Applications of Nanomaterials to Enhance Plant Health and Agricultural Production

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1 Introduction

Agriculture is the most fundamental and stable sector as it is the producer which provides raw materials to the food and feed industries. Therefore, the development of agricultural sector is very necessary to clean up the hunger and poverty from our society (Manjunatha et al. 2016). The increasing growth of population and limitations in the natural resources (productive land and water) in the world make researchers to think for the agricultural development economically, environmentally, and efficiently (Prasad et al. 2017).

In this text, nanotechnology has been described as the next great frontier in the agricultural science that focuses on getting better agricultural production and occupies a prominent position in transforming agriculture, development of soil fertility, and food production through efficient management of soil nutrients (Fig. 1) (Jhanzab et al. 2015; Venkatachalam et al. 2017). Nowadays, the devices based on nanotechnology are widely used in the field of genetic transformation and plant breeding (Torney et al. 2007). The development of nanomaterials could open up the novel applications in the field of soil science and food nutrition (Duhan et al. 2017; Shweta et al. 2018). Moreover, agriculture could also serve as a good source of bionanocomposites with improved physical-mechanical properties based on traditionally harvested materials such as soy hulls and wheat straw for bio-industrial purposes (Parisi et al. 2015).

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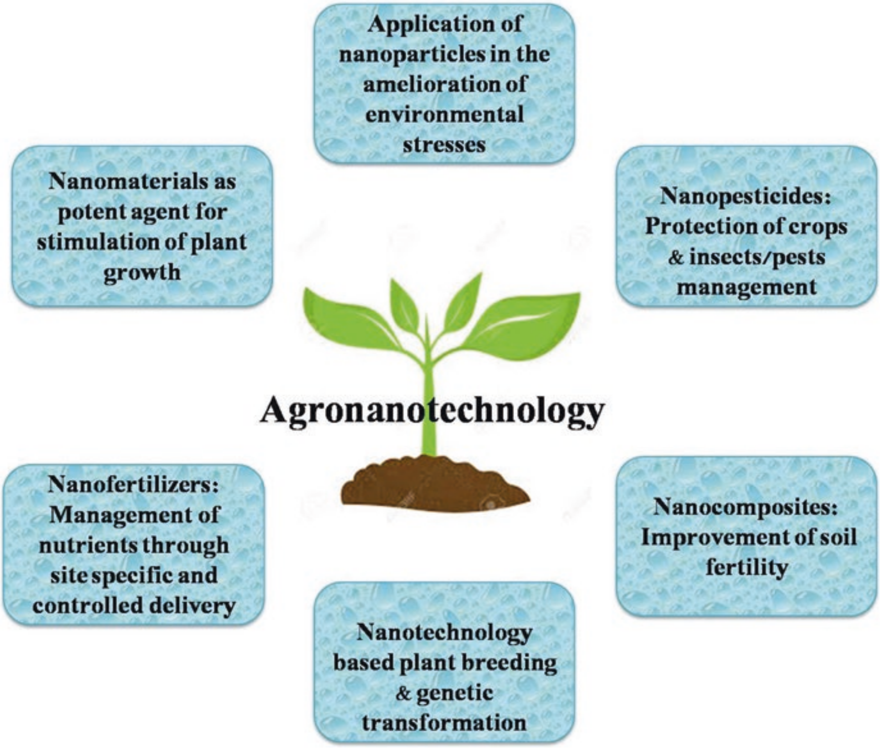

Fig. 1 Perspectives of nanotechnology in the sustainable agriculture

In the field of agriculture, benefits of nanotechnology are directly improving crop productivity by increasing water use efficiency; uptake of nutrition from the soil or irrigating water; precision farming; plant protection against insects and pests, fungal infections, and diseases; and innovative tools for pathogen detection, molecular biology, and environmental protection (Parisi et al. 2015; Duhan et al. 2017; Tripathi et al. 2017a, b; Ojha et al. 2018). The use of nanomaterial-based pesticides and insecticides can resist the plants against predators, and nanoparticles (NPs)-encapsulated fertilizers increased the absorption and transportation of nitrogen (N), phosphorus (P), and potassium (K) to seed; therefore, nanotechnology has great influence in strengthening the agricultural practices (Ojha et al. 2018). Use of nanofertilizers revealed better catalytic ability with enhanced surface area; hence, they are highly dispersible with high water-adsorbing properties. Therefore, nanofertilizers can increase the efficiency of nutrient, ions, and water uptake, ultimately improving the yield and nutrient content in the edible parts of the crop plants (Venkatachalam et al. 2017; Vishwakarma et al. 2018).

Moreover, exogenous application of nanoparticles (NPs) for the growth augmentation of plants and also for the amelioration of several types of environmental stresses is one of the recent and effective approaches and has attracted attention of the researchers worldwide (Tripathi et al. 2015, 2016; Venkatachalam et al. 2017;

Yadu et al. 2018). Due to the high volume and surface effect, NPs can interact with cellular biomolecules and stimulate various biochemical pathways in the cell. Some NPs have the ability to protect the protein oxidation and membrane damage of the cells caused due to oxidative stress imposed by the exposure of plants to various environmental factors such as heavy metals, salinity, high temperature, ultraviolet (UV), etc. (Tripathi et al. 2017c; Venkatachalam et al. 2017).

In agriculture, the chief concern of using nanotechnology consists of specific applications like use of nanofertilizers and nanopesticides for the augmentation of plant growth and productivity without causing harm to the environment and also protection against several insects, pests, and microbial diseases. Here, we briefly discuss various nano-based materials and their properties and functions in plant growth intensification, pest management, and delivery vehicles for nutrients and fertilizers.

2 Nanoparticles: General Properties and Functions

2.1 *Silver Nanoparticles*

As silver nanoparticles (AgNPs) have a high surface area, fraction of surface atoms, and high microbial effect, they can be used as an antimicrobial agent for crop protection (Saber et al. 2017). Therefore, there is a mounting interest to utilize this property of AgNP to diminish the burden of insects from crops and for the management of plant diseases. Like other nanomaterials, AgNP can also be synthesized by biological, chemical, electrochemical, photochemical, and physical methods (Banerjee et al. 2014; Salem et al. 2015). Owing to prerequisition of extreme conditions and toxic chemicals used in other methods, biological methods are nontoxic, eco-friendly, and widely accepted (Duhan et al. 2017).

Due to higher antifungal activity of silver than that of other metals, it inactivates the sulfhydryl groups of fungal cell walls, thereby disrupting the transmembrane, electron transport chain, and energy metabolism (Duhan et al. 2017). The biosynthesized AgNP has a strong antibacterial activity and is effective against both gram-negative and gram-positive bacteria. Moreover, AgNP neutralizes the electric charge of the surface of bacterial cell membranes, which changes its permeability and consequently leads to cell death (Prasad et al. 2017). This crucial property of silver metal makes it an ideal alternative for different aims in the medical and biotechnological fields (Salem et al. 2015). The efficacy of AgNP is dependent on particle size and shape, surface coating, concentration and duration of exposure, and species and developmental stage of plant and decreases with increasing size of the particles (Jhanzab et al. 2015). Pal et al. (2007) reported that truncated triangular AgNP showed higher “cidal” effect than that revealed by spherical and rod-shaped particles. This property of AgNP is a boon against a variety of harmful microorganisms. This AgNP sequesters the free radicals formed in the cells when exposed to various environmental stresses and facilitates the stabilization of cellular macromolecules

(Kim et al. 2007; Yadu et al. 2018). Also, AgNP has great influence on plant growth and development such as germination, root growth, root elongation, root-shoot ratio, and senescence inhibition (Jhanzab et al. 2015). The possible reason for this enhancement might be attributed to high specific surface area of AgNP which may be responsible for sequestering nutrient ions on their surfaces hence serving as a nutrient supplier to the germinating seeds and give support in their growth (Banerjee et al. 2014). In agriculture, its application of AgNP might be a feasible, effective, and safer mode as it possesses ability to reform the field by enhancing the efficiencies of plants to uptake and translocate more nutrients, and boosting antioxidant defense system thereby withstanding against various environmental stresses and consequently improving crop yield (Yadu et al. 2018).

2.2 Zinc Nanoparticles

Zinc (Zn) is one of the important micronutrients for plant and human diet. In human, its deficiency is considered to be one of the leading risk factors as it causes severe health disorders in infants and also leads to development of chronic diseases in the youngsters (Rameshraddy et al. 2017). In plants, its deficiency is the most widespread micronutrient crisis that adversely affects the agricultural production in highly alkaline soils with calcium carbonate (Duhan et al. 2017). The parameter that restricts the availability of Zn to plants in calcium carbonate-loaded soils of agricultural field is the alkaline pH, which decreases solubility of Zn and increases calcium carbonate content which can absorb and precipitate Zn (Rashid and Ryan 2004). Although the oxides and sulfates of Zn are commonly used as Zn fertilizers to overcome its deficiency in soils, yet their applications are limited due to the nonavailability of Zn to plants. Therefore, global challenge for food and nutrition security is to increase the agricultural crop production without negotiating their nutritional content (Quasem et al. 2009).

Therefore, use of zinc nanoparticles (ZnNPs) is the easiest, simplest, and sustainable way to achieve the target by supplying more soluble and available form of Zn to plants due to their higher reactivity (Duhan et al. 2017). The use of this NP as Zn fertilizers may augment Zn dissolution and its bioavailability even in soils with calcium carbonate. With these NP dissolved, Zn can easily diffuse from fertilizer to plant tissues and thereby fills the Zn crisis (Gangloff et al. 2006). Due to small size as less than 100 nm and high surface-to-volume ratio of ZnNP, it shows much better antimicrobial activity and allows better interaction with bacteria (Xie et al. 2011). Synthesis of ZnNP from plants is more cost-effective and eco-friendly as compared to chemically synthesized NP (Duhan et al. 2017). Usually, plant leaf extract dissolved in solvents such as water, ethanol, or methanol has been used for its synthesis, which was mixed with appropriate aqueous solutions of either zinc sulfate heptahydrate or zinc acetate dehydrate at desired pH. This NP has been tested in the laboratory and was proved to be a good antifungal agent, bactericide, and environment friendly (Rajiv et al. 2013). Elumalai et al. (2015) has reported the antimicrobial activity of 16- to 20-nm-sized ZnNP, synthesized from leaf extract of *Moringa oleifera*, which was effective against a number of bacterial strains such as *Escherichia coli*, *Bacillus subtilis*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa* and fungal strains like *Candida albicans* and *Candida tropicalis*. Moreover, according to the reports of Rajiv et al. (2013), ZnNP synthesized from the leaves of *Parthenium hysterophorus* showed antifungal activity against plant pathogens like *Aspergillus flavus* and *Aspergillus niger*. Thus, the use of ZnNP in the agricultural field has given promising results against diseases and enhanced plant growth and nutrition.

2.3 Silicon Nanoparticles

In the composition of the Earth's crust, after oxygen, there is 28.8% silicon (Si) based on dry weight. The biological role of Si was firstly well known for improving the growth and development of cells in diatoms, sponges, and corals (Alsaeedi et al. 2017). It is ubiquitous in nature and exists in all forms of life including humans and plants. Higher plants absorb Si from the aqueous solution more easily than the other essential nutrients. Due to having ability of regulating the defense mechanisms of plants, its amelioration potential has been well reported in several studies against varied biotic stresses such as insects and diseases and abiotic stresses including salinity, metal, and drought (Mateos-Naranjo et al. 2013; Farooq and Dietz 2015; Tripathi et al. 2015). Application of Si in plants reduces their sensitivity for toxic organisms, enhances water use efficiency by lowering evapotranspiration, and strengthens the activities of antioxidant enzymes (Roohizadeh et al. 2015). Therefore, Si has popularly been used in nanotechnology to form silicon nanoparticles (SiNPs) to expand crop productivity and improve its quality (Lu et al. 2002; Siddiqui and Al-Whaibi 2014). Thus, engineering silica in nanosize makes silica more easy to pass the cell wall passively which plays a key role in improving the plant's tolerance to abiotic stresses (Alsaeedi et al. 2017). A bird's-eye view of the literature survey indicates that exogenous application of SiNP played a greater role in the alleviation of abiotic stress-induced toxicity in crop plants (Tantawy et al. 2015; Tripathi et al. 2015, 2016).

Under stressed conditions, use of SiNP improved the rate of seed germination and growth and biomass accumulation of crop plants (Alsaeedi et al. 2017). This alleviation of stressed conditions may be assigned due to more than one mechanism(s): (i) SiNP-mediated decrease in heavy metals uptake and accumulation, (ii) elevated levels of macro- as well as micronutrients, (iii) decreased accumulations of free radicals, (iv) stabilization of photosynthetic apparatus, (v) reduced markers of oxidative damage, (vi) as a plasma membrane and protein stabilizer, (vii) enhanced enzymatic antioxidant defense system, (viii) adjusting the levels of non-enzymatic antioxidants, etc. (Tripathi et al. 2015, 2016). Also, SiNP releases Si which gets deposited underneath the cuticle layer of leaves, thereby reducing the rate of transpiration and thus maintaining a higher relative water content in leaves which makes the plant to withstand the stressed conditions. According to Alsaeedi et al. (2017), use of SiNP in agriculture is expected to improve the crop production by boosting the uptake of plant nutrition, water use efficiency, precision farming, and crop protection against insects and diseases. Thus, exogenous use of SiNP in agricultural fields emerged as an innovative tool for pathogen detection, amelioration of various biotic and abiotic stress-induced toxicities in crop plants, and environmental management.

2.4 Carbon Nanotubes

Carbon nanotubes (CNTs) are a new form of cylindrical-structured carbon and a two-dimensional graphene sheet rolled into a tubelike configuration (Zaytseva and Neumann 2016). Depending on the number of concentric layers of rolled graphene sheets, it is categorized as single-walled nanotubes with outer diameter of 0.8–2 nm and multiwalled nanotubes with outer diameter of 5–20 nm (De Volder et al. 2013). Lengths of CNT range from 100 nm to several centimeters, depending on its desired application in various fields such as optics, nanomedicines, electronics, biosensors, etc. (Mukherjee et al. 2016). This CNT soaks the water-containing contaminants such as toxic organic solvent dichlorobenzene, oil, fertilizers, pesticides, and pharmaceuticals (Camilli et al. 2014). Agrochemicals or any potential compounds can be targeted to hosts by CNT-based delivery systems; therefore, it can cut down the level of chemicals discharged into the environment and hence can reduce the damage caused to other parts of the plants (Hajirostamlo et al. 2015).

Due to the extraordinary unique optical, electric, and magnetic properties and tiny size, these CNTs are gaining much attention in recent decade from scientists in the field of plant genetic engineering too (Akhter et al. 2011). According to Lin et al. (2009), when the *Arabidopsis thaliana* cell cultures were exposed to CNT, it provoked hypersensitive signals that lead to defense responses in the cells causing cell death. Applications of nanosensors with metal/metal oxide NP based on electrochemically functionalized single-walled CNT for gases, viz., sulfur dioxide, nitrogen oxides, ammonia, hydrogen sulfide, and volatile organics, are very effective in monitoring agricultural pollutants and also for assessment of their effects on living matter or health and in increase of crop productivity and yield (Sekhon 2014).

Silver-coated CNT hybrid NPs have shown antimicrobial activity. More particularly, single-walled CNT showed the strongest antifungal activity (Zaytseva and Neumann 2016). Tripathi et al. (2011) reported that in *Cicer arietinum*, citrate-coated water-soluble CNT created an aligned network that enhanced the water uptake capacity and consequently improved the plant growth and development. An increased rate of germination, root length, biomass accumulation, shoot growth, and nutrient and water uptake in response to CNT have been well reported (Tripathi et al. 2011; Khodakovskaya et al. 2012; Mukherjee et al. 2016). An upregulation in the aquaporin genes upon CNT exposure was reported by Khodakovskaya et al. (2012); thus, CNT has also proven to be involved in water transport, cell division, and cell wall formation.

2.5 Quantum Dots

In the field of nanotechnology, quantum dots (QDs) have been commenced as a promising innovative tool for basic and applied life sciences (Muller et al. 2006; Chakravarty et al. 2015). Due to having unique optical properties, QDs are far better and rapid than organic fluorescent dyes because of more efficient luminescence, small characteristic emission spectra, outstanding photostability, and tenability according to the particle sizes and material composition and can be applied more effectively in bioimaging and biosensing (Jaiswal and Simon 2004). Recently, QDs have been used for labeling the plant proteins and hence are widely used in the detection of pathogens related with several diseases (Chahine et al. 2014). Use of QDs has been proven a boon in the field of food technology also. For the chemical conversion of water molecules into hydrogen, QDs have been utilized as a photocatalyst in the solar fuel pathway (Jaiswal and Simon 2004). The layer-by-layer assembly technique comprising the optical transducer of highly sensitive biosensors based on nanostructured films of acetylcholinesterase and cadmium telluride QDs has been used in the detection of pesticides (organophosphorus) present in the vegetables and fruits (Zheng et al. 2011).

The exogenous application of QDs at a very low concentration revealed no any toxic effects and also proved to be a plant growth regulator (Chakravarty et al. 2015). Therefore, QDs can be applied as smart treatment delivery systems for the regulation of seed germination and seedling development and can easily enter the plant's cell walls due to the smaller size than that of pores of the cell wall. Also, QDs can be used for bioimaging in plant root systems for the verification of known physiological processes (Duhan et al. 2017). Chakravarty et al. (2015) reported that exogenous application of graphene QDs enhanced the growth rate of *Coriandrum sativum* and was involved in the production of proteins that are essential for the development of plants. Also, their study on QDs has revealed that application of QDs increased the average length and weight of the roots with the enhancement in the size, strength, and green color of leaves as compared with untreated *Coriandrum sativum* plants.

3 Nanoparticles as an Agent In

3.1 Plant Protection

Plants are continuously exposed to various types of stresses which include both biotic and abiotic (Chandrakar et al. 2016). These stresses induce oxidative injury in the plant cell which causes damage to the important cellular macromolecules such as nucleic acids, protein, enzymes, and lipid. In the extreme conditions, the plant's inbuilt tolerance mechanisms become slower or inhibited to withstand against this condition (Yadu et al. 2019). Therefore, exogenous applications of some of the compounds are needed to enhance the tolerance against environmental stresses

(Chandrakar et al. 2018). Since the last decade, exogenous application of NPs has come into limelight to protect the plants from various abiotic stresses such as heavy metal (Venkatachalam et al. 2017), arsenic (Praveen et al. 2018), fluoride (Yadu et al. 2018), etc.

Nanoparticles have been proved to be a very promising compound because of its unique properties and important roles in integrating the environmental and intrinsic cues that help the plants to withstand under growth-limiting conditions. This has significance in agronomy because NPs represent a novel means of providing tolerance to important crops against biotic and abiotic stresses, thereby promoting sustainable agriculture (Yadu et al. 2018). In plants, exogenous application of NPs may act as a powerful tool against various abiotic stresses by inducing a wide range of processes involved in their tolerance mechanisms (Praveen et al. 2018).

Rameshraddy et al. (2017) reported that application of zinc oxide nanoparticles (ZnNPs) plays an important role in protecting the plants against oxidative damage catalyzed by reactive oxygen species (ROS) by increasing the activities and gene expressions of antioxidant enzymes. Their results revealed that because of having higher surface area, the NPs can deliver higher Zn content to the plants. According to Abdel Latef et al. (2008), titanium dioxide NPs have the ability to boost photosynthesis, biomass accumulation, and antioxidant defense, which help plants to enhance their growth potential and tolerance under salinity stress.

3.2 Plant Growth Augmentation

Application of NPs in the crop plants enhances their growth and development due to the high surface-to-volume ratio that increases the reactivity of NPs and possible biochemical activity. The NP-mediated plant growth augmentation may probably be the resultant of several mechanism(s) such as i) NP-mediated decrease in accumulation of toxic metals present in the soil/water that reduces the plant growth, (ii) decreased level of free radicals and oxidative damage caused by several environmental factors, (iii) activated antioxidant defense system, and (iv) enhanced level of macro- as well as micronutrients available for the plants (Tripathi et al. 2016).

Also, nanomaterials upregulate the expression of water channel genes (aquaporins) and thus play a crucial role in the permeability and enhancement of water, and nutrient uptake during seed germination (Lahiani et al. 2016; Singh et al. 2016). Thus, the application of engineered NPs in the agricultural land should always be a beneficial step to sustain an eco-friendly approach for the agricultural sector. The origin of these NPs can be either chemically or green synthesized. More efficient and eco-friendly is the green synthesis of NPs using extracts of some of the other potential plants, which can be applied to protect the crops from the adverse effects of several abiotic stresses. Green synthesis provides advance technique over chemical method as it is cost-effective, nontoxic, and environment friendly. Moreover, in the agricultural field, the application of polymeric NPs loaded with insecticides of plant origin (green synthesized) is a distinctive and widely accepted technique.

4 Nanotechnology and Agricultural Development

Without the use of agrochemicals like pesticides and fertilizers, better production and efficiency in modern agriculture are inconceivable these days. Although there are some potential issues related with every agrochemical that can negatively affect both the human being and environmental health, this risk needs to be reduced up to safer level by putting control in the inputs and precise management (Fraceto et al. 2016; Prasad et al. 2017). Therefore, to bring a revolution in agricultural practices, the development of high-tech agricultural system could be an excellent strategy, following the use of engineered smart nanotools. The influence of agrochemicals on the environment could lessen and/or be eliminated by exploiting the nanotools that can enhance both the quantity and quality of crops (Sekhon 2014; Parisi et al. 2015; Prasad et al. 2017). Nowadays, for site-specific and controlled delivery of fertilizers and pesticides to the plants, nanoencapsulation, nanoformulation, and functionalized nanomaterial of next-generation fertilizers and pesticides are exploited for reducing the risk of excess runoff (Gogos et al. 2012; Chowdappa and Gowda 2013). Therefore, for sustainability of agrisector, the development and utilization of smart delivery system as nanocomposites, nanosensor, nanofertilizer, nanopesticide, and nanoherbicide have been inaugurated as a new mode of applications (Manjunatha et al. 2016; Chhipa 2017).

4.1 Nanofertilizers

Today, half of the agricultural productivity relies on the chemical fertilizers. However, increasing the doses of fertilizers does not provide assurance of the improvement in the crop yield; rather, it leads to serious environmental problems like soil degradation and pollution of surface and groundwater resources (Chowdappa and Gowda 2013; Chhipa 2017; Duhan et al. 2017). Nitrogen, P, and K are the main constituents of chemical fertilizers, and it is estimated that about 40–70% of N, 80–90% of P, and 50–70% of K of the applied fertilizers cannot be absorbed by the plants and are lost in the atmosphere. So the major portion of fertilizer added resides in soils, thereby causing eutrophication by entering into the aquatic system (Oosterhuis and Howard 2008; Liu and Lal 2015). Therefore, to overcome the problems like imbalanced fertilization and low fertilizer use efficiency, nanofertilizer technology is a modern approach (Duhan et al. 2017; Anjum and Pradhan 2018). Nanofertilizers have several advantages over the conventional chemical fertilizers and are as follows: (a) they increase the fertility of soil, (b) improve the quality and yield of crops, (c) are nontoxic and eco-efficient, and (d) minimize cost and maximize profit (Sekhon 2014; Liu and Lal 2015; Prasad et al. 2017).

Slow release of fertilizers can be achieved by the use of nanomaterials. Nanocoatings or surface coating of the fertilizer particles by nanomaterials has the potential to hold not only the fertilizer material but also plant roots more strongly due to the higher surface tension than the conventional surfaces (Oosterhuis and Howard 2008; Manjunatha et al. 2016). The stability of nanocoating reduces the rate of dissolution of the fertilizer and allows slow, sustained release of coated fertilizers so that all the available/required nutrients are absorbed by the plants and restore the energy due to which the productivity and yield increase drastically (Wilson et al. 2008; Anjum and Pradhan 2018). Nanofertilizers balance the release of N and P with the absorption by the plant, thereby averting the loss of nutrients and avoiding their interaction with microorganisms, water, and air. To meet the demand of soil fertility and crop productivity, nanocoated urea and phosphate and their sustained release will be beneficial. For the sustained release of fertilizers, several natural and synthetic polymers have been used (DeRosa et al. 2010; Chen and Yada 2011). Corradini et al. (2010) have reported that biodegradable polymeric chitosan nanoparticles (approx. 78 nm) showed good results for the slow release of NPK fertilizer. A study on nanofertilizer-encapsulated nanosilica was performed by Wang et al. (2002) which revealed that after absorption of nutrients, nanosilica formed a binary film on the cell wall of fungi or bacteria and prevented infections, hence perking up the growth of the plant under high temperature and humidity and improving plant's resistance to diseases. Titanium (TiO_2) is a nontoxic material and hence can be used as additives in fertilizers for increasing the food production and water retention capacity of the plants. In *Spinacia oleracea*, increase in total N, protein, and chlorophyll was observed after the application of TiO_2 as an additive (Gao et al. 2006). Srinivasan and Saraswathi (2010) have reported that CNT can be used as nanofertilizer which promotes water uptake capacity and growth by entering into the germinating seeds of *Lycopersicon esculentum*.

To achieve slow release of nutrients in the environments, another nanomaterial, i.e., zeolites, can be used. These are group of naturally occurring minerals having a honeycomb-like layered crystal structure. The N and K can be loaded in its network of interconnected tunnels and cages which can combine with other slowly dissolving ingredients containing P, calcium (Ca), and other trace elements (Manjunatha et al. 2016). For slow and controlled release of N, and for longer time length, urea-coated zeolite chips have been synthesized and utilized (Millan et al. 2008; Kottegoda et al. 2011). An alternative of conventional Ca macronutrients, Liu et al. (2004) synthesized Ca NP and observed increment in the nutrient content in shoot and root of *Arachis hypogaea*. Likewise, Delfani et al. (2014) used iron oxide (FeO) and magnesium (Mg) NP fertilizer as alternate of Fe and Mg, and increments in seed weight and chlorophyll content of *Vigna unguiculata* were observed. Similarly, nanoforms of micronutrients are synthesized as micronutrients are also essential for different metabolic processes of plants, although they are required in minute amounts. Pradhan et al. (2013) have recorded that use of manganese (Mn) NP on *Vigna radiata* increased the root and shoot lengths, biomass, and chlorophyll content in comparison with bulk manganese sulfate. Zinc is another essential micronutrient which regulates the different enzymatic activities in plants. Enhancement in the plant growth and root-shoot dry mass was registered in *Vigna radiata* and *Cicer arietinum* by Mahajan et al. (2011) after addition of zinc oxide (ZnO) NP.

4.2 Nanopesticides

To control pests and insects, nowadays, biopesticides occupy a unique position in the agrimarket as an alternative of synthetic pesticides (Chhipa 2017; Duhan et al. 2017). The deployment of engineered nanomaterials is an efficient and novel technology in the field of biopesticides. In the agronomic sector, it is well known that insects and pests are the predominant destroyers which affect growth and productivity of crops adversely, in general (Nair et al. 2010; Ghormade et al. 2011). Therefore, in order to control insects/pests and host pathogens, nanopesticides may have key role due to their typical properties like enhanced solubility, specificity, stability, and permeability (Prasad et al. 2017; Thakur et al. 2018). Hence, for increasing agriculture production, syntheses and exploitation of nontoxic and environment-friendly nanopesticide delivery systems are urgently required, which will not only be better substitute of chemical pesticides but also helpful in reducing destructive impacts of toxic chemicals on the ecosystem (Agrawal and Rathore 2014; Duhan et al. 2017). Due to the electrostatic interaction of NPs with cell membranes of bacteria and their accumulation in cytoplasm, most of the metal NPs exhibit good antibacterial, antifungal, and antipathogenic activities (Chinnamuthu and Boopathi 2009; Bansal et al. 2014).

Nanomaterials including silver, silver oxide, gold, ZnO, TiO_2, magnesium oxide (MgO), and copper oxide (CuO) NPs possess antimicrobial activity due to which these are popularly explored for their insecticidal, bactericidal, and fungicidal activities against phytopathogens, alone or in combination with other metallic NPs (Khot et al. 2012; Agrawal and Rathore 2014). Because of their diverse mode of inhibition, these NPs inhibit or delay the growth of a number of pathogens. Therefore, these NPs can be used as new antimicrobial agents and as an alternative to synthetic pesticides (Li et al. 2008; Ghormade et al. 2011). Reports suggested that AgNPs are toxic against a broad range of plant pathogens. Alghuthaymi et al. (2015) demonstrated that AgNP not only inhibited the nutrient uptake phenomenon of *Raffaelea sp*. hyphae but also hindered their growth and conidia formation activity. Silver NPs are considered as a potent nanopesticide as they obstruct microbial growth by inhibiting germination of their spores. Mondal and Mani (2012) have reported that CuNP showed antibacterial activity against *Xanthomonas axonopodis* pv. *punicae* in *Punica granatum*. These CuNPs can bind with nucleic acids inside the bacterial cells and cause intermolecular cross-linking. These are also shown to damage the proteins by binding with their sulfhydryl groups and/or carboxyl groups of amino acids so that the biological processes of bacteria are hampered. Debnath et al. (2011) tested the entomotoxicity of SiNP against *Sitophilus oryzae* in *Oryza sativa* and compared its efficiency with bulk-sized silica. These authors found SiNP to be highly effective against this pest, which indicated the effectiveness of SiNP toward insects/pests control.

Further, to improve efficiency and stability, and reduce effective concentration of a pesticide, nanoformulation was developed such as nanoformulations of insecticide-coated liposome, *Azadirachta indica* oil, *Eucalyptus globulus* oil, pyridalyl, *Allium sativum* essential oil, *Syzygium aromaticum* oil, carbofuran, thiram, atrazine, and simazine (Nuruzzaman et al. 2016; Chhipa 2017). A significant insecticidal activity of *Allium sativum* essential oil was observed by Yang et al. (2009) against *Tribolium castaneum* following the use of polyethylene glycol (PEG)-coated NPs. Anjali et al. (2012) reported that nanoemulsion of *Azadirachta indica* oil was an effective larvicidal agent against *Culex quinquefasciatus*.

Hence, formulation of nano-encapsulated pesticide is quite effective than the normal agrochemical due to its slow and sustained release, allowing proper absorption of the chemical into the plants, and has a long-lasting and persistent effect (Nuruzzaman et al. 2016; Ojha et al. 2018). The specificity of synthetic pesticides toward the targeted pests is high, but they have detrimental impacts on human health and environment too. So there is an urgent need to expand the frontiers for nanomaterial-based technologies in insect/pest management (Ghormade et al. 2011; Prasad et al. 2017).

4.3 Nanocomposites

Nanocomposites are composites in which at least one of the phases has dimensions in the range of nanometer. Just like conventional composites, nanocomposites are comprised of at least two components: (i) matrix or continuous phase, in which nanosized particles are dispersed and (ii) the nanosized particles/nanoparticles constituting the second phase, i.e., dispersed phase (Othman 2014; Ojha et al. 2018).

Nanocomposite can be classified, depending on the matrix materials, into three groups: (1) metal matrix composites [Ni/Al_2O_3,Fe-Cr/Al_2O_3, Co/Cr, Fe/MgO, Al/CNT], (2) ceramic matrix composites (Al_2O_3/SiO_2, Al_2O_3/CNT, SiO_2/Ni, Al_2O_3/TiO_2, Al_2O_3/SiC), and (3) polymer matrix composites (polymer/CNT, polyester/TiO_2, polymer/layered silicates) (Camargo et al. 2009; Gupta 2018).

Nanocomposites have potential applications in growth and development of plants and insect/pest management. Metal matrix nanocomposites consist of an alloy metal reinforced with nanosized materials. Metal nanocomposites, like AgNP, CuNP, and TiNP possess antimicrobial activity due to which they can modify the properties of bacterial cell membranes by adhering on their surfaces (Navarro et al. 2008; Rai and Ingle 2012; Ojha et al. 2018). Metal nanocomposites having positive charge interact with the negatively charged cell wall/membranes of bacteria or fungus via electrostatic interactions. This interaction can result into destruction of cell structure and increase in membrane permeability leading to the leakage of intracellular stuffs. After entering into microbial cells, these metal nanocomposites bind with various cellular organelles, start disturbing the metabolic processes of the cells, and ultimately lead to death of the microbe (Navarro et al. 2008; Tripathi et al. 2017a). One of the study performed by Tejeda et al. (2009) observed that soda lime glass powder containing Cu nanocomposites possesses antibacterial activity against *Escherichia coli* and *Micrococcus luteus*. Likewise, Pallavi et al. (2016) have reported that Ag nanocomposite showed antibacterial activity against rhizospheric bacterial diversity and enhanced the root-shoot lengths and dry mass of *Triticum aestivum*, *Vigna sinensis,* and *Brassica juncea*.

Due to the multifunctional structure and property, polymer/CNT has also been used as a nanocomposite (Peigney et al. 2000; Thostenson et al. 2001). Sarlak et al. (2014) have encapsulated the pesticides zineb and mancozeb into the multiwalled CNT-grafted poly-citric acid hybrid which showed a marked effect against *Alternaria alternata* as compared to the bulk ones. In some other experiments, chitosan/CNT nanocomposite has been applied for the controlled and improved delivery of a broad-range insecticide azinphosmethyl and was used to protect fruits like *Citrus limon*, *Pyrus malus*, and *Prunus persica* from various insects (Bibi et al. 2016).

5 Future Perspectives of Nanotechnology in the Field of Agriculture

To maximize the production and yield of various crops in agronomic sector, new technologies, approaches, innovative ideas, increased use of nano-chemicals, and policies of the government should be adapted. It is mandatory to exploit the new technology in the food industry to overcome the problems occurring due to the usage of agrochemical products. After few years, without the use of pesticides and fertilizers, the viable production and efficacy of crops are unconceivable in the agriculture as these pesticides and fertilizers have some prospective issues like contamination of water with toxic chemicals or their residues in food chain that affects the human health and atmosphere. Thus, the alternative eco-friendly and controlled delivery system can diminish these risks. Therefore, the main motives of using nanomaterials/NPs in the agrisector are to reduce the amount of hazardous chemicals, curtail the loss of nutrients in fertilization, and increase the productivity and yield of crops via insect/pest and nutrient management.

Nanoparticles are usually manufactured by using chemical methods, and studies have illustrated that the use of a chemical-reducing agent consumes more energy and generates larger-sized particles. Additionally, the chemically synthesized NPs are accounted to show less stability and more agglomeration. Hence, alternate eco-friendly protocols should be adopted which can utilize bacteria, fungi, and plant extracts as reducing agents, which is considered as “bio-nanotechnology/green nanotechnology.” These biological/green syntheses methods can produce stable and dispersible NPs of desired size by consuming comparatively less energy. Moreover, these are not only environment friendly but also cost-effective, rapid, and less arduous, generate less waste, and are more proficient than the conventional chemical procedures. Hence, the development of smart “nanotools” with high-tech agricultural system makes a revolution in agricultural practices. The nanotechnology-based delivery of NPs has improved the crops production and yield via site-specific delivery and controlled release of nanofertilizers and nanopesticides.

In the near future, more attention and research toward some of the focused areas are required in the field of agro-nanotechnology or nanofoods:

(a) Nanotechnology may provide green, efficient, and eco-friendly strategy for insects/pests management in agriculture, so main emphasis should be on green nanotechnology: a new environmentally safer delivery system.
(b) The biosensor-based nanotechnology can have an effective role in pests/insects control and cross contamination of agriculture and food products.
(c) Some reliable and analytical methods are required to identify, characterize, and quantify different forms of NPs and for the assessment of their impacts on both the human being and environment prior to their delivery in the field.

6 Conclusions

Currently, in the field of agriculture, we are facing varied challenges due to the growing global population and climatic change. In such situation, the application of modern nanotechnologies as well as the introduction of potential nanomaterials in agriculture can greatly contribute in the sustainable growth of this very important sector. Nanotechnology has the potential to provide a great and promising future with the use of nanomaterials in agronomic sector and food industry through rapid and precise disease diagnosis and desired delivery of fertilizers and nutrients to the plants. Although ample of information are available about individual NPs, the level of toxicity of many of them is yet to be diagnosed. Therefore, due to the inadequate knowledge of risk assessment and effects on human health and environment, its application in agriculture and food industry is still at the inceptive phase. So for better acceptance of this emerging and modern technology, public awareness regarding the advantages and challenges of nanotechnology is must.

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