



Nanotechnology in Agroecosystem: Implications on Plant Productivity and its Soil Environment

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Abstract

Compared to conventional or other contaminants, nanoparticles pose some new environmental challenges for scientists and environmentalists worldwide. Nanotechnology will leave no field untouched including agriculture by its ground breaking scientific innovations. So far, the use of nanotechnology in agriculture has been mostly theoretical, but it has begun to have a significant effect in the main areas of the food industry. Nanoparticles finding great potential as delivery systems to specific targets in living organisms and is being used in medical sciences. In plants, the same principles can be applied for a broad range of uses, particularly to tackle phytopathological infections, nutrition supplement and as growth adjuvant. Nanoparticles can be tagged to agrochemicals or other substances as delivery agent to plant system and tissues for controlled release of chemicals. Doing so, the negative effects of nanomaterials must not be overlooked, such as toxicity generated by free radicals leading to lipid peroxidation and DNA damage. Under this scenario, there is a need to predict the environmental effect of these nanoparticles in the foreseeable future. Key focus of the discussion will particularly relate the nanoparticles as adjuvant for agricultural crops, which may be toxic to plants and microbes naturally present in soil and generation of nanowaste in agroecosystem.

Highlights

- I) Nanotechnology in agriculture will significantly affect the agriculture ecosystem.
- II) It finds broad range of uses for plants in defence, nutrients and growth.
- III) NPs seems to be useful for plants, however, phytotoxicity cannot be neglected.
- IV) Literatures clearly indicating nanoecotoxicity and needs proper attention.

Keywords

Phytotoxicity; Agro-ecosystem; Nanoparticle; Soil microbe; Nanowaste

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Introduction

In recent years, a lot of attention is being paid to nanotechnology with its research and applications for its beneficial effects. Nanoparticles (NPs) with sizes typically below 100 nm, have been applied in several fields of bioscience and biomedicine with an increasing number of commercial applications [1]. There are many types of man-made nanoparticles produced by nanomanufacturing technologies which are being used in nanomedicine and classified elsewhere in detail [2]. In contrary to the benefits, so far no information is elaborated on systematic investigation that raising concerns about impacts on environmental organisms and processes [3], especially in the context of plants vis-a-vis agricultural and forest crops and its environment. Though, plants and microbes have evolved themselves in presence of natural nanomaterials (NMs), however, in recent time, the probability of plant exposure to NMs has increased to a greater extent with the ongoing increasing production and use of engineered nanomaterials (ENMs) for variety of products [4]. Nanotechnology being perceived as advanced technology and will leave no field untouched by its ground breaking scientific innovations. The agricultural and allied industry is no exception [5].

So far, the use of nanotechnology in agriculture has been mostly theoretical, but it has begun and will continue to have a significant effect in the main areas of the agriculture and food industry. Use of nanotechnology in these industries is mainly towards development of new functional materials, product development, and design of methods and instrumentation for food safety and bio-security [6].

This report highlights effects of some nanomaterials such as silver [7-10], nanoceria [11], copper [12], TiO₂ [13-15], ZnO [11,14-16], etc., on plants and microbes. Further, it expresses concern with emphasis on ecology for assessing nanoecotoxicology in relation to fate, nanowastes and toxicity to agricultural/ forest crops and its soil microbial environment.

Nanoparticles as Delivery Systems in Plant Sciences and Technology

Potential applications in plant systems

Nanoparticles are finding great potential for applications as 'smart' delivery systems to specific targets in living organisms and are being used in medical sciences. They were already postulated in 1906 by the Nobel Prize winner P. Ehrlich as 'magic bullets' [17]. Nanoparticles tagged to agrochemicals or other substances could reduce the damage to non-target plant tissues and minimize release of non-specific chemicals into the environment [18,19].

Delivery of proteins or codelivery of proteins and DNA to plant cells has great biological significance towards enhancing genetic transformation and gene targeting in plants [20]. Similar to medical sciences, same principles could be applied in plants for a broad range of uses; in particular to tackle phytopathological infections [21] and sustained release of nutrients and growth promoters [22]. Advancements in techniques in nanotechnology make it possible to deliver agrochemicals into targeted plants, tissues, and organs by using nanoparticles as carriers. The great opportunity of NPs in agriculture have been reviewed elsewhere in detail [23].

Existing nanoparticle based methods to deliver molecules in plants

Gene transfer by bombardment of DNA-absorbed on gold particles has been successfully used to generate transgenic plants in a species-independent manner [24]. Carbon nanotubes and zinc oxide nanoparticles were shown to penetrate tomato (*Lycopersicon esculentum*) plant root or seed tissues indicating that new nutrient delivery systems can be developed through exploiting the nanoscale porous domains on plant surfaces [25]. Torney et al. reported the efficient delivery of DNA and chemicals through silica nanoparticles internalized in plant cells, without the requirement of specialized equipment [26]. To achieve this efficiently, investigations are needed on the ways of penetration and transport inside the whole plant, tissues and cells. Furthermore, Martin-Ortigosa et al. reported protein and DNA co-delivery to plant cells via the biolistic method using mesoporous silica nanoparticles [27]. The experiment demonstrated the *in vitro* uptake and release profiles of fluorescently labeled bovine serum albumin (BSA) and enhanced green fluorescent protein (eGFP) by Au-MSN.

Recently, field experiments with *Brassica juncea* plant shows that foliar sprays of gold-nanoparticles positively affect the growth profile; including plant height, stem diameter, number of branches, number of pods and seed yield etc. Presence of Gold-nanoparticles in the leaf tissues was confirmed through atomic absorption spectroscopy. Application of nanoparticles also improved the redox status of the treated plants [28].

These methods for DNA and protein delivery can efficiently be used in future for enhancement of functionality of plants towards production of biomass and improvement of nutritional qualities.

Concerns on Nanoecotoxicology

Phytotoxicity of nanoparticles resulting to reduced growth and biomass

Most people know little or nothing about nanotechnologies, many feel that nanotechnology's future benefits will outweigh its risks if any [29]. Though, nanoparticles seem to be a beneficial delivery system in plants, however, a decline in growth of *Cucurbita pepo*, on treatment with silver and copper nanoparticles has also been reported [30]. Miao et al. reported that silver nanoparticles have shown to exert a negative effect on the growth of phytoplankton [31]. It is also important to mention that the bioaccumulation, bio-magnification and biotransformation of engineered nanoparticles in food crops are still not well understood [32]. Very few nanoparticles and plant species have been studied with respect to the accumulation and subsequent availability of nanoparticles in food crops [16].

In one of the studies, that reports phytotoxicity of five types of nanoparticles was evaluated. Only Zn and ZnO particles were observed to have significant inhibition on seed germination and root growth of the six plant species. Inhibition was predominant in the seed incubation process rather than the seed soaking process [33]. In similar study, wherein, the toxicity effect of ZnO and TiO₂ nanoparticles was evaluated in rice seed germination. No significant reduction in the percent seed germination from both nanoparticles was observed, however nano-ZnO shows detrimental effects on rice roots at early seedling stage. Nano-ZnO is found responsible to stunt roots length and reduce number of roots. Whereas nano-TiO₂ found

to have no effect on root length [34]. Effect of alumina nanoparticles loaded with and without phenanthrene was investigated by means of root elongation in hydroponic experiments. The non-loaded particles showed decreased inhibition of root elongations in this study [35]. Similarly, in hydroponic experiment, Ma et al. demonstrated that plant seedlings of two common plant species: cattail (*Typha latifolia*) and hybrid poplars (*Populus deltoids* × *Populus nigra*) at different concentrations of nZVI (0–1000 mg/L) found to exhibit strong toxic effect on *Typha* at higher concentrations (>200 mg/L) but enhanced plant growth at lower concentrations [36]. It has been also noted that nZVI significantly reduced the transpiration and growth of hybrid poplars at higher concentrations. Microscopic studies indicated that large amount of nZVI coated on plant root surface as irregular aggregates and some nZVI penetrated into several layers of epidermal cells of poplar root cells.

Among the studied nanoparticles, most of these studies are focused on the potential toxicity of nanoparticles to plants and both positive and negative or inconsequential effects have been reported [37]. Among the positive effect reports on plants, nano-TiO₂ was observed to promote the growth of Spinach through an increase in photosynthetic rate and nitrogen metabolism [38,39]. In one of the studies both positive and negative effects were observed by Lopez-Moreno et al. [11]. In this study, seeds of alfalfa (*Medicago sativa*), corn (*Zea mays*), cucumber (*Cucumis sativus*), and tomato (*Lycopersicon esculentum*) treated with nanoceria at 0–4000 mg L⁻¹. Uptake of nanoceria were significantly correlated with reduced corn germination (about 30% at 2000 mg L⁻¹, p<0.05), and at 2000 mg L⁻¹ germination of tomato and cucumber was reduced by 30% and 20%, respectively (p<0.05). On the other hand, root growth was observed to be significantly promoted (p<0.05) in cucumber and corn except in alfalfa and tomato where it was reduced (p<0.05). Almost at all concentrations nanoceria promoted shoot elongation in these four plant species.

Pal et al. suggested that the arsenic nanoparticle (As₀) has the potential for many applications such as medicine and sensors [40]. Small amounts of disodium methanearsonate (DSMA, or cacodylic acid) were historically applied to cotton and other agricultural crop fields as herbicides, but its use has been prohibited under the US EPA (2009) organic arsenical product cancellation [41]. The cancellation was made against EPA's conclusion, that these pesticides which convert over time to a more toxic form in soil, inorganic arsenic, and potentially contaminate drinking water through soil runoff. One of the plants, brake-fern (*Pteris vittata*) is not an agricultural crop, but is reported as arsenic hyper accumulator [42]. Even though the application of moderate doses of arsenate to this plant increase the plant phosphate uptake, but at high doses it decreases phosphate uptake because of its phytotoxicity [43].

Genotoxic as well as cytotoxic effect in plant systems due to NPs are also reported in literature. Kumari et al. on treating the *Allium cepa* cells with various concentrations of Ag NPs, observed different forms of chromosomal aberrations such as stickiness, chromosomal breaks, gaps, disturbed metaphase, and cell wall disintegration at different doses [8]. In line with this study, an initial increase of DNA damage by TiO₂ in *A. cepa* at low concentration followed by a gradual decrease as concentration increased up to 10 mM. The decrease was correlated with the precipitation of NPs at high concentrations. The genotoxic potential of TiO₂ was confirmed by comet assays

technique. The effects of genotoxicity and cytotoxicity observed were significantly correlated with generation of superoxide radicals resulting in lipid peroxidation in these plant cells [13]. Similarly, the generation of oxidative stress and DNA damage was also reported in bacterial system [44]. There are studies showing that NPs in algae and tobacco are transmitted to the next trophic level [45,46].

In line to above studies, ZnO and TiO₂ NPs reduced the wheat's biomass, and thus were reported to be harmful to the plant. The TiO₂ NPs, considered having low solubility, remained in the soil for long periods and stuck to the plants' cell walls, which might create potential environmental risks for deeper soil layers. Additionally, a few individual small-sized TiO₂ NPs (around 20nm) were able to penetrate the cell wall. The ZnO NPs, known to have higher solubility than TiO₂, dissolved in the soil and increased the wheat's uptake of toxic zinc [47]. Copper oxide is used in agriculture as a fungicide to protect coffee, cocoa, tea, banana, citrus, and other plants from major fungal leaf and fruit diseases such as blight, downy mildew, and rust [48]. Copper is toxic to life at levels that vary depending on the organism. Humans are mandated to not exceed 1–2 mg/L copper in their drinking water [49,50], while some freshwater animals and plants experience acute toxic effects at concentrations as low as 10 µg/L [51]. Because the human food chain begins with plants, it is critical to understand how plants tolerate heavy metals including copper, which is frequently concentrated in soils as a result of pesticide application, sewage sludge deposition, mining, smelting, and industrial activities.

The review of reported literature suggests that the knowledge on phytotoxicity of NPs is at the early stage (Table 1). So far, there are no conclusive studies on the nanotoxicity have been elaborated elsewhere; however, with the limited information it has begun to address the effects of NPs on the plants.

Impact on soil microbial environment

The effect of NPs on bacteria is very important since bacteria are essential elements of aquatic and terrestrial ecosystems as decomposers of organic matter and primary base for many food webs. These microbes are also efficient to adsorb and accumulate one or other form of nanomaterials, which in turn initiates the mobilization of nanomaterials through food chains and can alter communities comprising multiple populations (e.g., plant, fish, bacteria) within food webs [52]. Plants generally depend on soil bacteria and fungi to help mine nutrients from the air and soil. Therefore, the antimicrobial effects of nanoparticles such as silver nanoparticles could have impacts at the ecosystem level. A new study finds that the popular microbicidal silver nanomaterial negatively impacts the growth of plants as well as kills the soil microbes that sustain them [53]. ZnO and TiO₂ NPs significantly reduced activity for several soil enzymes: soil protease, catalase, and peroxidase [47].

Not only this, but also significantly affects the soil microbial communities. Soil microbes, which are abundant and versatile catalysts, can sorb and disperse engineered nanomaterial agglomerates [54]. Study based on mixed and enriched nitrifying bacteria which were cultivated in a continuously stirred tank reactor were analyzed by electron micrographs and found that Ag NPs attached to the microbial cells, causing detrimental effects probably due to cell wall pitting [7]. Treatment of Aroclor-1242 contaminated and uncontaminated soil over 28 days with nZVI shows limited effect on Aroclor congener

profiles, but, cause changes to soil physico-chemical conditions such as pH, Eh. It was observed that nZVI addition leads to perturbation to soil bacterial community composition, and reduced the activity of chloroaromatic mineralizing microorganisms [55].

Nanomaterials can indirectly cause membrane damage by generating reactive oxygen species (ROS), which can oxidize double bonds on fatty acid tails of membrane phospholipids in a process known as lipid peroxidation. This process may further leads to membrane permeability and fluidity, making cells more susceptible to osmotic stress and failure to nutrient uptake [44]. Peroxidized fatty acids can trigger reactions that generate other free radicals, leading to more cell membrane and DNA damage. Moreover, inorganic TiO₂, SiO₂ and ZnO found to exert toxic effect on bacteria, the toxicity of these elements further significantly enhanced in presence of light [56]. A range of studies has been reviewed focused on nanoparticle–microbial interactions to correlate the physico-chemical properties of engineered metal and metal oxide nanoparticles to their biological response. Further, it has been concluded that the species specific toxicity can be attributed to nanoparticle, its size and shape. However, the surface coating of the material, which can be altered significantly by environmental conditions, can ameliorate or promote microbial toxicity [57].

The engineered nanoparticles was also found to significantly alter the bacterial communities in a dose-dependent manner, with some taxa increasing as a proportion of the community, but more taxa decreasing, indicating that effects mostly reduced diversity [15]. In line to this, the uptake of manufactured nano-CeO₂ nanomaterials into roots and root nodules found to eliminate N₂ fixation potentials and impaired soybean growth [58].

Likewise, most of the toxicity studies on ecologically relevant bacterial species such as *E. coli*, *Bacillus subtilis*, *Pseudomonas putida* and other have been conducted for growth inhibition and cell viability clearly indicating that NPs can be taken up by microbes (Table 2), but more studies are needed in regards to beneficial soil microbes such as N₂ fixing, phosphate solubilizers, AM fungi to establish the uptake mechanisms and consequences of their accumulation in soil and microbes.

Particle size dependable toxicity

The application of MNs are in some ways exploiting the altered properties of nanosized particles with respect to enhanced surface area and high surface reactivity compared to otherwise identical larger particles. In one of the reported study by Yin et al. found inhibition of seedling growth while exposed to 40 mg L⁻¹ GA-coated silver nanoparticles, also seedlings failed to develop root hairs, had highly vacuolated and collapsed cortical cells, broken epidermis and root cap [16]. In contrast, seedlings exposed to identical concentrations of silver nitrate or supernatants of ultracentrifuged AgNP solutions showed no such abnormalities. AgNP toxicity was influenced by total NP surface area with smaller AgNPs (6 nm) more strongly affecting growth than did similar concentrations of larger (25 nm) NPs for a given mass.

Likewise, the potential environmental toxicity of zero-valent iron nanoparticles (nZVI) and three types of nanosilver differing in average particle size from 1 to 20 nm was evaluated using seed germination tests with ryegrass, barley, and flax by El-Temsah and Joner [9].

In this study, complete inhibition of germination was observed at higher concentration (1000–2000 mg L⁻¹) for nZVI, whereas, at low concentrations of nZVI no detrimental effects was observed on plants. Silver nanoparticles found to inhibit seed germination at lower concentrations, but showed no clear size-dependant effects on to tested plants.

Similarly, copper nanoparticles shows 15 to 65 fold increase in toxicity when nano-sized copper particles are used [59]. *In vitro* studies provided evidence to show that copper nanoparticles have the ability to cause mitochondrial [60] and DNA damage [61]. The toxicity of copper nanoparticle has not been thoroughly studies so far, but the findings to date suggest that both ionic copper and nanoparticulate copper are responsible for the toxicity that is produced. Similarly, a direct acute toxicity of nano-CuO acting on soil bacteria have been recently reported, while the macro particulate (bulk) form of CuO was not toxic [62]. Existing studies indicate that copper toxicity depends on particle size. As particle size decreases, toxicity increases which was also pointed out by Murashov [63] in the study reported by Yang and Watts [35], who proposed that surface characteristics of the alumina played an important role in the phytotoxicity of alumina nanoparticles while performing root elongation studies in hydroponic system. Competence of the NPs to cross cell barriers and their interactions with intracellular structures is reported due to their small size and high surface reactivity that contribute to potential cellular and genetic toxicity by the induction of oxidative stress [45,64].

Although the mechanisms of nanoparticle toxicity are not well understood, the existing studies related to cellular and genetic toxicity indicate that negative effects and the toxicity strongly depends on size of nanoparticles (Table 1). Further, detailed study of NPs on individual basis with special emphasis on particle size and its specific response to individual plant-species needs to be evaluated.

Fate of nanoparticles after use and generation of nanowaste

Quantitative data related to concentrations of nanoparticles in natural waters have not been reported so far, but a recent report using a simplified box model and their known uses [65] suggested environmental concentrations of approximately 1 to 100 µg/L, as compared to typical dissolved and colloidal organic matter in freshwaters may be found at 1 to 10 mg/L concentrations [66].

Soils and water are likely to be increasingly at receiving end of nanoparticles due to growing consumer products that uses nanoparticles, indeed, it has been reported that NPs have been detected in waste streams [67,68]. This has necessitated an investigation into the fate and bioavailability of nanoparticles in soils. Retention of nanoparticles in soils was studied by Cornelis et al. [69], wherein the dominant properties that determine the retention of AgNP in natural soil was correlated to negatively charged AgNP which was found to be adsorbed preferentially at positively charged surface sites of clay-sized minerals. The high organic carbon content in the agricultural soil likely contributed to an organic surface coating and resulted in

Table 1: Nanophytotoxicity on some food and agricultural crops.

Crops	Toxicity	Nanoparticals	Particle size (nm)	Reference
Onion	Cell wall breaks, deformed chromosomes, indistinct disturbed metaphase and mitosis	Ag	< 100	Kumari et al. [8]
Flax, ryegrass, barley	Reduced germination and shoot length	Ag	0.6 – 2	El-Temsah and Joner [9]
Flax, barley	Reduced germination and shoot length	Ag	5	El-Temsah and Joner [9]
Ryegrass, barley	Reduced germination and shoot length	Ag	20	El-Temsah and Joner [9]
Corn, lettuce	Decline in root length	Al		Lin and Xing [33]
Ryegrass	Reduced germination and decreased root length	Al		Lin and Xing [33]
Corn	Reduced root length	Al ₂ O ₃		Lin and Xing [33]
Carrots, cabbage, cucumber, maize	Decline in root growth	Al ₂ O ₃	13	Yang and Watts [35]
Alfalfa, cucumber, maize, soybean, tomato	Reduced germination, biomass, shoot and root growth	CeO ₂	7	Lopez-Moreno et al. [11]
Mungbean	Reduced seedling and shoot growth	Cu		Lee et al. [12]
Wheat	Decline in root and seedling growth	Cu		Lee et al. [12]
Onion	DNA damage, lipid peroxidation	TiO ₂	10	Ghosh et al. [13]
Ryegrass, radish, rape, lettuce, cucumber, corn	Decline in root growth	Zn		Lin and Xing [33]
Lettuce, radish, rape, ryegrass, corn, cucumber	Reduced germination and root growth	ZnO		Lin and Xing [33]
Ryegrass	Seedlings failed to develop root hairs, reduced biomass, had highly vacuolated and collapsed cortical cells, broken epidermis and root cap	ZnO	9-37	Yin et al. [16]
Soybean	Decline in root growth	ZnO	8	Lopez-Moreno et al. [11]
Typha latifolia, hybrid poplars (Populous deltoids × Populous nigra)	Strong toxic effect, reduced the transpiration and growth, penetrated into several layers of epidermal cells	nZVI		Ma et al. [36]

Table 2: Nanotoxicity on diverse microbes.

Microbes	Toxicity	Nanomaterial	Reference
<i>E. coli</i>	Cell wall pitting	Ag	Choi et al. [7]
<i>E. coli</i>	Inhibition of bacterial growth, bactericidal action	Ag	Pal et al. [73]
<i>E. coli</i> , <i>P. aeruginosa</i> , <i>Staphylococcus aureus</i> and <i>Salmonella typhimurium</i>	Antibacterial activity	Ag	Sahu et al. [10]
<i>E. coli</i> , <i>S. aureus</i>	Low toxicity to bacteria	Au	Goodman et al. 2004; Zharov et al. 2006
Nitrogen fixing root nodules	Decrease of N ₂ fixation potentials	CeO ₂	Priester et al. [58]
<i>B. subtilis</i> , <i>S. aureus</i>	Antibacterial activity	MgO	Huang et al. [6]
<i>E. coli</i>	Solar disinfection through photocatalytic activity and reactive oxygen species (ROS)	TiO ₂	Rincon and Pulgarin, 2004
<i>Micrococcus luteus</i> , <i>B. subtilis</i> , and <i>Aspergillus niger</i>	Photocatalytic oxidation	TiO ₂	Wolfrum et al. 2002
<i>B. subtilis</i> , <i>E. coli</i>	Mild toxicity due to ROS production	TiO ₂ , SiO ₂ , ZnO	Adams et al. [56]; Sapkota et al. [74]; Li et al. [75]
Soil bacterial community	Reduced microbial biomass and diversity	TiO ₂ , ZnO	Ge et al. [14]
Rhizobiales, Bradyrhizobiaceae, Bradyrhizobium, Methylobacteriaceae	Decline in bacterial communities and reduced diversity	TiO ₂ , ZnO	Ge et al. [15]
<i>Pseudomonas putida</i>	Inhibition of bacterial growth	ZnO	Li et al. [75]

NP mobility through the soil and will come in contacts with the soil microbes as shown in Figure 1.

The surface properties of the nanoparticles are known to be one of the most important factors that govern their stability and mobility as colloidal suspensions, or their adsorption or aggregation and deposition. Zhao et al. observed that ZnO NPs coexisting with Zn dissolved species were continuously released to the soil solution to replenish the Zn ions or ZnO NPs scavenged by roots as compared to soil treated with alginate which promotes the bioaccumulation of Zn in corn plant tissues [70]. In another study, the fate of Cu and ZnO NPs was monitored over 162 days. Both NP types travelled through the soil matrix at differential rates, Cu NPs reported to be retained in the soil matrix at a higher rate compared to ZnO NPs. Leaching of Cu and Zn ions from the parent NPs was also observed as a function of time [71]. Physico-chemical characteristics of nanoparticles (e.g., shape, size and surface charge) and soil (e.g., pH, ionic strength, organic matter, and clay content) will affect physical

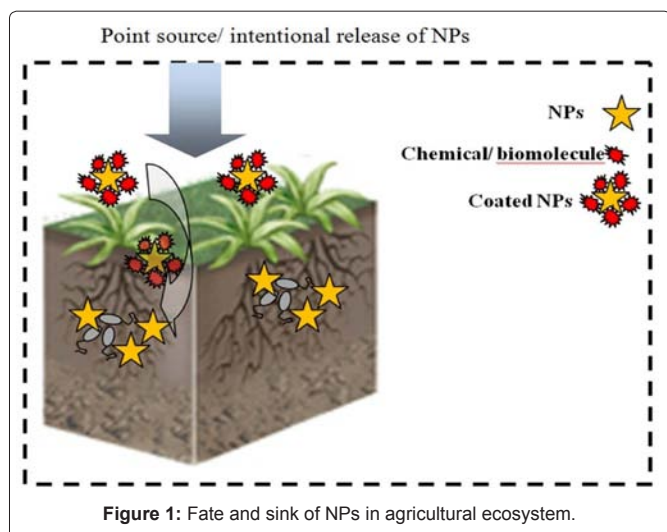


Figure 1: Fate and sink of NPs in agricultural ecosystem.

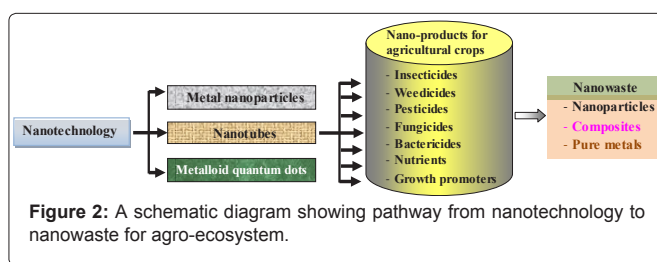


Figure 2: A schematic diagram showing pathway from nanotechnology to nanowaste for agro-ecosystem.

and chemical processes, resulting in NP dissolution, agglomeration, and aggregation. The behaviour of NPs in soil will control their mobility and their bioavailability to soil organisms. The combined results reported in the literature, suggests that metallic Cu NPs can be considered the least mobile NPs when compared to Fe₃O₄, CuO, TiO₂ and ZnO NPs [72].

The leachates of excess and after use NPs will accumulates over a time period in the form of aggregates and colloids which will generate an additional anthropogenic waste (nanowaste) in the agroecosystem. These nanowastes may interact with beneficial soil microbes and negatively impact their survival due to toxic nature of nanoparticles on microbes. A simplified schematic pathway (Figure 2) highlights the need for continuous monitoring of the fate of nanoproducts vis-a-vis the left over nonowaste and soil microbial environment.

Conclusion

Recent rapid advances in understanding, synthesis and manipulation of nanoparticles undoubtedly will continue with alarming growth of products encompassed with nanomaterials. The relative production and its use will correspondingly increase release of NPs into the environment and will generate nanowastes. The existing knowledge based on usage of nanoparticles playing an astonishing role in medical and diagnostics, whereas their effects on plants are not clearly emphasized elsewhere. The knowledge available on the positive or negative effects of some nanoparticles on the physiology and biochemistry of plants is meagre, and does not convey any clear

evidence on this issue. Moreover, the impacts of nanoparticles on beneficial soil microbes such as N₂ fixing, phosphate solubilizers, AM fungi have not been studied.

In view of the foreseeable use of nanoparticle based products in diverse application, there is a need for systematic study to evaluate the effects of nanoparticles on crop plants and its environmental consequences as well as generation of data on standard acceptable limits of nanomaterials on timely basis well in advance.

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