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REVIEW ARTICLES

Expanding the horizons of nanotechnology in agriculture: recent advances, challenges and future perspectives

Ravi Kumar Yadav[1] · N. B. Singh[1] · Ajey Singh[1] · Vijaya Yadav[1] · Chanda Bano[1] · Shubhra Khare[1] · Niharika[1]

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Abstract

The speedy progress towards the utilization of nanomaterials (NMs) is being extensively carried out in the fields of agriculture and food industry due to their varied properties. In recent years, a number of studies have been accomplished to interrogate intricate mechanism by which nanoparticles (NPs) influence plant growth, metabolism and development. Both positive and negative impacts of NMs on the growth of plant at various developmental stages are well documented. The effect of NMs on plant growth and development differ greatly depending on the concentration, composition, size and various important physicochemical properties of NMs. Synthesis as well as utilization of nano-fertilizers is one of the promising approaches regarding significant enhancement in the agricultural yield across the world. Application of biosynthesized NMs in the field of agriculture has progressed in sustainable development. The biological synthesis of NMs consisting of natural reducing agents without the use of toxic chemicals and the consumption of high energy has attracted the focus of scientists towards biological methods. This review summarizes the application of NMs on plant growth and development, uptake and translocation of NMs within plant tissues. This evaluation also attempts to examine the biological synthesis of NMs and their antimicrobial activity as well as their roles in agricultural sector could prove to be a boon for the society in the coming future.

Keywords Nanomaterials · Agriculture · Nano-fertilizers · Green synthesis · Sustainable development

Introduction

The population of the world is around 6 billion and the developing countries are facing daily life challenges for food, agriculture, health and pharmaceuticals. Globally, the growing anthropogenic activities along with the technical advancement have led to the addition of huge waste materials in the biosphere hampering ecological balance. The imbalance in ecosystem environmental stability is progressively increasing the damage to biosphere and ecosystem facilities. The increase in population continues to intensify the ecosystem degradation in the near future (Lee et al. 2010). Nanoparticles (NPs) measure up to 100 nanometer (nm) at least in one dimension and have certain physical properties such as uniformity, conductance and unique optical properties that make them desirable in material science and biology. Nanotechnology and nano-biotechnology are the novel fields which have remarkable possibilities to renew agriculture and related fields (Shukla and Wattal 2013). Nanotechnology targeted farming techniques that involve the use of NPs with distinctive properties to boost crop and livestock productivity. NPs possess unique physicochemical properties viz. lower melting point, higher specific surface area, specific optical properties, mechanical strength, and specific magnetization properties that might prove attractive in various industrial applications. NPs are composed of three layers i.e. (a) the outer layer, which is functionalized with a diversity of small molecules, metal ions, surfactants and polymers, (b) the middle shell layer, which possess chemically different material from the core and (c) the core, which is essentially the central portion of the NP and usually referred as the NPs itself (Khan et al. 2017). The NPs have various applications in ecology, nourishment, healthcare, optics, human services, and so forth. Nanobiotechnology is multidisciplinary in nature which evaluates the use of NPs in the biological system (Paladini et al. 2015; Das et al. 2019).

Nanotechnology as a pioneer field proved to be a new industrial revolution with great potential to improve the agriculture and crop productivity. Nanoparticles showed a

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✉ N. B. Singh
singhnb166@gmail.com

[1] Plant Physiology Laboratory, Department of Botany, University of Allahabad, Prayagraj 211002, India

wide range of application in environmental biotechnology like reduction of pollution, water treatment, remediation, dye degradation and water purification development (Singh et al. 2020).

NP causes several morphological and physiological changes in plants, depending on the distinct properties (Maurya et al. 2012). Nanotechnology proved in resource management of agriculture sector, specific nutrient delivery in plants and helps maintaining the fertility of the soil. The role of NPs has been evaluated progressively in the utilization of biomass and agro-wastes in food processing and packaging as well as risk assessment (Floros et al. 2010). Nowadays, the main focus of the research area is the utilization of different kinds of NPs and their effects on crops and the environment (Singh et al. 2016). Nanotechnology has exhibited its great prospects in the achievement of controlled release of fertilizer, a specialized bottleneck mechanism utilizing nanostructured or nano-scale materials, for example, fertilizer bearers or controlled-discharge for developing allegedly called smart fertilizer (Qureshi et al. 2018). Nanotechnology is a smart and intelligent framework that conveys exact measure of supplement and different agrochemicals required by plants, limiting utilization of pesticides and anti-infection agents. Nanotechnology plays significant role in enhancing crop yields by improving the fertilizers use efficiencies (Choudhary and Kumar 2018).

Synthesis of nanoparticles

In the last couple of decades, demand of different metallic and non-metallic NPs has increased drastically. The NPs are synthesized by "top down" and "bottom up" approaches (Sepeur 2008). The top–down method follows the complex to simpler process i.e. reduction in size of bulk material (Meyers et al. 2006; Hussain et al. 2016). In this process different chemical, physical treatments can be used for the size reduction of the NPs (Fig. 1). In the process of bottom–up approach, NPs synthesis takes place through joining smaller entities of atoms, molecules and simpler particles (Mukherjee et al. 2011; Singh et al. 2019). This approach includes both chemical and biological methods. The green NPs show unique properties and thus increase its application in the fields of biomedical, pharmaceutical, biotechnology, and agriculture. NPs such as gold (Au), silver (Ag), platinum (Pt), and palladium (Pd) are commonly used NPs in the industries and products range from cosmetics to pharmaceuticals. Various physical, chemical and biological techniques aids in the development of NPs of different size, forms, and compositions and among them chemical approaches are the most popular. The physical approach systems include laser ablation (Mafune et al. 2001) angle-resolved colloidal lithography (Zhang and Wang 2008), high-energy irradiation

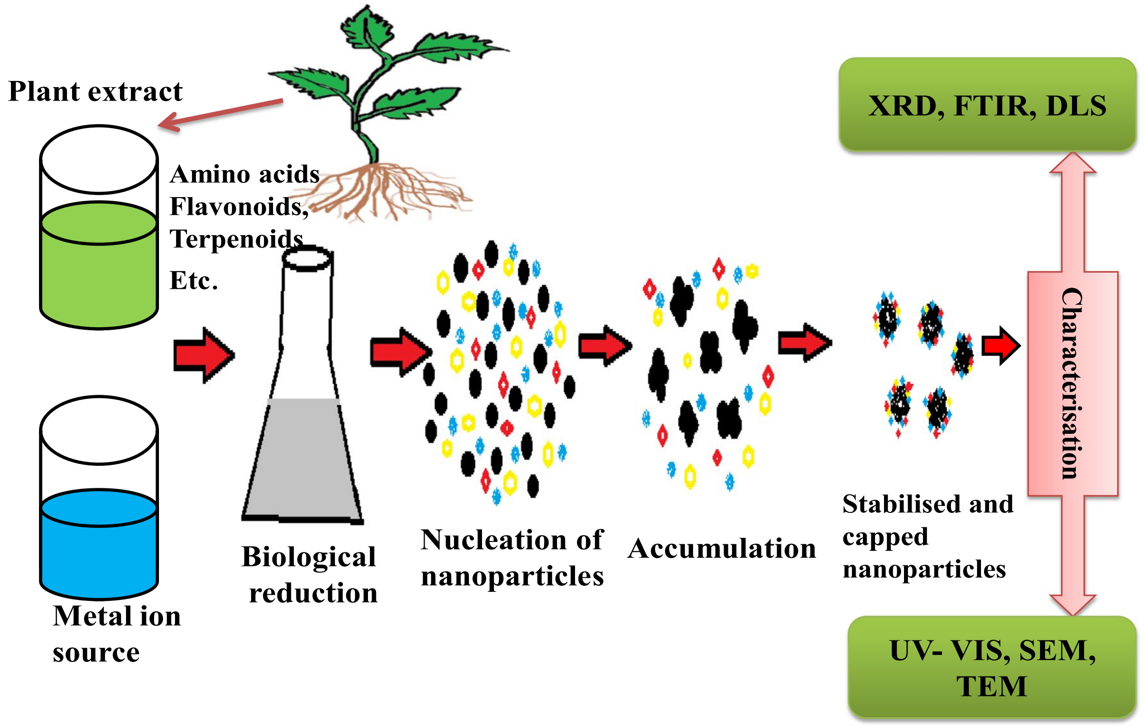

Fig. 1 A diagrammatic representation of possible mechanism involved in green synthesis of NPs

through dose rate condition (Treguer et al. 1998), chemical vapor deposition (CVD), supercritical fluids, sonochemical reduction and gamma radiation (Charitidis et al. 2014). The chemical method is another approach to synthesize NPs which is different from physical method due to the difference in techniques and chemical reactions. The techniques involved in chemical methods are chemical reduction, electrochemical reactions photochemical reduction (Eustis et al. 2005) and formation of ions via chemical reaction series (Dupas and Lahmani 2007). The conventional NPs synthesis methods are very expensive due to consumption of high energy and materials. Furthermore, it also causes toxic effects on environment and human life. There is no well-established method to detoxify these chemicals formed during synthesis. Presently, the scientific community has developed the new green approach for synthesis of NPs which is eco-friendly and involves synthesis of NPs with the help of living agents like plant extract, fungi, bacteria and biological particles. In some cases, additional properties are shown by biologically synthesized NPs as compared to the conventional methods. The use of biologically synthesized silver NPs on antibacterial activity found to be very effective (Zhang et al. 2016). In the green synthesis of NPs different plant materials viz. leaf, flower and bark can be used (Fig. 1). The leaf extract of *Eclipta prostrata* by aqueous reduction method was used to synthesize TiO_2 NPs (Rajakumar et al. 2012). Leaf extract of *Catharanthus roseus* was successfully used for the extracellular synthesis of ZnO NPs by using aqueous zinc acetate which helps increase antimicrobial activity against *Pseudomonas aeruginosa* followed by *Staphylococcus aureus* (Bhumi and Savithramma 2014). Synthesis of gold NPs was done using mushroom *Volvariella volvacea* and aqueous solution of chloroauric acid tetrahydrate ($HAuCl_4$) (Pushpavanam et al. 2014). The extract of marine algae *Sargassum muticum* (brown seaweed) was used for the biological synthesis of iron oxide NPs (Fe_3O_4) (Mahdavi et al. 2013). Green tea extract is also helpful for the green synthesis of iron NPs (Hoag et al. 2009). Materials used for the synthesis of gold and silver NPs are chloroauric acid ($HAuCl_4$) and silver nitrate ($AgNO_3$) respectively along with *Azadirachta indica* leaf (Shankar et al. 2004). Synthesis of TiO_2 NPs at room temperature using $TiO(OH)_2$ was performed by bacteria *Bacillus mycoides* (Órdenes-Aenishanslins et al. 2014). *Glycine max* and leaf extract of *Hippophae rhamnoides* were used for production of palladium NPs (Petla et al. 2012). Zinc NPs were synthesized by mixing 5 g of zinc nitrate with 50 ml of aqueous extract of *Cassia* petals (Ramesh et al. 2014). The latex of *Calotropis procera* was used for green synthesis of ZnO NPs at room temperature (Singh et al. 2011).

Application of nanoparticles in agriculture

The characteristics of NPs depend greatly on their chemical origin, affecting their fate and behavior in the environment. In recent years, application of NPs in the field of agriculture due to its specific property, shape, and size is getting more importance. Some devices and tools viz. nanodevices, nanocapsules and nanobiosensors developed by nanotechnology, etc. are being used for the detection and control of diseases in plant, deliver of active components to the desired target sites, waste water treatment and also in increasing the absorption of nutrients in plants (Tripathi et al. 2017).

The targeted delivery systems of NPs are very effective in specific cellular organelles but other parts of plant are not affected by these particles (Nair et al. 2010). Due to target based specific property, they serve as “magic bullets” containing herbicides, nano-pesticide, nano-fertilizers, or genes, target specific cellular organelles in the plant to release their contents (Elizabath et al. 2019; Sharma 2013). This process also minimizes the number of harmful chemicals that pollute the environment. Some NPs have the potential to improve the photosynthetic system. Nowadays, scientific community is trying to explore the new roles of NPs in the agriculture and food production due to its great potential.

Nanotechnology has ability to revolutionize the whole food industry by changing the food production, processing, packaging, transportation and consumption. In future, the agriculture fields can prove as a wide area, a bio-factory that can be monitored and managed from a work station and food can be designed so as to deliver nutrients and calories efficiently to the body.

Nano-biotechnology could increase potential of agriculture to harvest feed stocks for industrial processes. Rubber, cocoa, coffee and cotton, the major tropical agricultural cash crops may touch new targets relevant to a set a new nano-economy in cheaper and smarter way. The genetically modified (GM) crops could lead to new levels of success providing several choices to the consumers. With new nano-techniques of gene mixing and harnessing, GM plants could prove a boon for the society. Pesticides can be more specifically packed to remove unwanted pests and artificial flavors that may enhance the taste in the plate. Dream of a programmed, centrally-controlled industrialized agriculture can now be wondered using molecular sensors, automated delivery systems and low-cost technology.

Impact of nanoparticles on plant growth and development

In recent years, researches and experiments showed that the NPs have great significance on the plant growth and development (Zheng et al. 2005). Ag NPs can be used antibacterial, antiviral, anti-inflammatory and antiangiogenic agent due to its unique physical, chemical, and biological properties (Gurunathan et al. 2014). Titanium oxide (TiO_2) NPs favor naturally aged spinach seed germination, dry weight and photosynthetic rate (Singh et al. 2011). Seed germination depends on the penetration power of NMs due to small size as they are more beneficial for germination as compared to large size (Khodakovskaya et al. 2009). Due to photo-sterilization and photo-generation of "active oxygen like superoxide and hydroxide anions" by nano-TiO_2 has increased growth rate which could increase resistance of seed stress (Shukla et al. 2016). Some metal-based NPs such as Ag, Pt, Ce, and Zn possess antioxidant and anticancer properties as well (Ganguly et al. 2019). It also promotes penetration by capsule for uptake of water oxygen and nutrient needed for proper germination (Anjum and Pradhan 2018). TiO_2 showed the positive effect on germination (Feizi et al. 2013) and increased the absorption of inorganic substance and enhanced the breakdown of organic nutrient (Yang et al. 2007). SiO_2 NPs improved the seed germination, germination index, seed vigor index, fresh weight and dry weight in *Solanum lycopersicum* (Siddiqui et al. 2014) (Table 1). SiO_2 in hydroponic culture showed increased germination, dry weight and accumulation of silica and nutrient contents in plant (Suriyaprabha et al. 2012). SiO_2 may improve the defense system of the plant exposed to salt stress by the increased rate of photosynthesis, stomatal conductance, transpiration rate, water use efficiency, total chlorophyll, proline and carbonic anhydrase activity in the leaves of *Cucurbita pepo* (Siddiqui et al. 2014). It is illustrated that metallic nanoparticles showed significant growth in vitro conditions of carnation cultivars in a concentration dependent manner. It could also be concluded that nanoparticles could efficiently increase in vitro shoot multiplication and regeneration of plants in floriculture (Zia et al. 2019).

Nano-SiO_2 at any concentration could increase the soluble protein, amino acid, micronutrient enzyme activity and decrease the malondialdehyde (MDA) content (Li et al. 2012). TiO_2 mixed with SiO_2 improves the nitrate reductase (NR) and antioxidant enzymatic activities. Previous studies show that gold NPs increases the toxicity by suppressing the function of aquaporin (Shah and Belozerova 2009) but have positive effects in lettuce and cucumber (Barrena et al. 2009), *Brassica juncea* (Arora et al. 2012), *Boswellia ovalifoliolata* (Savithramma et al. 2012a, b), *Gloriosa superb* (Gopinath et al. 2014) by influencing seed germination (Table 1). CeO_2 NPs increased H_2O_2 accumulation in the complex tissue of plants, bundle sheath cells and epidermal shoot cells up to 2 weeks. In corn shoot the activities of catalase (CAT) and ascorbate peroxidase (APX) increased due to increased H_2O_2 levels. CeO_2 activated the up-regulation of the heat shock protein (HSP70) in root with systemic stress response. Some previous studies show that ZnO NPs and TiO_2 NPs affect the three-parameter, viz. root number, seed germination percentage, root length in rice (*Oryza sativa* L.). The NPs do not alter the percentage of seed germination but nano-ZnO changed the status of roots at early seedling stage, stunting the root length, decrease in number where as TiO_2 does not affect the root length (Boonyanitipong et al. 2011a, b). It has been reported that multi-walled carbon nanotubes (MWCNTs) in tomato plants increase the growth and germination (Khodakovskaya et al. 2009). Synthesized MWCNTs in factory having quality-controlled specifications were seen to increase the growth and germination but at higher concentration, they show harmful effect. CuO NPs have deleterious effect on DNA of crop plants and also decrease the growth and influence metabolism of seedlings of crops like *Raphanus sativus*, *Lolium rigidum* and *L. perenne* (Atha et al. 2012). In a study, the impact of mineral stress (Fe and Zn) on different physiological and biochemical parameters on shoot and root tissues of *Phaseolus vulgaris* under in vitro conditions on four different MGRL medium was investigated (Urwat et al. 2019).

Uptake and translocation of nanoparticles within plant

It is essential to expand our knowledge of the toxicity and bioavailability of NMs to achieve the promised benefits of synthesized NPs. The interactions between vascular plants and synthesized NPs are of particular concern and it is essential to forecast their fate in the terrestrial environment and their accretion in the food chain (Fig. 2). Size, chemical composition, and stability play a crucial role in uptake, accumulation and translocation of NPs (Wilson et al. 2008). There are two basic pathways for the penetrance of NPs into the plant through tissues: the apoplast and the symplast. In apoplastic movement, particle move across the plasma membrane through the extracellular spaces, xylem vessels and cell walls of adjacent cells (Kumar and Pandey 2013). Sieve plates and plasmodesmata play a crucial role in symplastic transport which involves the translocation of substances and water between the cytoplasm of adjacent cells (Concenco and Galon 2011). Further translocation takes place into stems, roots and leaves by charged ions. Positively charged ions are primarily associated with roots and negatively charged are found to be translocated more easily into shoots (Fig. 2). The apoplast accomplishes the radial movement within the plant tissues which allows NPs to reach into the central cylinder of root and the vascular tissues for further upward movement (Larue et al. 2012).

The NPs follow the transpiration stream after reaching central cylinder and move towards the aerial part through xylem (Cifuentes et al. 2010; Larue et al. 2012; Wang et al.

Table 1 Impact of some selected NPs on plant growth and development

S. no.	NPs	Plants	Family	Concentration	Size	Impacts on plant	References
1.	$AgNO_3$ and GA-Ag	*Lolium multiflorum*	Poaceae	1, 10 or 40 mg/L	20 nm and 6 nm	Rapid plant growth	Yin et al. (2012)
2.	Aluminum oxide	*Triticum aestivum*	Poaceae	0, 5000, 25000, 50 000 mg/L	13 nm	Reduced the root elongation	Yanık and Vardar (2015)
		Nicotiana tabacum	Solanaceae	0, 100, 500 and 1000 mg/L		Negative effect on the growth and development of tobacco seedlings	Burklew et al. (2012)
3.	Copper	*Brassica rapa*	Brassicaceae	2 and 4 mg/L	16.14 nm	At low concentration, promoted the growth response, while higher concentrations resulted in toxic response	Narayanan and Park (2014)
		Triticum aestivum	Poaceae	570 (450-722) mg/L	10.5 nm	Significant increase in germination percentage on soaking in NPs suspension and severe reduction on soaking and incubation in copper NPs	Lee et al. (2008)
4.	Cu, Zn, Mn, and Fe oxide on lettuce	*Lactuca sativa*	Asteraceae	Fe at 1 to 5 mg/L, Mn at 0.5 mg/L, Zn at 0.05 mg/L, and Cu at 0.02 mg/L.		CuO inhibited the seed germination. ZnO caused no enhancement of the seed germination. MnOx significantly enhanced root elongation. FeOx significantly enhanced root elongation	Liu et al., (2016a, b)
5.	CuO	*Lemna gibba*	Lemnaceae	100 to 400 mg/L	81 nm	Inhibited the plant growth at lower concentration	Perreault et al. (2010)
		Lemna minor	Lemnaceae	200 mg /L	81 nm	Increase the production of reactive oxygen species in the cell, causing a saturation or a destruction of the antioxidative systems	Frankart et al. (2002)

Table 1 (continued)

S. no.	NPs	Plants	Family	Concentration	Size	Impacts on plant	References
6.	Iron	*Triticum aestivum*	Poaceae	20000 mg/L	10 nm	Severe reduction in root growth when seeds were soaked in and incubated in distilled water while root growth enhanced on soaking in distilled water and incubation in	Antisari al. (2016)
7.	Iron oxide	*Arabidopsis thaliana*	Brassicaceae	100 mg/L	22.3–67.0 nm	Plants treated with Fe NP presented less chlorophyll	Marusenko et al. (2013)
8.	Silica	*Ocimum basilicum*	Lamiaceae	1000 mg/L	7 nm	Increase leaf, dry and fresh weight	Kalteh et al. (2018)
9.	Silicon dioxide	*Lens culinaris*	Fabaceae	1 and 2 mM	30 ppm	Favorable effect on lentil seed germination under salinity stress.	Janmohammadi and Sabaghnia (2015)
10.	Silver	*Zea mays*	Poaceae	200 mg/L	21 nm	Shoot and root lengths increased at low conc. and bio uptake was higher in AgNP treatment than the control	Pokhrel and Dubey (2013)
		Arabidopsis thaliana	Brassicaceae	1 mg/L	20–80 nm	Seedling toxicity	Ma et al. (2013)
		Lemma minor	Lemnaceae	5 mg/L	20, 100 nm	Inhibition of plant growth was dependent of NP size and this became more acute with longer exposure time	Gubbins et al. (2011)
		Phaselous radiates	Fabaceae	0, 5, 10, 20, 40 mg/L	5–25 nm	Reduced root growth, root length and biomass.	Le et al. (2010)
		Oryza sativa	Poaceae	30–60 mg /L		At higher concentration: affected and damaged cell wall; shoot growth more susceptible	Mirzajani et al. (2013)

Table 1 (continued)

S. no.	NPs	Plants	Family	Concentration	Size	Impacts on plant	References
11.	Titanium dioxide	*Phaseolus vulgaris*	Fabaceae	0–30 mg/L	25 nm	No change in plant biomass ;rooted plants showed high content of Ti in the root; all plants showed translocation of Ti	Jacob et al. (2013)
12.	Zero-valent iron	*Arachis hypogaea*	Fabaceae	10–320 mg/L		Stimulated both the seedling development and growth.	Yang et al. (2015)
13.	Zinc and zinc oxide	*Allium cepa*	Amaryllidaceae	20 mg/L	20 nm	Inhibition of root growth	Lawre and Raskar (2014)
		Cyamopsis tetragonoloba	Fabaceae	10 mg/L	1.2–6.8 nm	Increased biomass, root and shoot length, chlorophyll content and protein synthesis	Raliya and Tarafdar (2013)
		Sesamum indicum	Pedaliaceae	1000 and 2000 mg/L	10–15 nm	Decreased photosynthetic pigment, biomass and protein content	Narendhran et al. (2016)
		Oryza sativa	Poaceae	500 mg/L	50–100 nm	Stunted root length and reduction in number of roots	Boonyanitipong et al. (2011a)
		Brassica nigra	Brassicaceae	10 mg/L	> 100 nm	Shoot emergence, root hair formation and enhanced radical scavenging activity	Zafar et al. (2016)

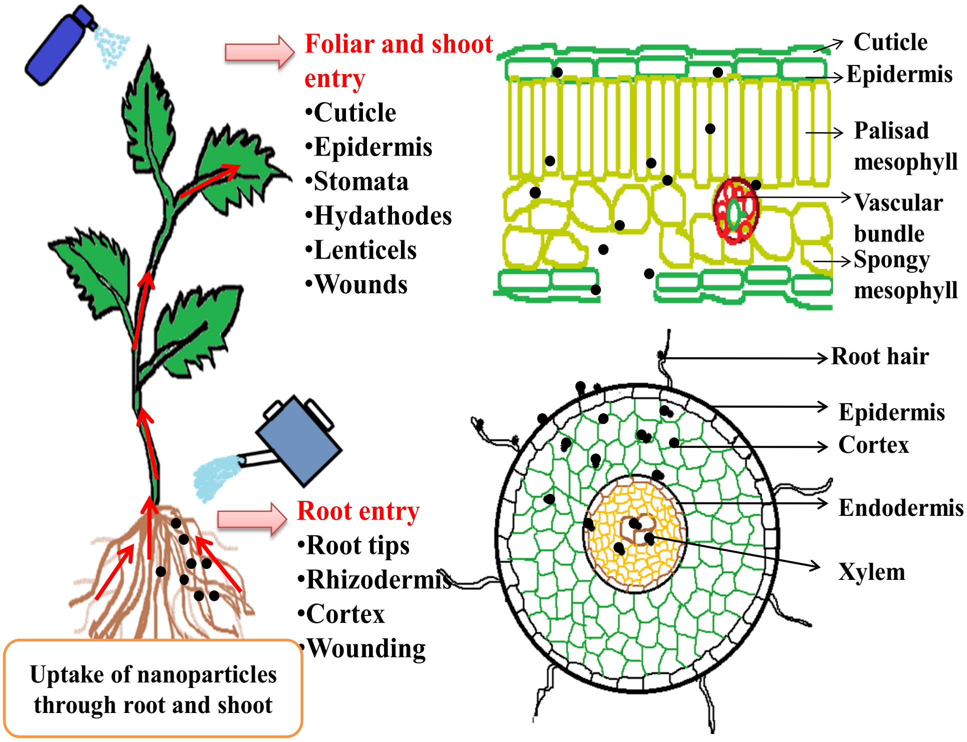

Fig. 2 Mechanism of uptake and accumulation of NPs in plants through shoot and root system

2012). Casparian strip inhibits the apoplastic pathway which acts as a barrier, and further translocation takes place via endodermal cells following symplastic way (Larue et al. 2012; Lv et al. 2015). Another possible symplastic way of translocation, distribution towards non-photosynthesis apparatus is done by sieve tube elements in the phloem (Wang et al. 2012; Raliya et al. 2016). In the lipophilic or the hydrophilic pathway NPs must cross cuticle present on leaves act as a barrier in foliar treatment (Schonherr 2002). Diffusion through cuticular wax takes place in lipophilic pathway, whereas polar aqueous pores present facilitates the hydrophilic movements of the particles in the cuticles or stomata (Eichert and Goldbach 2008; Eichert et al. 2008). Pore diameter of cell wall ranging from 5 to 20 nm exhibits the sieving properties. Estimated diameter of pores of cuticles is about 2 nm (Eichert and Goldbach 2008) hence, the most expected way for NPs and their aggregates entrance is stomatal pathway with a size barrier limit above 10 nm through which NPs could simply translocate and reach the plasma membrane (Eichert et al. 2008). Plasma membrane forms a cavity like structure around the NPs and such type of internalization is called as endocytosis. They may also cross the membrane using embedded transport carrier proteins or through ion channels. When NPs are introduced into leaves by foliar treatment, they enter leaves through stomatal openings or through trichome bases and then get translocated to various tissues (Nair et al. 2010). However, NPs accumulation on the photosynthetic apparatus results in foliar heating due to which stomatal obstruction changes take place in gas exchange that affects different cellular and physiological functions of plants.

The way NMs move inside plants play a crucial role, as it can give indications about parts of the plant they can reach, and parts where they might end and accumulate. NPs could likely move from root to shoot and leaves, and not downwards, hence they are transported mainly through the xylem and not to the phloem (Basiuk et al. 2011).Therefore, in order to get a good distribution in the plant they should be applied in the roots. The fruits and grains act as a sink where NPs translocated through phloem could accumulate and is to be considered when trying to avoid further animal and human digestion of NMs. However, NPs could move laterally between xylem and phloem and translocation is not necessarily constrained to a specific cell type. Translocation and accumulation of NPs in plant tissues are greatly influenced by their characteristics and nature. The crop species belonging to different families when exposed to either magnetic carbon-coated TiO_2 or Au NPs exhibited a diverse absorption and accumulation patterns inside the plants (Cifuentes et al. 2010; Larue et al. 2012). Sunflower and wheat show low rate of accumulation of carbon-coated iron NPs than roots of pea plant (Cifuentes et al. 2010). During reproductive stage, drought and heat stress cause reduction in yield due to rise in temperature in wheat plants (Sarlach et al. 2013). Sunflower and tomato also show low rate of translocation to the aerial parts as compared to pea and wheat (Zhu et al. 2012). Cell walls of plants have negative ions which facilitate the accumulation of NPs in the tissues carrying positive charge causing hindrance in its movement throughout the plant. Transformation and degradation of some NPs in plants could take place after sometimes as they simply get stored in various tissues that will not be used after harvesting (Wang et al. 2012; Zhang et al. 2012; Lv et al. 2015). Various researches and studies on the uptake and formation of NPs within the plants focus deeper on the further exploration use of plants as a source for NPs synthesis. Uptake of NPs is enhanced by the foliar release which mitigates the harmful effects of chemical fertilizers (Raliya et al. 2016). Gold NPs are used because of inert properties. They are used in nanotechnology through DNA adsorption to be delivered to cells (Ghosh et al. 2010; Thakor et al. 2011). Copper oxide nanoparticles at different concentrations were exposed to soybean plants to assess various parameters like germination percentage, root and shoot length, vigor index and total chlorophyll (Gautam et al. 2016).

Nanofertilizers

Recent agricultural practices influenced the green revolution and had enormously increased the food supply globally. They are posing unintentional, negative effect on natural and biological systems of organism highlighting the need for strategies for more sustainable agriculture (Tillman et al. 2002). Excessive use of chemical fertilizers and pesticides has increased toxicity in ground and surface water reservoirs which has adverse effect on human health and water purification methods. It has also exposed the aquatic life and fishery. Recent agricultural practice applied today humiliates soil quality and is responsible for eutrophication of water bodies. Increased fertilization, irrigation, energy to maintain productivity on degraded soils has increased and needs heavy cost. Water irrigation is done in excess amount as compared to the rate of irrigation through rain water which resulted in decrease in groundwater level (Rodell et al. 2009). The long-standing irrigation practices increased the rate of reduction in the minerals, varied soil pH and salt imbalance hence decreased the quality of best agricultural fields (Presley et al. 2004; Osterholm and Astrom 2004; Mukhopadhyay 2005).

There are few reports on affirmative role of NPs on plants, previous studies explored the effect of Ag, Au, ZnO_2, TiO_2, SiO_2 NPs, carbon nanotubes, etc. on the improvement of plant growth and development and their mechanisms. Nowadays nanotechnology has become a magical tool for the improvement of plant growth, development and crop yields. Nanofertilizers balance the release of fertilizer nitrogen and phosphorus with the absorption of the plant, thereby preventing the nutrient losses and avoiding unwanted nutrients interaction with microorganisms, water and air (Blois and Lay-Ekuakille 2018). Nanotechnology in plant used in the fertilizer industry, bio-production of vitality, purification of water, control of plant diseases and disinfection (Moraru et al. 2003; Nair et al. 2010). The various products viz. nano-herbicide, nano-pesticide, and nanosensor are shaping the nature of agriculture production and their protection in the field of agriculture. Absorption of nutrients by the plants from soil can be maximized using nanofertilizer. Nanofertilizer encapsulated nanosilica can form a binary film on the cell wall of fungi or bacteria after absorption of nutrients and prevent infections, hence improve plant growth under high temperature and humidity and to improve plant resistance to disease (Wang et al. 2002). Silicon-based fertilizers used to increase plant resistance as silicon dioxide nanoparticles can improve seedling growth and root development (Hutasoit et al. 2013). To increase food production, TiO_2 or titanium that is non-toxic can be used as additives in fertilizers. The additives in fertilizers can increase water retention (Blois and Lay-Ekuakille 2018). There is no regulatory body at any national or international level, no definitions, licensing or declaration requirements related to the use of nanotechnologies. The knowledge about the effect of NPs on the ecosystem and human health is to be broadened for the use of NPs but precaution is necessary for the used nanotechnology in agriculture to increase food production (Jahanban and Davaria 2013). The loss of biodiversity, water and wind erosion may be controlled with the help of organic farming. Use of fossil fuel and greenhouse warming potential can be reduced when we adopt relative organic farming in comparison to conventional agriculture systems.

Antimicrobial activity of nanoparticles and role in disease suppression

NMs are the new drugs that can effectively control infection of resistant bacteria (Li et al. 2008). Recent studies reported that NMs can be used as strong agents for safe and efficacious chemotherapeutics (Rai and Bai 2011; Li et al. 2010). NPs have different modes of antimicrobial activity when compared to antibiotics. Recently eight broad fields of nanotechnology are reported to be pertinent for the development of research in field of biomedicine: synthesis and use of nanostructures (Becon et al. 2000). Antimicrobial activity of the NPs against microorganisms is specially related to its large surface area, unusual crystal morphologies with edges and corners and reactive sites (Allaker 2010). The smallest NPs possess the strongest antimicrobial activity but $Mg\ (OH)_2$ NPs had the weakest antibacterial effect. Thus, the size effect is not the dominant factor hence undoubtedly the size of NPs is of great significance (Table 2). This is the major reason for consideration of NPs as a real improvement in antimicrobial strategy. The NPs of silver, copper, gold, aluminum, titanium, iron, zinc, are the most tested metallic NPs (Fig. 3). Recently, ceria, bismuth, and others were included in the list (Andreini et al. 2008; Mukherjee et al. 2011; Sweet et al. 2012; Ivask et al. 2012).

Table 2 Antimicrobial activity of different nanoparticles

S. no.	Nanomaterials	Nanomaterials composition	Bacteria	Bacterial properties	Mechanism of toxicity action	Applications	References
1.	Silver (Ag)	Ag-coated SPIONs	*S. aureus*	Biofilm formation, normal flora of skin, production a matrix of exopolymeric substances	Bacterial toxicity by penetration within the biofilm and increase of the bacterial toxicity in the presence of external magnetic field	Potable water filters, clothing, medical devices, coatingsfor washing, refrigerators, food containers	Oesterling et al. (2008), Li et al. (2008), Hussain et al. (2005) Sinha et al. (2011)
		Ag–Au-coated SPIONs			ROS generation, electrostatic interaction and physical damage of bacteria		
		Ag Caron Complex-L-tyrosine polyphosphate NP (SCC23-LTP)	Vancomycin resistant Enterococcus	Medically important pathogens, vancomycin-resistant			
		Ag	(Halophilic) bacterium sp. EMB4	Non-pathogen Gram-positive halophilic, has a thicker PG layer with higher percentage of neutral phosphatidylglycerol	Bulk Ag and nanosized Ag did not affect the growth and cell wall		
2.	ZnO		(Halophilic) bacterium sp. EMB4	Non-pathogen Gram-positive halophilic, has a thicker PG layer with higher percentage of neutral phosphatidylglycerol	Electrostatic interaction, morphological changes in the presence of bulk and nano ZnO, increase in membrane permeability and ZnO accumulation in the cytoplasm	Antibacterial creams, lotions and ointment, deodorant, self-cleaning glass and ceramics	Li et al. (2008) and Chang et al. (2012) Sinha et al. (2011)
3.	Cu or CuO		*B. subtilis*	Non pathogen, protective endospore forming	Release of Ag^{1+} and Cu^{2+}, electrostatic interaction, cell wall damage, rupture of the plasma membrane, and disrupt biochemical process	Medical devices	Chang et al. (2012), Xia et al. (2008)
4.	CeO_2					Modify the material to exert antioxidant effects through altered electronic states	Xia et al. (2008)

Table 2 (continued)

S. no.	Nanomaterials	Nanomaterials composition	Bacteria	Bacterial properties	Mechanism of toxicity action	Applications	References
5.	Al_2O_3		*B. subtilis*	Non pathogen, protective endospore forming	Bacterial attachment (electrostatic interaction) damage to the bacterial cell wall and increase the permeability	Coating surfaces.	Dey et al. (2008) and Oesterling et al. (2008) Simon-Deckers et al. (2009)
6.	Cu	Cu-doped TiO2	*M. smegmatis*	Non pathogen	Release of Cu2+, decreased enzymatic activity NADPH production, no cell damage, no internalization of	Air purifiers, water treatment systems for organic contaminant degradation, biofouling resistant surfaces	Hebbalalu et al. (2013) and Li et al. (2008)
		CuO	*Sh. oneidensis* MR-1	Reduce poisonous heavy metals, resistant to heavy metals such as iron and uranium	Cu-doped TiO_2 do not affect *Sh. oneidensis* MR-1 growth		Wu et al. (2010)
			P. putida KT2442	Non-pathogen, biofilm formation, beneficial soil bacterium	Cell membrane damage and bactericidal effect		Gajjar et al. (2009)
7.	TiO_2		*B. subtilis*	Non pathogen, protective endospore forming	TiO_2 has no toxicity in dark condition	Mainly used as pigment and photocatalyst. Find in food cosmetics, medicine, building materials and electric devices	Simon-Deckers et al. (2009)

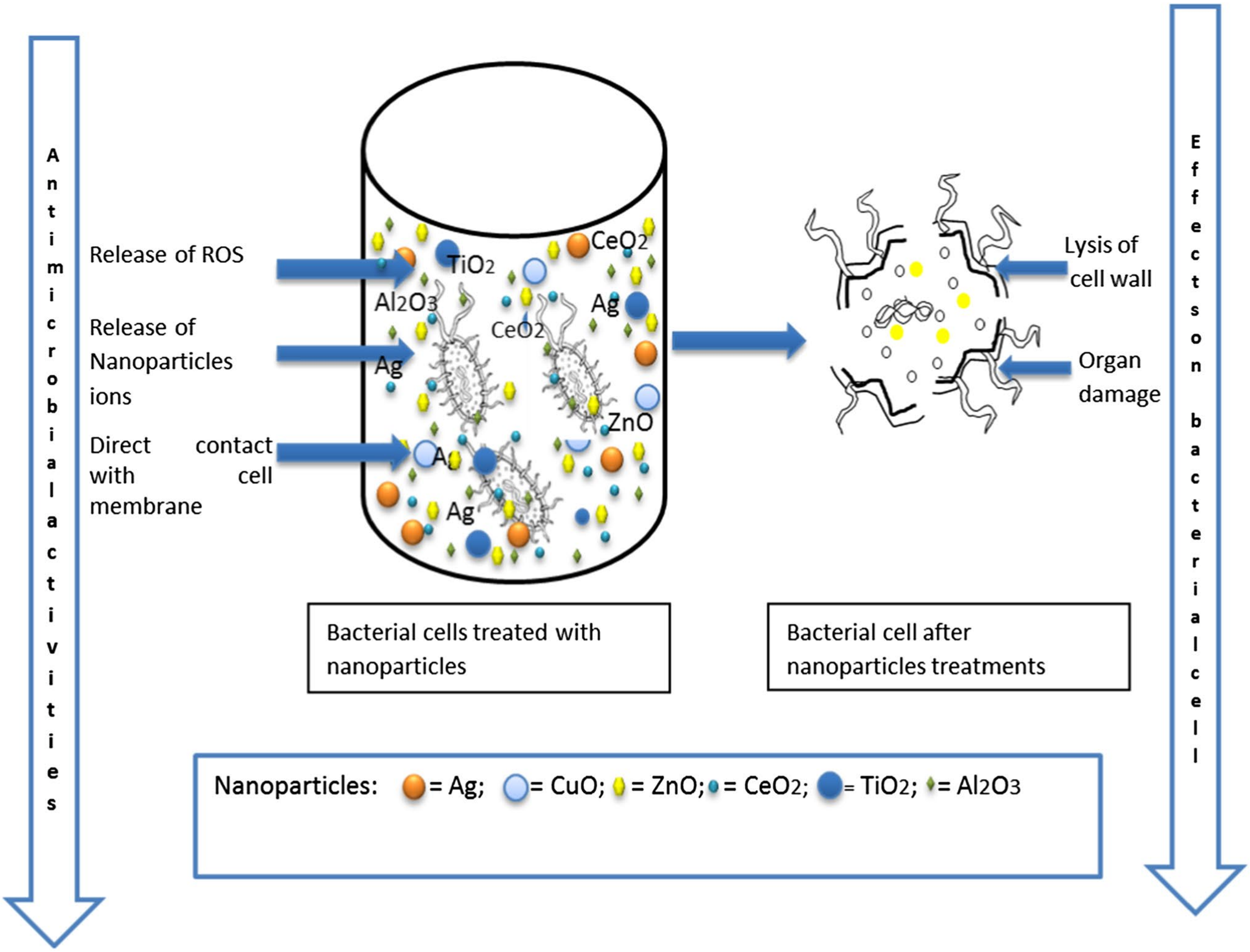

Fig. 3 Graphical representation of antimicrobial activities of different NPs

The utilization of these metals into substrate like polymethylmethacrylate (PMMA) or dental restorative materials are used as another strategy (Stoimenov et al. 2002; Boldyryeva et al. 2005; Wang et al. 2012). Most frequent used microbes for experiments are *Staphylococcus aureus, Pseudomonas aeruginosa, Escherichia coli, Klebsiella pneumonia,* and *Bacillus subtilis* (Allaker 2010; Azam et al. 2012; Leid et al. 2012; Brown et al. 2012; Wang et al. 2012). The inorganic compounds such as metal oxide and metals are reported as more effective and stable antibacterial agents as compared to the organic compounds (Sawai 2003). ZnO has drawn special position as the antibacterial agent among the metal oxides. ZnO in enterocytes are efficient in inhibition of adhered and internalization enterotoxigenic *E. coli* (ETEC) (Roselli et al. 2003). Antibacterial properties are also reported in ZnO NPs which inhibits the attachment and viability of microbes on biomedical surfaces. Prokaryotic systems are prone to ZnO toxicity, even the killing of cancer cells by this is well known (Reddy et al. 2007; Hanley et al. 2008). ZnO has potential to interact with lipids of the membrane and disrupts the structure of the membrane, resulting in loss of membrane integrity, malfunction, and ultimately leading to bacterial death (Zhang et al. 2007; Krishnamoorthy et al. 2012). Toxic oxygen radicals are synthesized when ZnO penetrates the bacterial cell causes damage of genetic material, cell membranes or cell proteins, which hinder bacterial growth and finally lead to decease of bacterial growth (Moody and Hassan 1982; Zhang et al. 2007; Apperlot et al. 2009; Irzh et al. 2010). Mechanism for the mode of Ag^+ action in *Vibrio alginolyticus* involves the direct FAD displacement from the holo-enzyme Na^+-translocating NADH:ubiquinone oxidoreductase (Na^+-NQR) resulting in loss of enzyme activities (Steuber et al. 1997). Silver treatments affect in various ways i.e. interference with the bacterial electron transport chain, blockage replication of DNA and suppression of other cellular proteins along with ribosomal expression (Bragg et al. 1974; Feng et al. 2000; Yamanaka et al. 2005). Ag-based compounds are being widely used in numerous bactericidal applications because of excellent antimicrobial activities and catalysis and surface-enhanced Raman scattering effects (Sastry et al. 2003; Yallappa et al. 2015; Dastmalchi et al. 2007) Ag NP can be synthesized various plant seed extracts such as *Medicago sativa* (Jagtap and Bapat 2013), *Artocarpu sheterophyllus* (Bar et al. 2009), *Jatropha curcas* (Kora and Arunachalam 2013), and *Strychnos potatorum* (Showmya et al. 2012), *Foeniculum vulgare* (Mohammadinejad et al. 2013), *Silybum marianum* (Venkateswarlu et al. 2014), and Ag possessed significant antimicrobial activity against *E. coli* and multidrug-resistant bacteria (Fankam et al. 2017). Some of the active chemical substances showed good antimicrobial properties extracted from the berries and bark of Juniper and oak respectively (Puišo et al. 2013).The silver NPs synthesized via biological methods could enhance these properties. The aim of this study is to enhance the antibacterial activity of TiO_2 by pure plant extracts of *Bauhinia variegata* and *Tinospora cordifolia* by making a composite of plant extract and TiO_2 (Maurya et al. 2012). Protection against oxidative damage was observed with several extracts as indicated by their antioxidant potential.

The synthesis of silver NPs using oak bark and Juniper berry extracts buttressed antimicrobial properties of these NPs against Gram-positive and Gram-negative reference cultures, and food-borne enterotoxin and non-enterotoxic *Bacillus cereus* were investigated. Previous literature suggests that tannic acid does not act as a stabilizer of silver. Therefore, silver NPs formed are mostly through biological methods. Antibacterial effect of silver against *Shigella* and *Bacillus* sp. has been studied (Prema and Raju 2009). Inhibitory effect of silver is associated with the concentration and size. Decrease in the number of feasible cells takes place corresponding to the increase in number of cells in solutions (Suriya et al. 2012).The unique property of NPs mediated targeting has become a significant focus in biological research in recent years. The emerging field of nanotechnology is nano-biotechnology which provides a new method for plant genetic engineering (Gogos et al. 2012). NPs mediated gene delivery gained significant advantages as compared to conventional carriers. NPs are applicable to monocot and dicot plants and plant organs. The gene carriers can effectively overcome transgenic silencing via controlling the copies of DNA combined to NPs.

The NPs can be made functional easily so as to further enhance transformation efficiency. NPs-mediated multi-gene transformation can be achieved without involving traditional building method of complex carrier. In comparison to mammalian systems, the gene delivery to plant cells is much more challenging because of the presence of cell walls and variety of factors including the plant receptor types. Thus, NPs as plant gene carrier can be useful option. The uptake of certain types of NPs exhibits phytotoxicity through vascular blockage, oxidative stress, or DNA structural damage (Tripathi et al. 2017). Trade-off between phytotoxicity and growth enhancement as a function of species, growth conditions, NP properties, and dosage are not well understood and require further studies with a focus on physical and chemical properties of NPs (Cunningham et al. 2018).

Plant diseases caused by various pathogens resulting in infestation causes economic loss by decreased quality and quantity of products (Patel et al. 2014). Various pesticides and fertilizers are inefficient and expensive currently used to increase crop yield. Out of necessity, larger quantities of these formulations must be used by the cultivator to effectively control pathogens to attain acceptable yield. The effectiveness and solubility of these agrochemical products could be improved through the use of NP additives as well as by the NPs themselves as an active ingredient (Naderi and Danesh-Shahraki 2013). This approach would increase nutrient availability and minimize wasteful interactions with soil or air that result in nutrient losses from the agricultural system. NPs alone can possibly be specifically related to plant seeds, foliage, or roots for insurance against pest and pathogens, i.e. insects, microscopic organisms, parasites, and infections. Metal NPs, silver, copper, zinc oxide, and titanium dioxide have been completely looked into for their antibacterial and antifungal properties, and are known for their antiviral properties (Kah and Hofmann 2014; Kim et al. 2018). Silver NPs have been demonstrated as antifungal control of *Alternaria alternata, Sclerotinia sclerotiorum, Macrophomina phaseolina, Rhizoctonia solani, Botrytis cinerea* and *Curvularia lunata* by well diffusion test. A reduction of 50% was observed in fungal colonies that cause disease in *Lolium perenne* when treated with 200 mg/L Ag NPs (Jo et al. 2009). In crop field Ag NPs inhibited the activity of *Colletotrichum* spp. (anthracnose pathogen) (Lamsal et al. 2011).

Several studies reported that combined activity of Ag NPs with the fungicide fluconazole had a greatest antifungal activity, attaining maximum activity against *Candida albicans*, followed by *Trichoderma sp* and *Phoman glomerata*. Zn NPs is another agent to have clear advantages over Ag for controlling fungal pathogen (Dimkpa et al. 2013). Application of ZnO NPs (3–12 m mol) in a mungbean control growth of *Fusarium graminearum* by 26% over bulk oxide and control. *Botrytis cinerea* (63–80%) and *Penicillium expansum* growth considerably prevented in plating assay under ZnO NPs treatment (He et al. 2011; Dimkpa et al. 2013). Green synthesized ZnO and MgO NPs (25 mg/L) suppress pathogenic bacteria (*Pseudomonas aeruginosa*) and fungus at its lowest concentration (100 mg/L). Germination rate of fungal spores of *Alternaria alternata*, *Fusarium oxysporum, Rhizopus stolonifer* and *Mucor plumbeus* were significantly inhibited by the treatment with NPs. (Jayaseelan et al. 2012; Wani and Shah 2012). TiO_2 have shown photo-catalytic and antimicrobial properties and inhibits infection of cucumber caused by *Psilocybe syringae* pv. *lachrymans* and *P. cubensis* by 69 and 91% respectively. Reduced atmospheric nitrogen is converted to ammonia by TiO_2 NPs directly, which consequently promoted plant growth (Yang et al. 2007).

Conclusion and future prospects

The developing new science and innovation, working with the smallest molecule, the nanotechnology raises the new advancements in the field of science, particularly in agriculture. More advanced research is required in the area of energy production, environment management, crop production, disease diagnosis and effective use of the resources and utilization for high yield without altering the natural environment. The green revolution is responsible for the usage of pesticides and chemical fertilizers which cause the infertility of soil and plant develop adaptive mechanism against the pathogen. This article focused mainly on the potential of nanotechnology in field of agriculture. The cutting-edge nanotechnology-based tool and systems can possibly address the different issues of regular farming and can reform this field. This review compiles the significance for different agricultural applications; further research is needed to explore their applications and their future prospects in agriculture. In the near future, nanotechnology can improve nutrient absorption capacity through use of nano based fertilizers, yield and nutritional quality. The scrutiny and management of pests and diseases, resolving the mechanism of host–parasite interactions, preservation and packaging of food, deduction of pollutants from soil and water bodies hence increasing soil quality of the fields. A thorough understanding of nano-science is essential along with the broad knowledge of the agricultural system. Nanotechnology in agriculture might take a few more years to progress from laboratory to land and for this to happen, sustainable funds and plans should be provided for this hopeful field to blossom.

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Compliance with ethical standards

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