

[30]. Rossi L., Fedenia L. N. (2019) Sharifan H., Ma X., Lombardini L., *Plant Physiol. Biochem*: 135, 160.

[31]. Royal Society (2004). Nanoscience and nanotechnologies: opportunities and uncertainties. Royal Society: London

[32]. **Sadik OA (2013) Anthropogenic nanoparticles in environment. Environ. Sci.: Processes Impacts 15**, 19-20

[33]. Saheli P., Prasun P., Sumistha D., Sourov C., Shouvik M., Kumar D. K., Shirin A., Pratip P., Arunava G. (2014) *Environ. Sci. Technol.* 2013, 47, 13122.

[34]. *Salama H.M.H. (2012) Effects of silver nanoparticles in some crop plants, common bean (Phaseolus vulgaris L.) and corn (Zea mays L.) Int. Res. J. Biotechnol: 3: 190–197*

[35]. Salem N. M., Albanna L. S., Abdeen A. O., Ibrahim Q. I., Awwad A. M. (2016) J. Agric. Sci. 8, 179.

[36]. Salem N. M., Albanna L. S., Awwad A. M., Ibrahim Q. M., Abdeen A. O. (2015) J. Agric. Sci. 8, 188.

[37]. Sassine Y. N., Alturki S. M., Germanos M., Shaban N., Sattar M. N., Sajyan T. K. (2020) *J. Plant Nutr*: 43, 2493.

[38]. Scott N, Chen H (2003). Nanoscale Science and Engineering for Agriculture and Food Systems. A report submitted to Cooperative State Research, Education and Extension Service, USDA, National Planning Workshop, Nov 18-19 2002, Washington.

[39]. *Sharma P., Bhatt D., Zaidi M.G., Saradhi P.P., Khanna P.K., Arora S. (2012) Silver naoparticle-mediated enhancement in growth and antioxidant status of Brassica juncea. Appl. Biochem. Biotechnol: 167: 2225–2233.*

[40]. *Sharma V.K., Yngard R.A., Lin Y. (2009) Silver nanoparticles: Green synthesis and their antimicrobial activities. Adv. Colloid. Interface Sci: 145: 83–96.*

[41]. *Shaw A.K., Ghosh S., Kalaji H.M., Bosa K., Brestic M., Zivcak M., Hossain Z. (2014) Nano-CuO stress induced modulation of antioxidative defense and photosynthetic performance of syrian barley (Hordeum vulgare L.) Environ. Exp. Bot: 102: 37–47.*

[42]. *Shaw A.K., Hossain Z. (2013) Impact of nano-CuO stress on rice (Oryza sativa L.) seedlings. Chemosphere: 93:906–915.*

[43]. Shaw, A.K., Hossain, Z. (2013) Impact of nano-CuO stress on rice (Oryza sativa L.) seedlings. Chemosphere: http:// dx.doi.org/10.1016/j.chemosphere.2013.05.044

[44]. Spielman-Sun E., Lombi E., Donner E., Avellan A., Etschmann B., Howard D., Lowry G. V. (2018) *Environ. Sci. Technol.* 52, 9777.

[45]. *Stampoulis D., Sinha S.K., White J.C. (2009) Assay-dependent phytotoxicity of nanoparticles to plants. Environ. Sci. Technol. 43:9473–9479.*

[46]. *Thwala M., Musee N., Sikhwivhilu L., Wepener V. (2013) The oxidative toxicity of Ag and ZnO nanoparticles towards the aquatic plant Spirodela punctuta and the role of testing media parameters. Environ. Sci. Process. Impacts 15: 1830–1843.*

[47]. *Tran Q.H., Nguyen V.Q., Le A.T. (2013) Silver nanoparticles: synthesis, properties, toxicology, applications and perspectives. Adv. Nat. Sci.4: 033001.*

[48]. Wang A., Kang F., Wang Z., Shao Q., Li Z., Zhu G., Lu J., Li Y. Y. (2019) Adv. Sustainable Syst. 3, 1800132.

[49]. Wang YXJ, Hussain SM, Krestin GP. (2001) Superparamagnetic iron oxide contrast agents: physicochemical characteristics and applications in MR imaging. *Eur. Radiol.* 11: 2319–2331.

[50]. Yu T. N., Gonchar O. M., Lopatko K. G., Batsmanova L. M., Patyka M. V., Volkogon M. V (2014) *Nanoscale Res. Lett* : 9, 289.