Current Prospective of Nanomaterials in Agriculture and Farming

Kamla Dhyani, Sobha, Maninder Meenu, Achintya N. Bezbaruah, Kamal K. Kar, and Pankaj Chamoli

Abstract Recently, nanotechnology has gained an intense attention in agriculture and quality farming system to meet the demand of sustainable agriculture. The unique properties of nanomaterials at nanoscale enables their employment for the design and development of diverse range of novel tools that supports sustainable agriculture. It is popular among the scientists due to its positive impact on agrifood sector by reducing the adverse impact of agripractices on environment, human health and improving food quality and productivity. In present chapter, application of various kinds of nanoparticles (NPs) in stress management of crops, as pesticides, herbicides, as nanobiosensors for disease detection, as seed growth promotes, for management of agricultural waste and shelf-life enhancement of agriproduce has been discussed in detail. Nanotechnology in agriculture significantly reduced the wastage of natural resources such as water, biofertilizers and also reduces the environmental pollution by reducing the application of harmful chemical fertilizers and pesticides. The application of nanomaterials found to be beneficial for sustainable agriculture. The recently available literature revealed the positive impact of nanotechnology application in different practices of agriculture such as crop nutrient management, stress resistance, insect and pest management, agriculture waste management, improving food security and productivity that, in turn, meet the food demands of global population.

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1 Introduction

Nanotechnology exhibits great potential in production and processing of agriproduce. Researchers are using biodegradable waste for green synthesis of nanoparticles (NPs). During green synthesis, the various plant secondary metabolites such as phenolic compounds, alkaloids, co-enzymes and terpenoids are reduced as NPs. The application of these NPs exhibits positive response in plant disease control, promoting plant growth, development and plant nutrient availability by the site-specific delivery system. For herbicide and pesticide application, encapsulated nanomaterials showed better penetration and allow slow release of herbicides and pesticides in the plant cell; therefore, nanotechnology provides an environment-friendly technique for herbicide and pesticide application in agriculture (Fig. 1) (Schils et al. 2018a). With advancement in the tool and techniques, the site selected delivery of pesticides and herbicides will further improve the agricultural practices. NPs loaded with fungicides, herbicides, fertilizers, nutrients and nucleic acid have a great potential to release at a specific part of the plant to achieve a site-specific control of plant diseases, abiotic stress management and nutrient management. With the advancement in biotechnological tools and techniques, nanomaterials have been extensively employed as disease diagnosis tools for advanced and precise diagnosis. The application of inorganic (micro or macro) nanomaterials during the growth cycle of crop increased the growth of plant by providing the appropriate nutrition to the plants

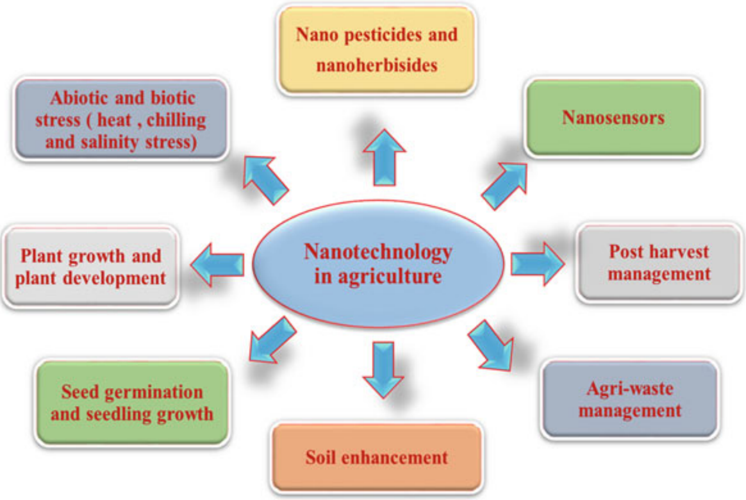

Fig. 1 Different aspects of nanotechnology in agriculture

(Schils et al. 2018a; Prasad et al. 2012). The metal-oxides NPs are proved to be effective to enhance the growth of plants in dry seasons by acting as a growth stimulator that, in turn, enhances the productivity and nutritional quality of the agricultural produce (Prasad et al. 2012; López-Vargas et al. 2018; Yang et al. 2006). In addition, in modern agricultural practices, nanomaterials are also reported to be useful as an effective antipest material (Bellesi et al. 2019). Nanotechnology deals with the use of NPs of dimensions 100 nm or less to meet the concept of quality and precision agriculture that enhanced the yield of the crop by efficiently utilizing resources in a precise manner by reducing the load of unnecessary chemicals on soil. (Auffan et al. 2009). Several materials like semiconductors, metal oxides, magnetic ceramics, synthetic and natural polymer lipids have been extensively explored for application of nanotechnology in agriculture. The biological material chitosan in nanomaterial as bionanocomposite is well known due to potent biopesticide and fungicide properties of chitosan that is helpful for seed priming treatment against fungal infection (Puoci et al. 2008). Furthermore, the plant response towards NPs varies from plant to plant, depending upon the uptake mechanism and their impact on growth and development. Seed germination and plant growth are the two major phenomena that are highly affected by the various concentration of NPs (Zheng et al. 2005).

In addition, researchers are emphasizing on green synthesis of NPs by employing various biological sources with an aim to reduce the adverse impact on environment (Bansal et al. 2014). The application of nanofertilizer, nanopesticides and nanoherbicides reported to significantly enhance the quality and quantity of agriproduce in the modern agriculture system. It is known that cereals are the most important staple food crop (Schils et al. 2018b); the foliar and soil application of NPs on cereal crops have positive effects on their productivity during their growth cycle that, in turn, increases the rate of plant productivity by offering micronutrient source (Cik et al. 2019).

1.1 Role of NPs in Seed Germination

Researchers have also revealed the positive impact of seed treatment with NPs that result in enhanced rate of seed germination and enhanced adaptation of seeds towards environmental stress (Adhikari et al. 2016). The seed treatment with NPs also reported to enhance seedling growth, vigour and viability in an experiment seed priming with Fe NPs which was found to be very effective in case of seedling growth parameters like root length, shoot length, pigments and antioxidant potential in Triploid water melon (*Citrullus lanatus*) (Kasote et al. 2019). Researchers have also revealed that the coating of seeds with silver (Ag) NPs resulted in enhanced water absorption compared to the control seeds (Adhikari et al. 2016). In another seed germination study, the seeds treated with NPs showed 73% more dry biomass and three times more vitamins compared to control seeds (Dehkourdi and Mosavi 2013). In addition, seed treatment with NPs also resulted in 90% increase drought resistance compared to control (Jaleel 2009). Furthermore, polysuccinimide NPs

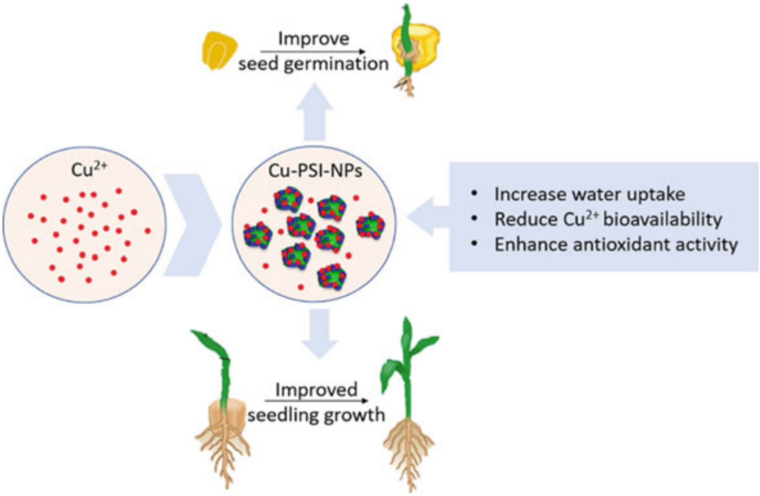

Fig. 2 Impact of polysuccinimide NPs (PSI-NPs) on corn (*Zea mays* L.) seed germination and seedling growth under Cu stress. Reproduced with permission of Xin et al. (2020)

(PSI-NPs) influenced the corn (*Zea mays L.*) seed germination and seedling growth under Cu stress (Fig. 2) in dose-dependent manner with an optimal rate of 200 mg L^{-1} (Xin et al. 2020) Thus, it can be assumed that nanoparticle treatment of seed or seedling results in significant increase in the quality, quantity and resistance of crop plants towards climate/environmental changes (Khodakovskaya 2009).

1.1.1 Plant Growth and Development

It is well known that the plant growth and development are significantly affected by the environmental regimes. The chemical treatment of plant propagating material could also promote or decrease the growth as well as the germination seed or seedling (Singh et al. 2015). Recently, several reports have been published related to the effect of nanomaterials on plants growth and germination and their advanced application in the agriculture field. The impact of various NPs such as titanium dioxide (TiO_2), copper (Cu), silicon (Si), gold (Au), quantum dots (QD), palladium (Pd), aluminium oxide (Al_2O_3), zinc oxide (ZnO), aluminium (Al) and cerium oxide (CeO_2) on germination of various plants namely, tomato, spinach, rice, lettuce, canola, radish, rye, grass, rape, corn, cucumber, cabbage and wheat was explored (Xin et al. 2020). These studies mentioned the positive impact of NPs on seed germination rate, photosynthetic rate, biomass and chlorophyll content of plants. In general, the seed germination rate was reported to be inversely correlated with the nanoparticle size. In addition, NPs mentioned to enhance the absorption level of inorganic nutrients, stimulate organic substance disintegrations and also improve the photosynthetic rate in plants

(Shojaei 2009). Furthermore, it is suggested to conduct extensive studies for deciphering the engineered nanomaterials, exploring their mechanistic application along with the agroecological toxicity (Khot 2012; Daniel and Astruc 2004; Kato 2011).

1.2 Role of Nanotechnology in Agriculture Innovation

Nanotechnology can play an important role to achieve the goal of sustainable agriculture and quality farming systems development. It is of immense importance to meet the food demands of increasing human and animal population. Thus, it is crucial to mindfully employ the available technologies for sustainable development. During the green revolution, fertilizers, pesticides and other agrochemicals have been used in excess with an aim to enhance the yield of crops. After decades of this unmindful practice, it was observed that excessive use of these agrochemicals leads to irreversible soil and environment pollution and reduction in soil microflora. To address this issue, application of nanotechnology in agriculture plays an important role by using significantly less amount of chemicals to achieve high protection against pests, herbs and high yield of agriproduce. However, it is also important to consider that excessive use of nanofertilizers, nanopesticides and nanoherbicides can also be toxic and harmful to the environment. Thus, further research is required to optimize the amount of nanomaterial to be used to achieve the goal of sustainable agriculture. Furthermore, nanotechnology can be helpful to improve the quality and production of agriproduce by employing nano-based sensors and monitoring devices in various agricultural practices. Thus, appropriate use of nanotechnology in agriculture may increase global food production and it will affect world agriculture positively (Kato 2011). Nanotechnology is an emerging field in the twenty-first century. Globally, researchers are exploring various means for the commercialization of nanoproducts. NPs have gained considerable attention compared to bulk counterparts owing to their unique properties. ZnO NPs mentioned to exhibit great potential to enhance crop yield due to their potent physical, optical and antimicrobial properties. The metal and metal-oxide NPs were also reported as an effective growth stimulator of crops in dry seasons resulting in an enhanced yield and nutritional quality of agricultural products by acting as an active antimicrobial agent. Nanomaterials are also employed as an essential part of different biotic and abiotic remediation strategies as NPs play a significant role in deciding the fate, mobility and toxicity of soil pollutants. When nanomaterials entered in the soil system, they may exhibit significant impact on soil quality as well as plant growth and development that has been conversed as their effect on nutrient release in soil, soil organic matter, soil biota as well as physiological and morphological responses of plants. In addition, the mechanisms involved in nanomaterial uptake and translocation within plants, as well as associated defence systems, are addressed in the following sections.

1.3 *Useful NPs in Agriculture*

NPs are also reported to play a significant role in plant growth, development and productivity. NPs' biological function is determined by their physicochemical qualities, application method and concentration. Previous studies have reported several NPs to be used in agri-innovation. It was also mentioned that different types of NPs exhibit different effect on plant materials such as increase in the seed germination, biomass or grain yield. Some of the NPs are toxic in nature; thus, it is recommended to use eco-friendly NPs synthesized by employing green methods and biodegradable and safe materials. Recently, researchers are also exploring different biological agents such as viruses, fungi, bacteria and plant extracts for NPs synthesis as these agents are green reducing agents and reduce the environmental impacts. Overall, Ag NPs, TiO_2 NPs and ZnO NPs are the most commonly employed NPs in agriculture for various purposes.

1.3.1 Carbon NPs

Carbon NPs have been used in different forms in several plant growth studies; C_{60} fullerene is the first stage carbonaceous NPs (Mukhopadhyay 2014). Carbon NPs of size 10 nm are the most advanced types of carbon nanomaterials. It is a nascent fluorescent molecule because of its unique trait of high photoluminescence that is proportional to its size. The cost, size, water solubility, transparency and biocompatibility of carbon NPs all play a role in their practical application. Based on its structure, two main types of nanotubes are available single-walled and multi-walled nanotubes. Carbon NPs have recently been added to the importance and extensive use of carbon materials. An extensive research in this field results in the development of novel exciting carbon nanomaterials that have attracted significant attention of researchers from various fields such as water filtration, hydropower, biochemical and agriculture production (Baker and Baker 2010). In literature, different types of methods have been reported for the synthesis of carbon NPs such as laser isolation, arc discharge, carbonization of carbohydrates, microwave-based pyrolysis and chemical vapour deposition (Mostofizadeh 2011; Chamoli et al. 2017; Singh et al. 2020; Wang 2011). Thus, by employing current breakthroughs in the field of nanotechnology, major improvements and enhancements in agricultural sustainability, disease management, crop protection, variety improvement and productivity can be realized. (Fig. 3) (Patel et al. 2019).

1.3.2 Metal-Oxide NPs

Ag NPs exhibit potent antimicrobial activity attributed to its high surface area (Wei 2013). Ag NPs have been extensively used against various disease-causing broad-spectrum human and plant pathogens (Cho et al. 2005; Morones et al. 2005; Tian

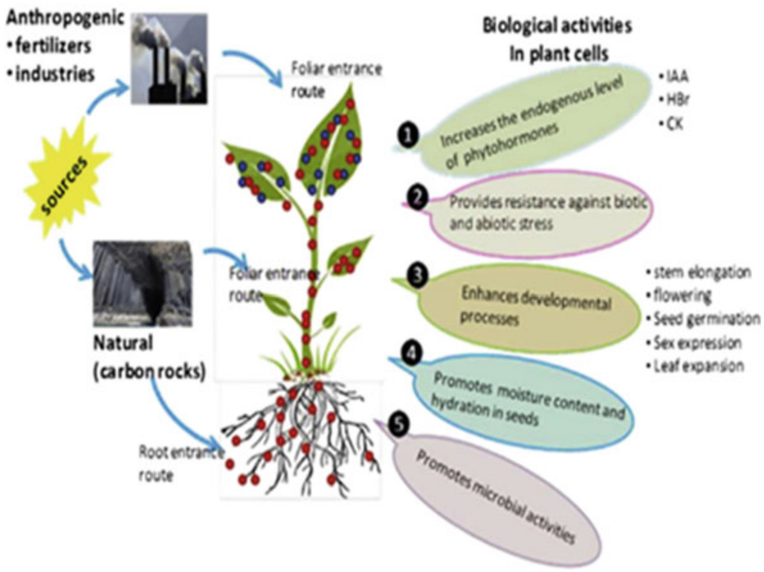

Fig. 3 Schematic representation of carbon nanotube sources (natural and anthropogenic), their uptake, accumulation and translocation, and their impact on growth and development of crop plants. CK, Cytokinin; HBr, homobrassinolide; IAA, indole-3-acetic acid. Reproduced with permission Patel et al. (2019)

et al. 2007; Chamoli et al. 2021a, b; Shukla et al. 2019; Ali et al. 2015). These particles have also been successfully employed for pest control of major food crops. Several methods for synthesis of Ag NPs have been documented in the literature, including chemical, physical and biological processes. Researchers have recently focused on environmentally safe, single-step methods for the synthesis of Ag NPs. Ag NPs have also been synthesized from a variety of sources, including plants, bacteria, and fungi. These Ag NPs are successfully employed for plant pathogen control in food crops. Researchers have also investigated the impact of Ag NPs (diameter = 20 nm) on fenugreek plant with positive results of pest control (Hojjat 2015). Researchers also found that seeds treated with Ag NPs at a concentration of 10 μg ml^{-1} exhibit the highest seed germination, germination speed, root length and root fresh weight. These results clearly revealed that the positive impact of Ag NPs on seed germination (Hojjat 2015). Ag NPs also reported to exhibit antibacterial properties, against the rice pathogen (*Xanthomonas oryzae* pv. *oryzae* (Xoo) which cause bacterial leaf blight (BLB) disease, NP synthesized from susceptible rice variety was used as an antibacterial agent against phytopathogen and results found to be very effective in mitigating the bacterial growth and colony formation of Xoo; therefore by this experiment, Ag NPs were found to be more powerful antibacterial agent (Namburi et al. 2021). Similarly, the Ag NPs coated with fructose reported to present antimicrobial activity against phytopathogens such as Erwinia amylovora, Clavibactermichiganensis, Ralstonia solanacearum, Xanthomonas campestris and

Dickeyasolani (Mishra et al. 2014). Zinc is also an important micronutrient for different agricultural crops. The deficiency of Zn significantly affects the agricultural production especially in the calcium carbonate-rich soil (Mishra et al. 2014). The soil of the Mediterranean region and arid region is mostly supplemented with calcium carbonate and this soil limits the zinc availability to plants (Thwala et al. 2013). ZnO NPs may be quite helpful to address this problem of zinc deficiency. However, exploration of harmful effect of ZnO NPs is crucial while addressing the problem of Zn deficiency of plants in calcium carbonate-rich soil (Elumalai et al. 2015). ZnO NPs increase the zinc dissolution and bioavailability of Zn to the plants in soil enrich with calcium carbonate. The diffusion of zinc from Zn fertilizer is an important part of zinc absorption by the roots of plants (Rajiv et al. 2015). ZnO NPs less than 100 nm in size exhibit better antimicrobial activity due to high interaction with bacteria as they exhibit high surface to volume ratio (Gangloff et al. 2006). ZnO NPs are also vital in the antioxidant defence system because they deactivate reactive oxygen species (ROS), which causes cell death. Thus, ZnO NPs are also reported to be helpful in the stress tolerance mechanism. The toxicity of Ag and ZnO NPs was suggested by the generation of reactive nitrogen species (RNS) and hydrogen peroxide (H_2O_2) when duckweed (*Spirodela punctuta*) was exposed to Ag and ZnO engineered NPs (Xia et al. 2006). In wheat, zinc NPs have been found to induce free radical production, resulting in increased malondialdehyde and reduced glutathione (Ryter et al. 2007) and chlorophyll concentration (Long et al. 2006; Lovric et al. 2005). To solve the zinc deficiency problem, ZnO and $ZnSO_4$ are mostly used zinc fertilizers but due to the non-availability of Zn to the plants, their use as Zn fertilizer is limited. ZnO NPs can address the above-mentioned problem by increasing the solubility of Zn and enhancing its availability to the plants. The enhanced solubility and bioavailability of Zn NPs attributed to its size in nanorange; thus, these NPs are more active as compared to Zn particles of millimetres in size (Xie et al. 2011).

1.4 Stress Management and Tolerance

1.4.1 Abiotic Stress Tolerance in Plants

Any adverse environmental condition such as temperature, moisture and salinity that affects the plants is known as abiotic stress. The abiotic stress of any kind can adversely affect the plants and limits their productivity. According to a report, global agricultural production should have been boosted to 70% to fulfil the fast-rising food demands of human population. Thus, increase in the different type of abiotic stresses and their adverse impact on crop yields triggers plant scientists to explore different means to control their impact on crop yield. (Lewinski et al. 2008). Under these abiotic stress conditions, plants have developed different mechanisms to combat these stress conditions. It is also important to note that the response towards these stress conditions may vary depending on the plants and their species. Therefore, screening or selection of stress tolerant genotype is a major concern for the plant scientists for sustainable agriculture. In this case, nanotechnology has opened new doors in the field of biotechnology and agriculture to deal with abiotic stress conditions such as salinity, alkaline soil condition, heavy metal stress, high- or low-temperature (FAO 2050; Meenu et al. 2016). Various physiological and molecular changes occur under abiotic stress conditions such as changes in gene expression, cell division and evolution of different energy pathways (Bromham et al. 2013). In such cases, NPs behave as stress signals and activate the defence mechanism of plants against abiotic stress conditions. The NPs also reported to act as antioxidative enzymes and scavenge the ROS (Manzer et al. 2015).

Drought

The depletion of water resources, desertification and salinity are the major challenges all over the globe in the field of agriculture, food production and food security. Among various abiotic stress, drought is the major problem as it limits the production of crops in arid regions (Rico et al. 2013). Recently, in case of *Crataegus spp.,* researchers have found that application of Si NPs at different levels of drought presented positive physiological and biochemical changes such as enhanced photosynthetic activity, MDA, high proline accumulation and more chlorophyll content (Wahid 2007). In addition, drought susceptible cultivars of Sorghum (*Sorghum bicolor* L.) presented an improved tolerance towards drought followed by the treatment with silicon NPs. Sorghum plants were also reported to exhibit improved root growth and photosynthetic rate. All these parameters revealed improvement in the drought tolerance of sorghum plants followed by treatment with silicon NPs (Rico et al. 2013).

Heat Stress

The exposure of food crops to high temperature more than the optimum is regarded as heat injury, temperature stress and heat stress. Heat stress severely affects the growth and development of plants when exposed for a long time (Rico et al. 2013). The exposure to heat stress or any other abiotic stress condition led to the production of ROS in that, in turn causes oxidative stress in plants that lead to ion leakage and lipid peroxidation. This will result in the degradation of some important proteins and reduction in photosynthesis rate and chlorophyll content (Wahid 2007). Se NPs had previously been shown to minimize the effects of heat stress by boosting chlorophyll content, plant growth and hydration ability at low concentrations. The expression of heat shock proteins (HSPs) is another important feature associated with heat stress. These HSPs work as molecular chaperones. The application of CNTs has also been reported to be linked with the HSP related genes (Ahmed et al. 2021). The excessive production of H_2O_2 and upregulation of HSP70 have also been reported to be associated with the application of CeO_2 NPs (Khodakovskaya et al. 2012). Furthermore, treatment with TiO_2 NPs was also shown to minimize the effects of heat stress by regulating stomatal opening (Zhao et al. 2012).

Chilling Stress

Chilling stress or low-temperature stress is the condition in mesophytes and xerophytes when they suddenly exposed to very low-temperature conditions, sometimes near freezing which causes serious damage in plant cells (Qi et al. 2013). The adverse effects of chilling stress include loss of permeability and ion leakage from the membrane, that, in turn lead to reduced germination, growth and overall development of plant (Hasanuzzaman et al. 2013). The tolerance to chilling stress varies significantly from variety to variety. The plants tolerant to chilling stress experience less damage while sensitive plants exhibit more damage followed by cold stress. The TiO_2 NPs were found to decrease the negative effects of chilling stress by minimizing plasma membrane damage, maintaining permeability and preventing ion leakage (Welti et al. 2002). The photosynthetic light reactions were also mentioned to be significantly influenced by the chilling stress. Chilling stress reported to exhibit several negative effects on plants such as reducing transpiration rate and CO_2 assimilation rate as chilling stress degrades RUBISCO and chlorophyll (Mohammadi et al. 2013). Furthermore, the nanoparticle treatment of plants leads to enhanced production of Rubisco enzyme in photosystem (Yordanova and Popova 2007). In addition, nanoparticle treatment also increases the light immersion ability of chloroplast (Gao et al. 2006a), as well as inhibits the production of ROS along with reducing the rate of ROS production. In addition, the plant treated with TiO_2 NPs presented high Rubisco activity (Ze et al. 2011), increased activity of the antioxidant enzyme (Xu et al. 2014), enhanced leaf pigments and increased tolerance to chilling stress. It was also mentioned that the upregulation of stress-related genes during low-temperature stress conditions increased the level of MDA reductase, glutathione reductase and dehydroascorbate reductase activities. These proteins/enzymes scavenge ROS that, in turn, reduces oxidative damage such as peroxidation of lipids, chlorophyll lose and generation of H_2O_2 and lead to enhanced tolerance to chilling stress (Hasanpour et al. 2015). Overall, nanoparticle exposure during chilling stress exhibits positive impact on growth, biochemical and physiological response towards the resistance (Haghighi et al. 2012a).

Salinity Stress

Application of NPs in salinity stress has been extensively explored. Among the NPs under investigation, SiO_2 NPs exhibit high potential to protect plant under salinity stress. A significant enhancement in the chlorophyll content, accumulation of proline and antioxidant enzyme activity was observed followed by the treatment with SiO_2 NPs that, in turn, will lead to enhanced abiotic stress tolerance in plants (Haghighi et al. 2012a). The treatment with Si NPs on lentil seed under salinity stress lead to a significant increase in the seed germination and seedling growth (Haghighi et al. 2012b). Furthermore, in the control condition, seed germination and seedling growth were lower than in the lentil seeds treated with SiO_2 nanoparticles under salinity stress. Thus, it can be assumed that SiO_2 NPs may increase the salinity tolerance in plants at seedling stage (Gholamreza et al. 2020; Sabaghnia and Janmohammad 2015). In maize, an increase in the fresh and dry weight of root and shoot was recorded followed by the application of SiO_2 NPs under salinity stress (Savvasd et al. 2009). Furthermore, Na toxicity is a major concern under salinity stress conditions, and it adversely affects crop growth and yield. In this regard, several studies reported positive impact of NPs treatment on plants along with increasing salinity tolerance in plants especially due to SiO_2 nanoparticle treatment. Thus, NPs treatment lead to overall improvement plant growth under stress/adverse conditions. Furthermore, salt stress raises Na toxicity, which reduced crop development and yield, and SiO2 NPs treatment was recommended to minimize Na ionic toxicity that result in improved crop growth and production and overall crop improvement under unfavourable conditions (Zulfikar & Asraf 2021).

Heavy Metal Stress

Heavy metal stress is another critical environmental issue being faced globally. Heavy metal stress suppressed the crop growth and yield by increasing the heavy metal toxicity by disturbing various physiological activities in plants (Gao et al. 2006b). Heavy metal stress interferes with the nutrient uptake process and also affects the regular antioxidant enzyme activity which exhibit positive effect on various activities associated with stress tolerance in crop plants (Rahimi et al. 2012). Heavy metal stress in soil and water increases the production of ROS that in turn increases oxidative damage in plants. The oxidative damage increases the stress condition plants by altering the structure of cells and degradation of various crucial proteins and enzymes. The stress conditions and oxidative damage decrease the nutrient uptake in plants that ultimately lead to nutrient deficiency and poor enzyme activity that, in turn, reduced the growth and development of plant (Capuana 2011). In response to heavy metal stress, plants have developed various defence mechanisms such as polyphosphates and metal chelators production which limit the excessive uptake of heavy metals and activate the antioxidant enzymes system that scavenges ROS production. However, application of synthesized NPs reported to reduce the load of heavy metal stress or toxicity (Rascio and NavariIzzo 2011; Gunjan et al. 2014; Tripathi et al. 2015). Previously, it was shown that using TiO_2 and hydroxyapatite nanoparticles reduced cadmium toxicity and increased photosynthetic rate and plant growth in *Brassica juncea* (Worms et al. 2012). It was also mentioned that supplementing growth media with Si NPs reduces chromium toxicity in peas (Gunjan et al. 2014). Furthermore, cowpea exposed to gold ion stress reduced Au31 to non-toxic gold NPs in the presence of phenolic compounds from germinating seeds (Singh and Lee 2016).

1.5 Nanotechnology in Food Industry

In addition, the introduction of nanotechnology to generate new generation packaging material reported to significantly enhance the freshness and quality of the fresh agriproduce. These novel packaging materials protect the packaged material from harmful rays, gases, chemicals and hindered the growth of pathogenic microorganisms. However, selection of base material packaging development and fast disintegration of packaging environment are two important factors to consider (Shabnam et al. 2014). In this context, polymer nanocomposites have emerged as an absolute substitute (Stewart et al. 2002) and its use as a packaging material which increase or extend the consumption of digestible and non-toxic degradable films. The application of nanocomposites results in edible and biodegradable films that protect the food against nutrient loss along with providing protection against cancerous materials (Stewart et al. 2002). Due to the availability of limited amount of natural polymers and weak mechanical strength of reported nanocomposite packaging material, their commercial utilization is limited. Thus, these natural biopolymer materials are usually combined with other man-made polymers with an aim to improve their mechanical strength and commercial utilization (Sinha Ray and Okamoto 2003). The packaging food material with bionanocomposites reduces the environmental load of packaging waste. These bionanocomposites are also maintain the freshness of food material for longer time and significantly enhance the self-life of packaged food. These nanocomposite packaging materials are associated with advantages such as low surface thickness, lucidity, easy flow, better surface properties and show properties of easy recyclability (Petersen et al. 1999). Furthermore, in the field of bionanocomposites as packaging material, the photo-catalysts mechanism by TiO_2 NPs under UV irradiation has gained significant attention due to its significant antimicrobial activity that in turn enhances the shelf life of packaged food. In addition, the catalyzing ability of nano-TiO_2 in presence of UV light can oxidize ethylene into water and CO_2 (Chen and Hu 2005). The development of edible and biodegradable films from natural resources promoted the exploration of innovative bio-based packaging materials that lead to shelf-life enhancement of food material along with reducing packaging waste (Hu and Fu 2003). Recently, Fuji apples packaged with nano-SiOx/chitosan presented better food processing qualities in comparison to non-degradable polymers (Tharanathan 2003). The development of advanced packaging materials with nanomaterials is able to meet the demand of advanced preservation techniques for storage of perishable food products, fruits and vegetables, and different beverages. With the addition of suitable NPs, normal biodegradable packaging material can be converted into durable and heat resistant packaging material. Furthermore, to ensure the food safety, nanobiosensors can be employed to detect the presence of unwanted biochemical reaction, generation of gases and presence of microorganisms (Tharanathan 2003). The functional ingredients of fruits, such as vitamins, antioxidants are the fundamental components, but they are rarely employed in their purest form; functional ingredients are commonly used as a part of a delivery system rather than the natural ingredients of fruits. Several functions can be performed by employing delivery system; however, the main goal is to deliver that functional element to its specific location. However, protecting of an ingredient from biotic and abiotic degradation is an important function of a delivery system. In addition, delivery system also responsible for the release of functional ingredient under specific environmental situations. Nanodispersions and nanocapsules are specific delivery systems employed for drug delivery of functional ingredients to specific sites. Nanobiosensors are used for labelling products with biodegradable sensors. In food industry, change the food colour with the change in pH of food products due to degradation, spoilage followed by microbial activity was determined by employing biosensors. Biological molecules such as sugars or proteins are frequently employed in the food industry as biosensors to detect pathogens and contaminants (Whistler and Daniel 1990). Nanotechnology may also be beneficial in coating or priming of seeds and grains with suitable materials that protect them against biotic and abiotic stress by various environmental factors. It is also used to design several food materials with potent antioxidants properties and different flavours. The primary goal of coating with nanoparticles is to improve the quality and functioning of ingredients by lowering their concentrations or dilutions as well as to improve the product by lowering the presence of chemicals by infusing innovative substances into foods (Charych et al. 1996) that can be achieved with greater exploration of delivery and controlled-release systems for biopharmaceuticals (Haruyama 2003).

1.6 Nanotechnology in Insect and Pest Management

Regarding the implementation of nanotechnology in insect and pest management, the major focus is the use of NPs for plant protection and nutrition in the form of nanopesticides or fertilizers. The application of pesticides and fungicides plays a crucial role in advanced agricultural practices but the area of food processing and packaging the application of nanopesticides and nanofertilizers has received less attention. Due to the direct application of nanochemicals in nature, they may be degraded or diffused in the environment. And this may be a critical condition for diffused nanoagrochemicals (Lawrence and Rees 2000). For wide applications of nanotechnology, several new products are being explored. Recently, nano-based agrochemicals were applied in agricultural pest management and in other fields of food processing and packaging with an aim to provide plant protection, nutrition management, development of eco-friendly, renewable energy resources, management of biomass, biocomposites and agrochemical industries (Sadowski 2010). Nanoformulations of ZnO, Ag, Cu, SiO_2, exhibit a wide range of protection against pest and insects, water stress and act as sustainable substitute for conventional pesticides to control the quality of soil and environmental pollution compared to the other traditional methods (Sadowski 2010). Zinc is essential for plant growth and development, yet it is only found in trace amounts in soil. As a result, Zn metal is a key target for the production of Zn NPs for pest control and nutrient delivery to plants. These nanoparticles are both cost-effective and safe, with strong antibacterial and antifungal activities. Thus, these NPs can be efficiently employed in agricultural fields to post-harvesting management practices. In addition, Ag NPs also exhibit antibacterial, microbial, fungal, larvicidal, pesticides and antiviral activity and efficiently employed in the field of agriculture, plant health management and pest control during pre- and post-harvest practices of food and grains (Chhipa 2017; Chopra et al. 1994; Gao et al. 2014; Iravani 2011). The nano-based formulations with ZnO NPs against the microorganisms show stability and slow kinetics, which is used for production in large amounts of antifungal reagents. The antifungal activity of bioformulation of nanomaterials may be the best alternative against harmful insects-pest control systems. In several experiments, the researchers were found that when an aqueous solution of bio-NPs was applied on several insects and pests, they found results like in the case of larvicidal activity of *H. armegera*. The aqueous extract from *Ecliptaprostrata* is useful to control mosquito; aqueous extracts of *E. prostrate* is used to control *S. oryzae*. Aloin from Alovera on formed Ag NPs is very effective, which is an eco-friendly approach to control the attacks of various insects and pests (Rajakumar and Rahuman 2011; Kantrao et al. 2017; Logaranjan et al. 2016; Devi et al. 2014). The use of nanotechnology in food packaging shows high efficiency in terms of biodegradation, a better solubility of nutrients and their slow release in the soil maintain soil fertility that, in turn, lead to quality improvement of crops. As a result, future researchers can investigate the use of nanotechnology in the field of plant protection and management in order to solve the fundamental issues associated with chemical fertilizers.

The properties of biopesticides such as thermal stability, stiffness, permeability and biodegradability are more advantageous in comparison with chemical fertilizers. Pests may experience indigestion followed by ingestion of nano-based material, which disrupt their water protection barrier, resulting in desiccation and death. Due to the presence of nanosize, nano-based formulations with nanocarriers have efficiently decreased the population of insects and pests. Bioactive compounds initiate the release of secondary metabolites from plants which can act on microorganisms present in its periphery (Kamaraj et al. 2012). Several studies have been carried out to determine the toxic effect of NPs on bacteria, fungi and pathogens, as well as a few experiments on insects and pests such as *Amsacta moorei* Butle, *Brachytrypesportentosus* Licht, *Episomus lacerta* F, *Gryllulus Domesticus* Linn, Chrotogonus sp. and *Helicoverpa armigera* (Nuruzzaman et al. 2016). The identification of plant species harbouring secondary metabolites with insect repellent properties as expressed by NPs such as Ag, ZnO, TiO_2 has recently been a hot topic. For future application and human welfare, the impact of nano-based biologically produced NPs on environment and living beings should be explained.

1.7 Agricultural Waste Management

In the agriculture sector, there is the production of large amounts of biowaste in each step, from planting to processing to till food vegetable and fruits storage. Agriculture biowaste management is a huge problem due to the shortage of skilled labour, proper mechanization and availability of adequate infrastructure. Agricultural biowaste processing has various limitations ;due to that, only 2% of the whole world biowaste is used, and all the other useable biodegradable material is degraded or decomposed by microbes; due to that, a large amount of biowaste is lost in the form of crop and energy loss. If this biodegradable waste product is properly managed and used, then we have a huge source of renewable energy. This is easily created and used by the whole world. By the use of nanotechnology or nanobioengineering, the enzyme extraction efficiency and energy production could be increased, and agricultural waste is easily utilized as a major source of renewable bioenergy which is very helpful in the conservation of biological resources and sustainable agriwaste management, nature and natural products. In nanotechnology by using metalloid enzymes, the biofuel production capacity was increased from agricultural wastes like rice husk, sugarcane waste, vegetable oils, shells of coconut, cotton stalk, groundnut covering corncobs, cotton and animal fats (Shiva et al. 2020; Shrivastava and Dash 2012; Sarkar and Praveen 2016). Nanotechnology provides natural replacement of harmful chemicals and also induce degradation of pesticides and herbicides. These hazardous pollutants can be degraded and converted to harmless compounds using NPs as reactive agents (Bharati and Suresh 2017). It is well recognized that all chemicals mixed with wastewater have a dangerous effect on the environment, and it is critical to remove these waste products in a systematic manner (Ditta 2012; Babula and Farming 2009). For the treatment of wastewater, several strategies have been developed, including nanotechnology. One of the most important nano-based wastewater treatments is photocatalysis. Purification, filtration and decomposition as well as the elimination of pathogens such as bacteria, viruses and other harmful agents have all been accomplished using photocatalysis. Photocatalysis is a catalytic reaction that takes place in presence of light. Several NPs have been used as catalysts, including metal oxides and sulphides such as TiO2, ZnO, SnO2 and ZnS (Mulligan et al. 2001; Ko 2009).

1.8 Nanobiosensors: New Tool for Detecting and Diagnosing Crop Diseases

All organisms can sense the various environmental changes. Disease detection and diagnosis is an important prospect in plant protection and the combination of biology and nanotechnology proved to be helpful in this aspect. Before controlling the disease, its detection is very important. Nowadays, NPs may be for disease detection, these compounds that could sense the presence of the pathogen. Nanobiosensors are every minute reproducible, solid and less toxic. They are helpful to maximize sustainable agriculture. With the help of signal receptors, biosenseros receives signals from the environment. Nanobiosensors have three components probe, bioreceptor and transducer. In comparison to the standard ELISA method, nano-based bioformulations with biosensors have a higher sensitivity for pathogen detection and disease diagnosis (Patel et al. 2021; Feigl et al. 2010). Nanosensors are used in plant pathology to detect disease-causing agents, contaminants in the environment and the presence of nutrients in soil. (Elmer and White 2018). Insect attacks in the crop plant can also be detected using nanosensors based on the detection of chemical substances generated by insects. (Brock et al. 2011). According to a study, QD nanosensors were also constructed to detect the presence of lettuce tobacco and cowpea mosaic virus, as well as beet necrotic yellow vein virus (Chartuprayoon et al. 2013; Lin et al. 2014; Safarpour et al. 2012). Several portable nanodevices have also been developed to detect environmental contaminants, insects, pathogens and diseases (Sharon et al. 2010). In wheat, gold-based immunological sensors were employed to detect kernel bunt disease (Singh 2020). Plants accumulate various stress-related chemicals when they are under stress. Previously, by sensing salicylic acid concentrations in soil, a gold electrode nanosensor and copper NPs detected a plant pathogenic fungus (Shang et al. 2019).

2 Conclusions

Nanotechnology have various application in agriculture as discussed in the chapter, NPs have the potential to change the scenario of global food security and agriculture problems. Nanotechnology has showed considerable promise in agricultural applications, as it has the potential to improve people's lives and the global economy. The focus of this chapter is on providing basic understanding regarding the optimal use of nanotechnology and different NPs for the improvement of crop productivity and sustainable agriculture. As advancement in nanotechnology going on, there are various tools and techniques available for a variety of agricultural nanotechnology applications, such as use of NPs in DNA sequencing, nanobarcodes, nanosensors, nanocatalysts, nanofertilizers and nanopesticides. Many studies have been undertaken to investigate the impact of carbon NPs on plant growth and development activities; nevertheless, different plant species respond differently to different nanoparticles, and the reason behind these variations are unknown. As a result of various studies, NPs are most popular due to their versatile properties, for water and wastewater purification. Ferrite-based adsorbents have low toxicity, high chemical stability and are economical to use as they can be easily separated from the purified liquid. Ferrites have shown great promise and are potential candidates for application for water and wastewater. Excellent magnetic properties make the use of ferrites in water systems attractive as they can easily be recovered at the end of the treatment train using a conventional magnetic field. While they can easily use in water treatment systems, their use in wastewater systems would need additional work given the complexity of wastewater. As a result, ferrites adsorbents are a top choice due to their versatile properties, reasonability and magnetic separation capability for water and wastewater purification.

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