Interaction of Nanoparticles with Microbes

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Abstract

Nanotechnology is a rising area emerged after the amalgamation of the different advanced scientific fields of physics, chemistry and biology, and it has resulted in engineering of nanoparticles (1–100 nm) and their applications. These nanoparticles have an extensive utility in electronic circuits, biochemical sensors, pharmaceuticals, agriculture, cosmetic industry, therapeutic medical science, garment, food industry, etc. The market of nanoparticles is growing substantially, and many different types of nanoparticles and nanoparticle-based products have launched in the recent past. At the same time, unprecedented increases in the usage of nanoparticles have raised concerns over their ultimate release in the ecosystem, posing serious health hazards and environmental impact. The consequences may be more pronounced because of higher surface area against the mass ratio for the nanoparticles than bulk chemistry bestowing them unique physicochemical, electrical, optical and biological properties. Interaction of nanoparticles to the microbes is, therefore, vital to interpret the influence of nanoparticles on the aquatic bodies and soil health. In this regard, it is crucial to know the stability of nanoparticles, and better to understand the interaction and resulting toxicity mechanisms of nanoparticles to the microbes. In the present chapter, we have discussed these aspects with critical insights. Further, antimicrobial and antifungal properties of the nanoparticles are elaborated with a focus on the toxicity mechanism. The impact of nanoparticles could be influenced by the concentration, size, shape, etc. The toxicity mechanisms include inactivation of enzymes because of the interaction of thiol group, oxidative stress leading to surge in reactive oxygen species, restricted nutrient availability due to the aggregation of nanoparticles on the microbial surfaces, ultrastructural membranes, subcellular organelles and DNA damage. Understanding the complex nature of the interaction between the consortium of diverse microorganisms with nanoparticles is thoroughly debated in this chapter.

Keywords

Ecosystem • Interaction • Mechanism • Microbes • Nanoparticles • Toxicity

1 Introduction

Nanotechnology mainly deals with the studies involving the fabrication, manipulation and utilization of nanoparticles (NPs; size between 1 and 100 nm) in different areas such as medical science, pharmaceuticals, electronics, textile, biochemical sensors and other allied areas. Several chemical and physical methods are developed for NPs synthesis with some merits and demerits. Chemical methods involve the use of solvents as reducing agent for NPs synthesis, but

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hazardous by-products are major environmental concern while, physical methods have high energy consumption (Huang et al. 2011). However, much attention is paid towards the biological synthesis approach, which has many advantages like eco-friendly nature, reliability, biocompatibility and low production cost (Roy et al. 2013; Emeka et al. 2014). NPs synthesized from plants, microbes and other biological resources are therefore considered as preferred way for synthesis of NPs (Khandel and Shahi 2018).

Nanotechnology is progressing rapidly in various fields due to widespread applications and substantial success. Nanotechnology seems to be a suitable option for the protection of plants from various agents of biotic stress (Rodríguez-Cutiño et al. 2018). Recently, interventions of nanotechnological applications in agriculture sciences have been studied like preparation of nanoscale fertilizers (Xu et al. 2015; Jahagirdar et al. 2020), pesticides (Grillo et al. 2016; Adisa et al. 2019), plant disease diagnosis (Prasad et al. 2017; Chen et al. 2019). It can be stated that agricultural productivity would be increased using better varieties and crop plant protection. The significant antimicrobial potential of NPs against plant pathogens has been widely investigated for advanced agricultural applications (Baker et al. 2017; Verma et al. 2018; Chen et al. 2019; Fu et al. 2020). Further use of nano-agro-particles is considered as a valuable alternative against several fungal pathogens. For instance, Ghasemian et al. (2012) demonstrated the role of CuNPs to ward off filamentous fungi *Penicillium chrysogenum*, *Alternaria alternata*, *Fusarium solani* and *Aspergillus flavus*. Giannousi et al. (2013) studied the efficacy of three types of copper oxide NPs against *Phytophthora infestans*, a pathogen for tomato crop. The authors reported, all the Cu-based NPs, which were tested, showed a significant inhibitory effect against the tested pathogen (Giannousi et al. 2013). At the same time, expected massive usage of NPs in the upcoming future poses serious environmental concerns, and therefore, the interaction of NPs to the microbes is of utmost necessity to formulate a sustainable release policy of the NPs, taking into these concerns.

2 Main Sink of Nanoparticles, Their Production, Applications and Environmental Concerns

The use of NPs raises major concerns for agro-ecosystems, and the soil and water are considered as their main sink. Some NPs be present naturally in the environment; however, the concentrations of these NPs are extremely low with the negligible impacts (Remedios et al. 2012). If the NPs release is inevitable, the objective must be to reduce the NPs release, which might pose a noteworthy threat to agro-ecosystems or human health (Yadav et al. 2014). Main sinks of NPs, i.e. NPs in soil and water, are described in detail in later sections.

2.1 Nanoparticles in Soils

From the starting of the Earth's history, NPs have naturally existed, and it is a known fact that they are not human innovation (Handy et al. 2008). Soils are considered as a source of natural NPs, as it is a multifaceted matrix with different colloidal mineral particles. At the same time, the pollutants immobilization in the soil matrix has a major concern, which greatly outweighs any anthropogenic production as its exposure to natural NPs (Sharma et al. 2015). With reference to the techniques of NPs formation, there are a number of mechanisms that are able to produce NPs in the environment, like geological and biological. Geological way of synthesis involves autogenesis, or the neo-formation found in the soils, physicochemical weathering, as well as the volcanic explosion activity. Typically, the mentioned geological processes are capable of producing inorganic particles, whereas, in biological mechanisms, organic nano-molecules could be produced, even though some organisms are capable of yielding in the cell the minerals granules (Handy et al. 2008).

In the soils, the movement of NPs is explained by Brownian motion and gravity has no role in this. Consequently, solitary NPs could be entering into micropores and unless they get absorbed on mobile colloids, the mobility is greatly improved, while the aggregates of NPs stay remnant in macropores, while the mobility was introverted, when they are adsorbed on particles which are non-mobile.

The NPs and the soil molecules attachment are depending upon collector and the NPs shape as well as onto the diverse properties, which transform NPs surrounding environment. Thus, the stipulations of soils are capable of improving or inhibiting the NPs mobility in soils. The aquifers and the humic acids present in soils could considerably manipulate NPs mobility of different metal oxides (Ben-Moshe 2010), which could persuade NPs composition monitoring and the soil nutrients fate, contaminants and pollutants as well (Ben-Moshe 2010; Mura et al. 2013).

A powerful rising significance in the exploitation of NPs for the various applications for soil is documented in various researches by several researchers (Pan and Xing 2012; Priester et al. 2012; Jośko and Oleszczuk 2013; Suppan 2013; Fernández et al. 2014; Garner and Keller 2014; Jośko et al. 2014; Conway et al. 2015; Schaumann et al. 2015a, b; Watson et al. 2015; Rabbani et al. 2016). Ge et al. (2011) observed the effects of NPs on bacterial communities' present in soil, in which reduced biomass, diversity of microbes and soil enzyme activity is impacted by the action of ZnO NPs. The aggregation and immobilization of NPs in the soil showed phytotoxicity which ultimately leads to decreased root length and biomass (Kim et al. 2011). Authors reported the toxic effect of ZnO NPs on maize and ryegrass, in which the inhibition in the germination was observed. In another experiment, Ma et al. (2010) reported that, when the aluminium oxide and rare element oxide NPs were applied to the plants, such as carrots, cabbage, cucumber, soybeans and maize, the toxic effect was demonstrated, as they act as an inhibitor for elongation of roots.

The field of soil science is related to all materials science, which are commonly found in soils. These matrices can provide the nutrition for organisms along with those microflora and fauna that assist these processes. This is a composite mixture of chemicals as well as organisms, from which some are pre-arranged at the nano-level while the others are unable to do so (Belal and El-Ramady 2016). The scope of the nanotechnology has been extended from the early phase of preliminary innovations of capability to progress and situate atoms (Belal and El-Ramady 2016). Soil is a composite mix of particles homing in size from millimetres (mm) to nanometres scale (nm). By means of some highly sophisticated techniques such as transmission electron microscopy (TEM) and atomic force microscopy (AFM), it may perhaps be promising to recognize these soils makeup. These preceding methods are capable to demonstrate the association of colloid materials in soils like humic acids and phyllosilicates, and the detection of novel material like iron oxides NPs. Thus, nanotechnology is able to offer additional possibility in classifying single cells, proteins, DNA, genes, as well as other biological structures in soils (Dasgupta et al. 2016a).

With reference to soil, nanotechnology is of vital significance, since a number of constituents of the soils have nanoscale features or are nanoparticulate (Mura et al. 2013). At the nanoscale level, interactions are either conquered by stronger polar and electrostatic interactions, weak Van der Waals forces, or covalent bonding. The particulars of interaction forces of nanoparticle-nanoparticle as well as interactions between nanoparticle-fluid are of major significance for illustrating the chemical and physical processes along with time-lapse progression of free NPs (Mura et al. 2013). Also, in soil, different nanomaterials (NMs) can be found such as nanominerals ranging from nanoparticle to nanosize NPs of mineral but larger sized particles are also present (Maurice and Hochella 2008). Sharma et al. (2015) reviewed the natural inorganic NPs formation, their fate as well as its toxicity issue (Sharma et al. 2015). Additionally, variable NPs are also found in soil matrix, bacterial appendages, clay minerals, amorphous substances as well as other nanominerals (Mura et al. 2013).

Manufactured or fabricated or engineered NPs (ENPs) may be present in soils, but these NPs may perhaps leach out in the surroundings deliberately in diverse forms, which include the metal oxides like CeO_2, TiO_2, ZnO NPs; metals with zero valency such as Au, Ag and Fe NPs; as well as metal salts like ceramics and nano-silicates; carbon derived NMs such as carbon nanotubes; nano-polymers, e.g. polystyrene and latex; and semiconductor materials like CdSe, CdTe; or accidentally by-products combustion or corrosion (Belal and El-Ramady 2016). Because of the distribution of NPs in soils, an alteration in their aggregated size, the stability of a suspension, transport as well as bioavailability could be perceived. Hence, the research on the ENPs is indispensable to comprehend their destiny along with associated danger (Philippe and Schaumann 2014; Sharma et al. 2015). The sol of these NPs is able to be exaggerated by conditions of soil such as ionic strength, the amount of dissolved organic matter as well as the biological and chemical reactions (Li et al. 2016). The NPs coated by dissolved organic matter, have their surface properties altered. These properties include pore size, organic contaminants sorption parameter, surface area, aggregation property and the toxicity mechanisms (Li et al. 2016).

According to Wang and Keller (2009), attributable to complexity, no particular property is able to apply as a common interpreter of the deposition as well as transport of ENPs. Therefore, it is significantly essential to illustrate quantitatively the transfer of ENPs in columns of soil (Pan and Xing 2012). Hence, in conclusion, applications for the environment and ENPs risk assessment in the soil significantly not independent on the appreciative of the interaction between the NPs with the various components of soil ENPs possibly will be functional for remediation of soil (Belal and El-Ramady 2016). By reason of the soil system complexity as well as the so primary stage of research of NPs in soils, the appreciative of behaviour of NPs in this system is exceptionally restricted.

2.2 Nanoparticles in Water

Nanoparticles are of different types like natural or engineered or incidental. Natural NPs include lunar dust, volcanic dust, soil particles and these natural NPs are present on the earth since its birth (Belal and El-Ramady 2016). Incidental NPs are formed by human economic activity like coal usage, fumes of iron welding, machinery in industries and vehicle emission (Smita et al. 2012). ENPs are designed and fabricated for their unique physicochemical property for different applications. Different shapes and types of NPs are made like metal-based NMs, carbon-based NMs, nanocomposites and dendrimers (Handy et al. 2008; Yadav et al. 2014). However, ultimately, all of these NPs are discharged into aquatic bodies (Sharma et al. 2015). The term colloid is sort of a generic term usually applied for particles having size between 1 nm and 1 µm. In aquatic bodies, these NPs form colloidal complex after interaction with organic materials like proteins, humic and fulvic acids, and inorganic species notably hydrous manganese, iron oxides. Further, to interpret the future usage of nano-fertilizers, a huge amount of N and P in nanoform is going to be released in the water bodies, which may affect the ecosystem and human health. Consequences of these interactions are completely unknown (Ma et al. 2014; Johnson et al. 2014; Yang et al. 2015). It is estimated that occurrence of NPs in aquatic system is quite low in comparison with the natural NPs (Delay and Frimmel 2012). Therefore, the movement and translocation of NPs within waters are a budding issue. Nano-pollution in aquatic body is a major cause of concern, and there are few reports available which have specifically dealt to remediate the nano-contamination in the water bodies. In one study published recently, it is reported that iron oxide nanoparticles can be accumulated inside the green algae *Coelastrella terrestris*. In this way, remediation of water containing excess NPs is possible. The accumulation factor reported in this study was found to be about 2.9, which means, about 2.9 times iron oxide NP is accumulated inside the algal cell than ambient environment (Saxena et al. 2020). It has been reported that NPs affect the life of aquatic ecosystem by inhibiting growth and nitrogen fixing capacity, increasing the level of ROS and MDA, decreasing the pigment content in photosynthesis organisms, negatively influencing antioxidant enzymes. Further, physical damage to subcellular organs like membrane damage, cell wall damage and intra-thylakoidal damage are also reported (Saxena and Harish 2018).

3 Toxicity Mechanisms of Nanoparticles

3.1 Proposed Mode of Antibacterial Action of Metal Nanoparticles

It is widely known that metal NPs such as AgNPs and CuNPs have significant antibacterial activity (Table 1), but the mechanism of their action is yet not known. There is some literature available on metal NPs mode of action, but until now, the mode of action is very unclear. Das et al. (2010) reported that CuNPs are capable of entering the cell because of their smaller size and subsequently takes place their protein or enzyme inactivation, producing hydrogen peroxide that results in the death of bacterial cells. In another report, it has been stated that the protein inactivation occurs because of the CuNPs and –SH group of proteins interaction with each other (Schrand et al. 2010). Likewise, metal NPs can disturb the DNA helical structure and degrade it. The cell membrane integrity is decided by the electrochemical potential, since according to Deryabin et al. (2013), CuNPs are responsible to reduce the cell membranes electrochemical potential, that eventually affected the cell membrane integrity. It was also understood that metal NPs liberate their respective ions, and these heavy metal ions are found to have unfavourably affected the cells of bacteria (Cioffi et al. 2005). Metal NPs and metal ions accumulation on surface of cell cause the formation of pits in the membrane, which mainly leading to the outflow of components from bacterial cells ultimately causing the cells death. The next significant reason for the bacterial cell death has been proposed is the oxidative stress development due to the action of NPs (Deryabin et al. 2013). Considering all these possibilities, Shende et al. (2015) have proposed a hypothetical mechanism of action of CuNPs in bacteria; in a similar way, metal NPs could impact the bacterial cells during the bactericidal action (Fig. 1).

3.2 Proposed Mechanism of Antifungal Action of Metal Nanoparticles

The mechanistic action of metal NPs as a fungicidal agent is still unclear; however, there are many ways by which metal NPs could serve as an antifungal agent depending on their mode of action. The probable antifungal action of metal NPs could be correlated with the commercial fungicides available in the market (Fig. 2).

Although the commercially available antifungal agents are target specific and are mainly limited to the plasma membrane and cell wall, which are the targets (Ngo et al. 2016; Scorzoni et al. 2017), the metal NPs which were capped with proteins in case of biogenic synthesize could get attached to the fungal cell wall and initiate a sustainable release of the metal ions inside the cell, which can act on the fungi by different ways.

A lipid responsible for membrane fluidity is ergosterol and essential for cell viability (Tatsumi et al. 2013; Song et al. 2016). A few antifungal agents generally target ergosterol, either by restraining its biosynthesis or binding to it, resulting in the formation of the pores in the membrane, this may be similar to the metal NPs or metal ions. The composition of fungal cell wall primarily constituted chitin, mannans, glycoproteins and glucans, essential for adhesion and pathogenesis of fungi and also provides a protective barrier, limiting the admittance of molecules to the plasma membrane (van der Weerden et al. 2013).

The two most important modes of action of antifungal agents targeting the cell wall are associated with the inhibition of chitin and β-glucan synthesis. Thus, metal NPs may perhaps target chitin synthase, which is responsible for the chitin chain elongation. Another mechanism is inhibition of nucleic acids, protein and microtubule synthesis. There are some antifungals, which may cause more than one effect on the fungal cells under adverse conditions, like in the

Table 1 Recent studies of using application of different nanoparticles for antimicrobial properties

Nanoparticle(s) studied	Microbes investigated	Approach	References
ZnO NPs	*Staphylococcus aureus, E. coli*	ZnONPs coated textile fabrics are tested for antibacterial property	Singh et al. (2020)
Silver nanoparticles (AgNPs)	*E. coli, Enterococcus faecalis* and *Salmonella typhi*	Aqueous leaf extract of *Cestrum nocturnum* is used to synthesize the NPs. Bactericidal activity was checked using growth inhibition assay	Keshari et al. (2020)
Silver nanoparticles (AgNPs)	*S. aureus, S. dysenteriae* and *S. typhi*	*Penicillium oxalicum* mediated synthesis of NPs. Antibacterial activity was evaluated using well diffusion method and spectrophotometric method	Feroze et al. (2020)
Silver and copper oxide NPs-decorated graphene oxide	*S. aureus, E. coli*	Incorporation of silver and copper oxide NPs through graphene oxide nanosheets is found suitable for clinical treatment	Menazea and Ahmed (2020)
Iron oxide nanoparticles (FeONPs)	Six human pathogenic strains including *E. coli* and *S. aureus*	Aqueous extract of leaf of *Psidium guajava* (PG) is used for synthesis of NPs	Madubuonu et al. (2020)
Silver nanoparticles (AgNPs)	*S. aureus* and *Pseudomonas aeruginosa*	Marine macroalgae *Padina* sp. is used for synthesis of NPs and	Bhuyar et al. (2020)
Chitosan encapsulated silver nanoparticles	*Bacillus cereus, S. aureus, Listeria monocytogenes, E. coli* and *Salmonella enterica*	Leaf extract of *Gynura procumbens* and chitosan is used for NPs synthesis	Sathiyaseelan et al. (2020)
MgO nanoparticles	*Bacillus cereus*	Fabrication of cubic structure of MgO nanoparticles showing antibacterial activity	El-Shaer et al. (2020)
Silver nanoparticles/activated carbon co-doped titania nanoparticles	*E. coli* and *S. aureus*	Zones of inhibition comparable to streptomycin were observed with zone of inhibition of 7 mm	Parvathi et al. (2020)
Fe_3O_4 nanoparticles	*S. aureus, Corynebacterium, P. aeruginosa* and *Klebsiella pneumoniae*	Synthesis of NPs using medicinal plants *Malva sylvestris*	Mousavi et al. (2020)
Silver nanoparticles (AgNPs)	Pathogens in Fish such as *Vibrio harveyi*, *Vibrio parahaemolyticus*, *Vibrio alginolyticus* and *Vibrio anguillarum*	NPs synthesis by red algae *Portieria hornemannii* and antibacterial activity against pathogens in fish	Fatima et al. (2020)
Iron oxide, Tobramycin, iron nitride conjugated nanoparticles	*P. aeruginosa*	Synthesis of iron oxide NPs capped with alginate. NPs found to have the potential to cross the bacterial biofilm barrier	Armijo et al. (2020)
Silver nanoparticles embedded guar gum/gelatin nanocomposite	*S. aureus, E. coli* and *P. aeruginosa*	Synthesis of NPs is done via in situ method by maltose sugar reduction	Khan et al. (2020)
V_2O_5 nanoparticles	*S. aureus, E. coli, P. aeruginosa* and *P. vulgaris*	Ultrasound assisted synthesis of NPs. NPs was found to useful in dye degradation and biomedical applications	Karthik et al. (2020)
$ZnTiO_3$ and Ag-doped $ZnTiO_3$ perovskite nanoparticles	*S. aureus* and *Vibrio* sp.	NPs were synthesized via the sol–gel method and found to have antibacterial activity	Abirami et al. (2020)

presence of UV light and oxidants, the mitochondria produce free radicals in large quantity, causing the damage to DNA, proteins and lipids, which leads to cell death due to reactive oxygen species (ROS) generation (Ferreita et al. 2013; Mesa-Arango et al. 2014), a similar mode of action by metal ions against filamentous fungi is reported by Vincent et al. (2018). There may be inhibition of heat shock protein 90 (Hsp 90) which has been associated with the fungal pathogenicity, phase transition, regulation of other heat shock proteins and antifungal resistance (Jacob et al. 2015; Scorzoni et al. 2017), due to the leaching of metal ions from metal NPs. On the other hand, Yang et al. (2011) reviewed the different action mechanisms of fungicides as well as their probable impacts on non-target microbes. During their study,

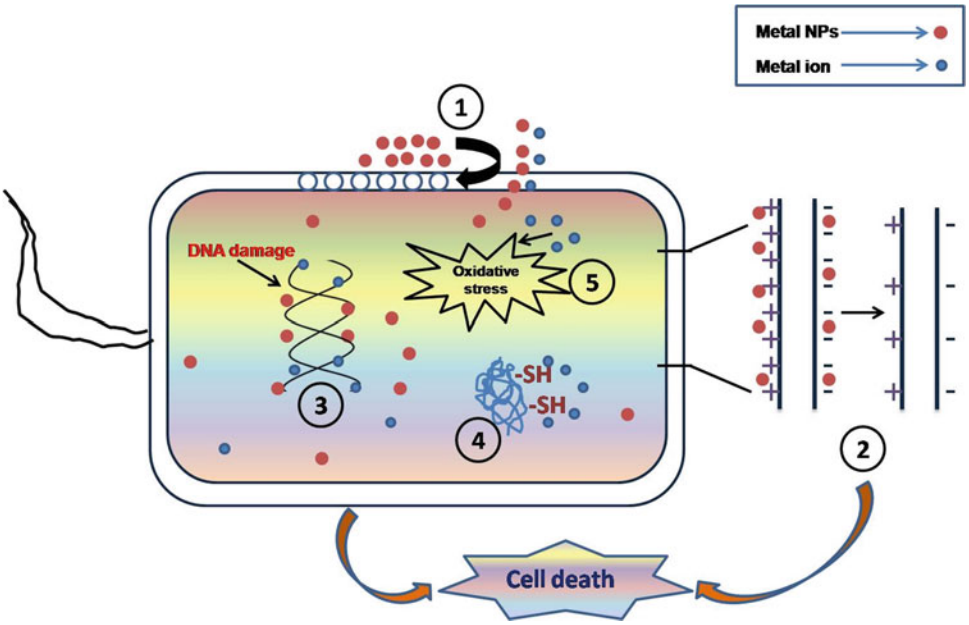

Fig. 1 Graphical representation of hypothetical mechanism of action of metal nanoparticles (NPs). (1) Metal NPs accumulation on the surface of cell, formation of pits in membrane; (2) Interaction of metal NPs with cell membrane, affects membrane integrity; (3) DNA damage; (4) Interaction of metal ions with sulfhydryl (-SH) groups of proteins, leads to protein inactivation; (5) Metal NPs and metal ions entry, oxidative stress development, leads to cell death

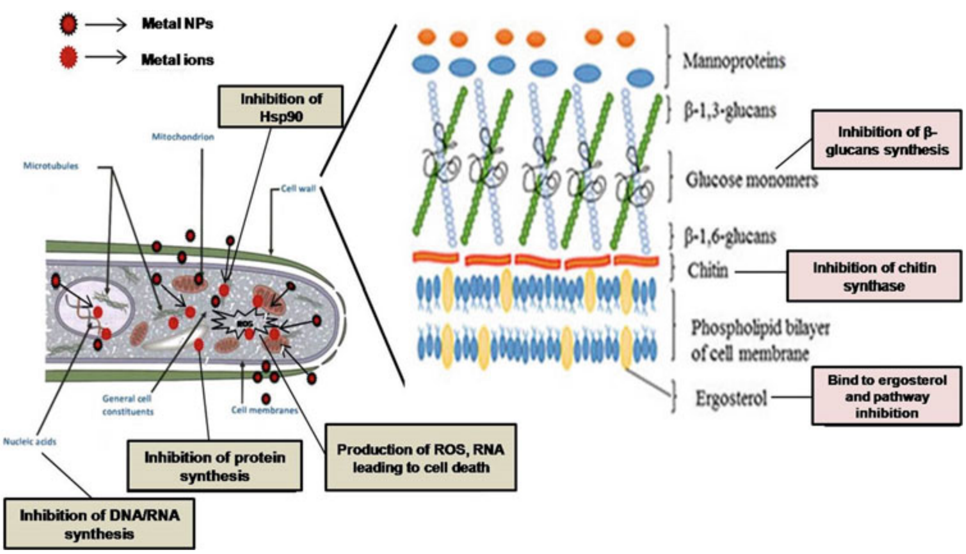

Fig. 2 Schematic representation of hypothetical mechanism of action of metal nanoparticles on fungi

they concluded that the fungicides affected target fungi in the variable ways such as affecting the synthesis of lipids, sterols and other components of membrane, amino acids and protein synthesis, respiration, signal transduction, cell division, and mitosis, multisite fungicidal activity, etc. (Yang et al. 2011). The metal NPs mechanism of action for fungicidal activity is still unclear, but from the above hypothetical mechanism it has been revealed that the metal NPs leaches the metal ions, which ultimately affected the growth and metabolism leading to the growth inhibition of fungus.

4 Effects of Nanoparticles on Soil Microbial Community

More than the last decades, the NPs discipline have progressed as an area of interdisciplinary studies that have fascinated the scientific community as it is very much interesting and challenging (Belal and El-Ramady 2016). Undoubtedly the field of NMs science is pertinent to the structure and composition examination of soil.

Nevertheless, nano-biology related to biology of soil as well as tools intended for distinguishing the substances at their nano-quantities, which are appropriate for soil processes and also significant as are different facets of NPs applications in the environmental sciences (Belal and El-Ramady 2016). It has been documented that the ENPs could possibly be fabricated with single elements such as carbon or silver or with combinations of elements or molecules. These NPs could be categorized depending on their size, their chemical composition or morphological properties. It may also describe these NPs keen on subsequent clusters involving—metal ENPs (elemental Ag, Au, Fe, Se, etc.), metal and non-metal oxides (Al_2O_3, CeO_2, CuO, FeO_2, SiO_2, TiO_2, ZnO), complex compounds such as Co–Zn–Fe oxide, fullerenes and polymer-coated quantum dots for instance cadmium selenide (CdSe) as well as organic polymers similar to polystyrene (Dinesh et al. 2012).

In terms of global biogeochemical cycles, microbes are to be considered as drivers as they are deeply involved in C, N, S and P cycling. Because they are exceptionally sensitive to changes in environmental conditions, the structure, as well as abundance of the microbial community, is likely to change towards the foreign NMs (Ge et al. 2011; Kumar et al. 2011). Since microbes facilitate the regulation and maintenance of overall health of the ecosystem and its function, microbial community alteration will enormously affect the whole ecosystem. Consequently, an improved understanding of how microbes act in response to NPs and/or NMs is able to facilitate our handling of environmental as well as health concerns brought with reference to the manufacturing as well as the application of these NMs (He et al. 2014). Alternatively, it is well documented that, a number of NPs have previously reported for their antimicrobial potential that is why they shown the direct effect on microbes. To date, no standard and established techniques for measuring the NPs toxicity on various soil microbes and microbial diversity.

4.1 Interaction of Soil Contaminants with Soil Microbes

The contaminants effect upon the microbe's community present inside the soil might be evaluated through various methods like viability count, carbon utilization patterns, molecular-based methods, along with fatty acid methyl ester analysis. It has been reported in the literature that, an interaction among the NPs as well as the bacterial cells leads to cytotoxic effect, which has assumed to include the mechanism having two steps (Kumari et al. 2014). The first step involves the oxidative damage by the NPs to the cell membrane, which results in loss of membrane integrity devoid of noteworthy decrease in viability of the cells. The step second is involving the outflow of the internal cellular components, which leads to the consequence of reduced viability and internalization of the NPs, thus causing cell organelles damage, e.g. the nucleus (Kumari et al. 2014).

The majority of microbes have produced efficient mechanisms at their molecular level as well as explicit pathways for the biochemical reactions for detoxification, efflux, along with to accrue the metal ions greatly previous to it was discovered by plants. In addition, microbes are again competent for the volatilization of a number of metal ions to dispose of their acute toxicity. Even though microorganisms have developed resistance as well as a prevention mechanism, further belowground level studies are essential in views to advantageous microorganisms present in soil like phosphate solubilizers, N_2-fixing, arbuscular mycorrhizal fungi (AMF) to set up the mechanisms of uptake as well as consequences for the soil and microbes (Thul and Sarangi 2015).

Many researchers have published the reviews on the interactions between NPs and microbes, which correlate the physicochemical properties of ENPs (metal and metal oxides) to their biological response (Dinesh et al. 2012; Ge et al. 2012; Pawlett et al. 2013; Holden et al. 2013, 2014; Tilston et al. 2013; Dimkpa 2014; Jośko et al. 2014; Burke et al. 2015; García-Gómez et al. 2015; Judy et al. 2015; Simonin and Richaume 2015; Sillen et al. 2015; Xu et al. 2015; Van Aken 2015; Aliofkhazraei 2016; Sirbu et al. 2016). Moreover, from the above discussion, in conclusion it could be mentioned that the specific toxicity towards the specific species can be attributed to shape and size of NPs. However, the coatings of the materials on the surface, which could be altered importantly by conditions of environment, that can ameliorate or accelerate toxicity to the microbes (Suresh et al. 2013; Thul et al. 2013).

Recent literature was reviewed, and it can be concluded that there are quite a lot of impacts of NPs on soil microorganisms; those involved in the soil enzyme activities, nitrogen cycle, iron metabolism processes, antibiotic and phytohormone production (Dimkpa 2014). These effects are considered to be either positive or negative and the results being dependent on the particular type of NPs, the charge on the surface, size, species of microbes or plant to be examined, dose tested, as well as test medium whether agar, soil, liquid or other used solid media. These communally published results have figured out that NT poses a substantial threat to soil microorganisms and proven that the agricultural processes are driven by microbes. However, it could be demonstrated that there is a prospective for soil and plant microbes to alleviate the NPs bioreactivity (Dimkpa 2014). While roots of all of the terrestrial plants are colonized by microorganisms, a number of studies of NPs interactions with microbes and plants are performed independently. A very few studies in real plant/microbes' systems established the NPs effects onto the implementation of arbuscular mycorrhizal fungi (AMF), nitrogen fixation, and on the fabrication of microbial siderophores in the plant rhizosphere. Hence, it might be recommended that, for a better understanding of the agro-ecological NPs implications, would necessitate additional exhaustive interactive studies in collective plant /microbes/nanoparticles system (Dimkpa 2014).

Regarding the microbes in soil, the comprehensible and metal NPs specific effect was observed on microflora in the soil. For instance, the TiO_2 NPs showed an impact on symbiosis of *Rhizobium*-legume in garden peas and Rhizobium (*R. leguminosarum* bv. *vivae* 3841). It was also found that TiO_2 NPs put forth morphological modifications in the cells of bacteria. Moreover, Fan et al. (2014) also reported that whenever there the interaction between these two organisms takes place, they disturbed the formation of root nodules and the succeeding postponement in the nitrogen fixation commencement. The immediate application of NPs keen on treated biosolids or soils having transportable NPs might interact with the microbes in the soil. These soil microbes are also competent towards the adsorption and accumulation in one or the other form of NMs that in turn begins the NMs mobilization and is capable to alter communities encompassing the populations of plants, animals and finally humans through the food chains (Holden et al. 2013; Ranjan et al. 2014; Thul and Sarangi 2015).

Conversely, plants, in general, get mineral nutrients from the soils with the help of the soil bacteria and fungi. A study discovered that the AgNPs, which are a popular microbicidal agent, negatively impact the plants growth and eradicates the microbes in the soil that maintain them. Not just microorganisms, but the several soil enzymes activity, e.g. soil peroxidase, catalase, as well as protease, was established to considerably diminished by TiO_2 NPs (Du et al. 2011). Furthermore, inorganic TiO_2, SiO_2 as well as ZnO had found to put forth a lethal effect on bacteria. In the presence of light, the toxicity of these elements further significantly increased (Adams et al. 2006). There are the variety of reports that have been spotted light upon the interactions between NPs-microbe's for associating the ENPs (metal and metal oxides) physicochemical properties and their responses in the biological systems. Additionally, in conclusion, the species-specific toxicity of NPs could be attributed to its shape and size. Research on the ecologically significant species of bacteria, e.g. *Bacillus subtilis*, *Escherichia coli*, *Pseudomonas putida* and other, has noticeably indicated microorganisms be able to take up NPs (Thul and Sarangi 2015; Załęska-Radziwiłł and Doskocz 2015).

In the terrestrial and aquatic ecosystems, bacteria are essential elements as they act as decomposers of organic matter as well as key bases for numerous webs of foods (Thul et al. 2013). Because the dependency of plants on the fungi and bacteria present in soil and air to get their nutrients, the antimicrobial and cellular toxicity effects of NPs for instance, Ag, TiO_2 and Au NPs and nano-emulsions as well might show the effect on the environment (Thul et al. 2013; Dasgupta 2016b, c; Jain et al. 2016; Maddineni et al. 2015; Ranjan et al. 2016). Hajipour et al. (2012) have examined the NPs for their antibacterial properties in a very illustrative manner. It has also been demonstrated that soil microbes, that are plentiful and flexible catalysts, are capable to adsorb and disband the aggregates of ENPs (Horst et al. 2010). It has been reported that the addition of nanoscale zerovalent iron leads to perturbation in soil bacterial community composition, as well as condensed the chloroaromatic mineralizing activity of microbes (Tilston et al. 2013).

4.2 Interaction of Engineered Nanoparticles with Soil Microbiota

The ENPs were also established to considerably modify the bacterial communities in a dose-dependent approach, and NPs are known to influence the dynamics of the microbial community (Ge et al. 2011). In order to this, Priester et al. (2012) reported the uptake of ENPs of CeO_2 into the soybean roots and root nodules, which reduced the nitrogen fixation potentials along with the damaged growth of crop plants (Priester et al. 2012). Further studies about the beneficial soil microbes, such as nitrogen fixers, AM fungi, phosphate solubilizers, have demonstrated the uptake mechanisms of the NPs as well as the significance to accumulate in the soil and microorganisms (Ge et al. 2011; Thul et al. 2013). The ENPs mobility in soils is totally dependent on their size, though that is the agglomerates size, not the primary size that is concerned with the transportability of them. There are several aspects, those organize the transfer of these ENPs in the soils; however, charge, size and the rate of agglomeration in the transport medium are prognostic of the mobility of these ENPs in the soils. The metal NPs survival as well as speciation in the soil solution and the understanding on interaction among soil solution or other ions and their active sites is significant for getting a better knowledge about the interactions between metal NPs and soil microbes. Nevertheless, the solution chemistry of metal NPs is somewhat restricted, and thermodynamic data like reaction constants and solubility of NPs are not available. In addition to this, the additional data is requisite to distinguish the effect of ENPs on the soil microbial community in a variety of soils having different physicochemical features and soils from the diverse ecosystem (Dinesh et al. 2012).

In conclusion, a number of novel ENPs from both environmental and industrial applications and resulting from various activities of human as by-products, act as xenobiotics and find their own way to enter into the soil. Thus, the fortification of microbial biomass and diversity present in the soil is most important challenging issue for sustainable resource utilization, since advanced higher levels of microbial diversity as well as biomass indicate higher turnover of nutrient. Very little studies have been performed and reported the toxicity of ENPs to soil microorganisms due to the complex nature of soil through which the organisms are rendered to these ENPs inside diverse phases of soil. For understanding the complete effects of ENPs on different soil organisms under different environmental conditions, more studies are required that detect the different parameters of soil, which influence the bioavailability in addition to the toxicity of ENPs.

5 Future Perspectives and Challenges

Nanoparticles from the environment and the ENPs interact with the microbes in the soil and agro-ecosystems. The NPs form of chemicals, metal (ions), smoke, etc., in air, water and soil cause the environmental pollution when occurring over a quantity of forbearance limit for living animals that is a problem from an age-old. Inappropriate as well as excessive utilization of pesticides and fertilizers has augmented nutrients as well as toxins in surface waters and groundwater, incurring health and water purification expenses, and lessening fish farming as well as recreational opportunities (Mukhopadhyay 2014). Moreover, the soil quality is degraded due to different practices in agriculture, which leads to the eutrophication in the aquatic habitats and may perhaps require the disbursement of augmented fertilization, irrigation and energy to maintain productivity on tarnished soils (Mukhopadhyay 2014; Belal and El-Ramady 2016). These preceding practices could also destroy beneficial soil microbes, insects and other wildlife.

It is well understood that the nanotechnology's application in the field of agriculture might be triumphant, whenever the naturally occurring processes are stimulated within huge articulation of science or sophistication intended for booming accomplishment. For example, the objective may be to build the soil extremely competent to advance the nutrient usage in efficient manner for productivity boosting and superior security of environment. Consequently, the nutrient management in the nanotechnology frame should be based on some imperative parameters, which includes (1) in the soil system, ions of nutrient should be available as an obtainable forms for the plant, and (2) within plant and soil systems, transport of nutrient relies on exchange of ions, desorption and adsorption and the precipitation or solubility reactions, as well as (3) NMs should ease the process that would guarantee the nutrients accessibility for the plants in the rate and manner as per their requirement (Mukhopadhyay 2014; Belal and El-Ramady 2016).

Nanotechnology provides a number of modern approaches or strategies that could employed for water management, fertilizers, pesticides, sensors and restrictions in the application of chemically prepared pesticides, and the NMs potential in the agriculture management in sustainable way (Prasad et al. 2014). There are a number of publications, which have determined the agriculture sustainability beneath the nanotechnology's roof and effect of NPs on the terrestrial environments (Mura et al. 2013; Mukhopadhyay 2014; Prasad et al. 2014; Sekhon 2014; Takeuchi et al. 2014; Ditta et al. 2015; Patil et al. 2016; Salamanca-Buentello and Daar 2016; Rajput et al. 2018a, b, 2020a, b). From these reports, it has been clearly noticed that nanotechnology will participate a progressively more significant role in the agriculture field. Moreover, the last decade researches demonstrated that the potential nanotechnology's applications in transforming the field of agriculture with the revolution in the fields such as regulators for plant growth, biosensors, smart delivery systems for drugs, plants and animals genetic improvement, food additives, pesticides and fertilizers transformed into nano-pesticides and nano-fertilizers (Hong et al. 2013). Hong et al (2013) suggested that for thwarting the probable unfavourable effects from the nanotechnology application in the agriculture sector, research on the issues like in the ecosystem, the transport and the fate of the NMs, uptake as well as its accumulation in animals and plants, with the NMs toxicity evaluation need to be performed. Risk assessment research should also be executed prior to nano-products application for agriculture, and the effects must be examined.

The prospect of the nanotechnology application in agriculture is extraordinary. The implementation of some novel technologies is an imperative concern in the sustainable development frame, and it is well-documented (Mukhopadhyay 2014). It has been proposed that the nanotechnology application in agriculture may take a timeline period of few decades to shift from the laboratory scale to field, particularly because of the drawbacks experienced to evade with biotechnology. Nanotechnology's application is important, as it provided the global population, who carry on the deficiency in access to safe water, education, health care, trustworthy sources of energy, as well as other basic development needs of human (Belal and El-Ramady 2016).

In conclusion, in the light of sustainability the potential nanotechnology applications needs to be re-assessed, considering the ethical (Salamanca-Buentello and Daar 2016), societal (Roure 2016), economic (Shapira and Youtie 2015) as well as environmental factors (Bottero 2016) and interdependencies. It means, the products based on nanotechnology needs sustainability, must not only while the phase of its manufacturing but also must be considered over the complete life cycle of the product. Thus, as presented in review by Rickerby (2013), an entire life cycle of product must be considered for an assessment of technology as well as it is also essential at preliminary stages of development for accomplishing the accurate balance between the cost-effectiveness as well as the environmental impacts. Besides this, the analysis of life cycle of product is expected to provide important insights regarding this issue. The standard methods, which are existing for the risk assessments may perhaps be insufficient for recognizing meticulous vulnerability related to NMs and tools for nano-specific risk assessments, have to be produced. Suitable recycling and strategies used for recovery in the sustainability frame also have to limit the NMs dispersal in the surrounding environments. Procedures should also be accepted for minimizing the environmental and health risks because of the NMs release at every stage of life cycle of products from its production phase, while its application, and towards the final dumping or recycling. If the trustworthy data as well as ethics do not appear, nevertheless, the most awful circumstances have to be supposed for nanotechnology risk management in the sustainable agriculture and development frame.

6 Concluding Remark

Currently, nanotechnology is expanding in each and every field; there is not a single area that is untouched with the nanotechnology and its pioneering modernizations in scientific manner involving the field of agriculture. The interaction of NPs with the soil microbial community played a vital role in agriculture; hence, the nanotechnology application in the agriculture field has been touched numerous fields involving plant protection, plant nano-nutrition, food industry, nano-fertilizers and nano-pesticides, plant productivity, etc. With reference to the ENPs effect on agroecosystem, the providence and performance of the ENPs and the probable toxic inferences to the agricultural crops and the plants, as well as naturally present microbes in the rhizosphere of soil and nano-waste generation in the agricultural ecosystem, etc., are of the major burning concerns. In addition, ENPs negative effects produced via free radicals lead to the DNA damage and lipid peroxidation affect the microflora of soil including bacteria and fungi, soil enzymatic activities, plant productivity and the entire environment. Therefore, there is an urgent need to forecast the ENPs effects on the environment to make their application a predictable opportunity in the direction of sustainable agriculture.

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