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REVIEW

A review on positive and negative impacts of nanotechnology in agriculture

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Abstract
Nanotechnology holds huge potentials in several fields and is envisaged as a technology to lead the way toward sustainable environment-friendly development in the coming years. The basic theme of nanotechnology is to use particles having size in nanometer range for various applications in medical fields, cosmetics industry, and agriculture and food technologies. The benefits associated with nanotechnology include among others increase in yield and quality of produce in agriculture, improved cosmetic products, directed delivery of medicines and sensor applications. Advancement in the development of nanosensors has made recognition of disease causing elements, toxins and nutrients in foods, and elements in environmental samples, easier and cost effective. However, immense focus on nanotechnology in past few decades has led to its unrestricted development and consequently enormous use of nanoparticles (NPs). It is considered that NPs may pose risks to the environment and biological systems. It is also becoming evident that the size, structure and type of nanomaterials, such as graphene/graphene oxide with gold NPs, carbon and carbon nitride nanotubes, have different effects on plants and environment. Hence, long-term life cycle analyses are needed to assess impacts of NPs. This review presents a brief overview of applications of nanomaterials in agriculture and discusses its positive and negative aspects in agricultural field. The review emphasizes that future development of nanotechnology must be based on scientific evaluations of benefits and risks associated to it in long term.

Keywords Agricultural usage · Growth · Metal oxides · Nanosensor · Nanotechnology · Reactive oxygen species

Introduction

Nanotechnology is an umbrella term used to describe technologies working on nanoscales for utilization in real-world applications. Nanoparticles (NPs) are atomic or molecular aggregates with variable sizes ranging between 1 and 100 nm (Roco 2003; Awasthi et al. 2016). Physicochemical properties of nanoparticles vary from their native bulk material (Nel et al. 2006). Nanoparticles can come from natural sources such as volcanic eruptions, meteoric dust, weathering and microbial action on organic matter in soil (Morales-Díaz et al. 2017). Anthropogenic sources include engineered nanoparticles production for a number of applications by physicochemical or biological methods with the help of microbes. The designed NPs can be divided into four categories: carbon-based materials (single-walled carbon nanotubes), metal-based nanoparticles (quantum dots, nano gold, nano silver etc.), dendrites (nano-sized polymers composed of branched units synthesized for specific chemical function) and composites (made of two or more substances). Traditionally, two approaches for the synthesis of nanoparticles are used: "top-down" approach and "bottom-up" approach (Fig. 1). In top-down approach, nanomaterials are constructed from larger entities without atomic level control. This method is slow, expensive and not suitable for large-scale production. The most commonly used top-down methods are milling, drilling and grinding. The bottom-up approach starts with molecular components which assemble themselves chemically to build nanostructures by using

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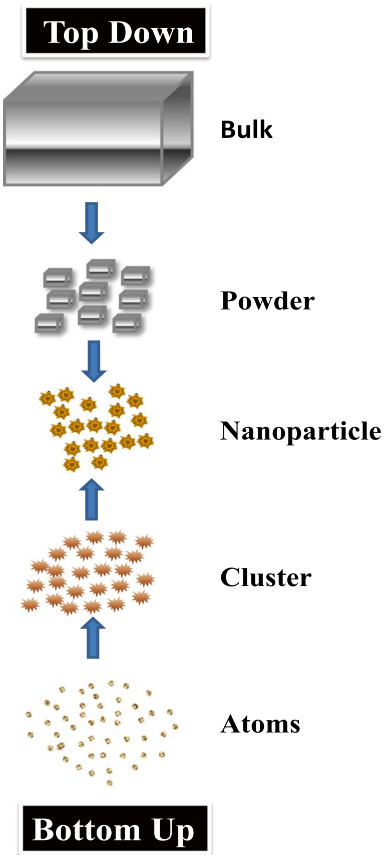

Fig. 1 Top-down and bottom-up approach for nanoparticle synthesis

principle of molecular recognition. This method is suitable as this is low cost and also causes less defects to the materials. The most commonly used bottom-up methods are wielding and riveting (Khandelwal and Joshi 2018).

The pathway analysis of NPs in soil includes understanding the entry routes, accumulation pattern, residence time and migration. In soil, NPs enter via precipitation, sedimentation in the form of dust, aerosols and abscission of leaves, absorption of gaseous compounds by soil and through several anthropogenic activities (Gladkovaa and Terekhovaa 2013). Soil indeed acts as a storehouse of NPs produced via different industrial and environmental practices or formed as by-products of human activities. For example, NPs containing sludge from wastewater treatment facilities are dumped to land sites, which is responsible for the build-up of NPs in soils (Wang et al. 2016a, b). The increasing concentration of NPs into soil is likely to have negative effects on plant growing on affected sites, animals feeding on affected plants and eventually would affect humans also due to biomagnification (Nowack and Bucheli 2007). The uptake of NPs by plant is governed by many features (Pérez-de-Luque 2017), and it is the uptake and metabolism of NPs in plants and subsequent bioavailability to humans that affect further fate of NPs.

The application of NPs in our daily life is quite old. The gold NPs have been used in colored glass seen in old buildings. While carbon black is used in ink, tires, toners etc. Nanotechnology has several applications in environmental and ecological fields. It can be used to treat wastewater, to enhance crop productivity and quality, to reduce resource consumption, to obtain clean energy, in catalysts, to precisely deliver drugs in humans and for improving health through better cosmetic and esthetic products (Nel et al. 2006). Nanoparticles may also play supportive roles to the action of microbes during remediation of various contaminants. This nanoparticles assisted microbial remediation is known as nano bioremediation. Due to their unique activity, nanoscale particles increase the efficiency of contaminant absorption and thus remediation process can be accomplished at a very low cost and in less time as compared to traditional methods. Nanomaterials like magnetic nanosorbents are considered to be appropriate for the development of next-generation super-adsorbers.

Nanotechnology has advanced rapidly in past one to two decades owing to advances of new methods of synthesis of NPs and development of technologies for analytical characterization of NPs. There are presently several products, and cosmetics readily available in markets that have NPs as ingredients. This tremendous rate of growth of nanotechnology has led to concerns regarding the fate and behavior on NPs in environmental systems (Bakshi et al. 2014). Rather uncontrolled growth of nanotechnology industry has been sparked by the absence of regulatory guidelines regarding the use of NPs in commercial products (Gottschalk and Nowack 2011). The NPs as contaminant can adversely affect the environment and human health (Jiang et al. 2009). Engineered NPs may enter humans through skin, inhalation (lungs) and ingestion (intestinal tract) and may reach to other tissues and organs. The understanding that NPs can be deleterious to human health, plants as well as microbes, has given rise to a new branch of science, nanotoxicology, assessing toxic effects of NPs (Koo et al. 2015). There are some studies which demonstrate that toxicity of NPs such as silver and sulfide NPs in water can be lowered by the presence of organic compound for instance perfluorocarboxylic acid, fulvic acid, and humic acid (Li et al. 2014; Shang et al. 2017). These organic compounds lessen the toxicity of NPs by decreasing dissolution, and aggregation of NPs and generation of reactive oxygen species (ROS). The cytotoxicity of carbon nanotubes to microbes can also be reduced by the presence of natural suspended solids in aquatic systems due to heteroaggregation between suspended solids and carbon nanotubes that limits the accessibility of carbon nanotube to microbes (Zhu et al. 2018). The microbes also show physiological responses, such as alteration of fatty acid composition of membranes, in the presence of carbon nanotubes to increase the adaptability toward NPs (Zhu et al. 2014). To scientifically assess the health hazards of engineered nanoparticles, their whole life cycle needs to be evaluated including their fabrication, storage, distribution, application and disposal. The situation demands for comprehensive assessment of pros and cons of nanotechnology for the environment and health of people.

The use of NPs may drastically change the property of a material like metals getting harder while ceramics getting softer. Clay NPs have been used to make materials stronger but lighter. Nanomaterials are linked to various aspects in our daily life, such as medicine (diagnostics, drug delivery, tissue engineering), environment (filtration), energy (reduction of energy consumption, increasing the efficiency of energy production), information and communication (memory storage, novel semiconductor devices, novel optoelectronic devices, displays, quantum computers) (Hillie and Hlophe 2007). By using nanotechnology, catalyst like Pt/Pd nanoparticles/polyoxometalate/ionic liquid nanohybrid was produced, which could act effectively on methanol (Medetalibeyoglu et al. 2018). Nanotechnology can also help in cleaning heavy metals contaminated waste water by detecting heavy metals via nanosensors and by removing them through nanoparticle-based technologies in a cheaper and eco-friendly way (Gupta et al. 2013a; Göde et al. 2017). Nanomaterials also help in heavy industry (aerospace, construction, vehicle manufacturers), and consumer goods (nano foods, household, optics, textiles, cosmetics, agriculture, sports) (Fig. 2).

Nanomaterials have already entered cosmetics industry with products like sunscreens having NPs with potential to enter deep into the skin. Other useful products with NPs include nanosensors, paints and lubricants, and various optical items (Yola et al. 2013; Yola and Atar 2014; Khan et al. 2017).Carbon nanotubes have been used by shoe making (Adidas) and tennis racket manufacturing (Babolat) companies to increase elasticity, power, durability and torsion and flex resistance of their products. Socks with silver (Ag) NP-based antibacterial fabrics are another product in common use now.

The major focus on NPs application has been on the development of drug delivery systems as NPs can penetrate better into various cells due to smaller size and can possibly deliver drugs right at the place where it is required in minutest of amount and in intact chemical form. Drug delivery systems with liposomes and nanoparticles are gaining popularity in nanotechnology (Hema et al. 2018). Another emerging field for the improvement of drug delivery systems is DNA nanobiotechnology. This utilizes DNA-based nanostructures for drug delivery, and hence, it is safe. DNA nanostructures can self-assemble, cross membrane barriers in various cells, and can accurately deliver the drug. The development of DNA biosensor has also attracted substantial attention for the detection of genetic disorders, tissue matching, forensic applications, gene analysis etc. (Gupta et al. 2013b). Carbon nanotubes (CNTs) have important biomedical applications due to combination of mechanical and chemical properties and biocompatibility (Lobo et al. 2011). Bio-analytical nanosensors have been developed to identify and quantify the minutest of amounts of organisms like viruses, bacteria, chemicals including toxins, micronutrients in agriculture, food industry and also in medical fields (Bhushan 2007; Awasthi et al. 2016; Duhan et al. 2017). Nanosensors have also been developed for determination of antibiotic cefixime (Yola et al. 2014), neurotransmitter serotonin (Yola and Atar 2018) etc. Several nanosensors such as gold NPs/carbon nanotubes composites, gold NPs/graphene

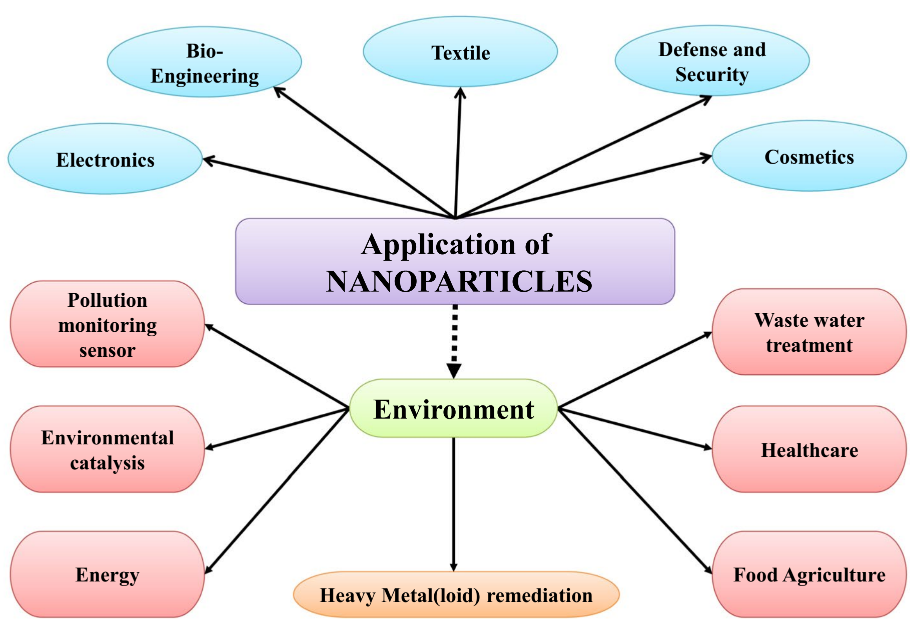

Fig. 2 Different applications of nanoparticles in various fields

oxide nanocomposite are widely used for the determination of quercetin and rutin flavonoids present in food and vegetables (Yola et al. 2013; Yola and Atar 2014). A carbon nitride nanotubes sensor has also been developed to determine the melamine in food samples such as milk. Melamine has high nitrogen rich content and is toxic if added in food products and can cause serious diseases and even death (Yola et al. 2016; Onac et al. 2018). Nanomaterials play significant role in agriculture via various practices. Hence, nanotechnology has found potential applications in wide-ranging fields related to almost every aspect of human life.

Application of Nanomaterial in Agriculture

Nutrient deficiency of soils (Zn, Se, S, etc.) and spread of a variety of pests are major agricultural problems that need to be tackled to ensure high and quality crop yields. Further, macronutrients like N, K, and P are required in high amounts by plants but their bioavailability is generally low. Agriculture sector therefore utilizes a number of chemicals (pesticides, fertilizers) in extensive amounts to obtain high and quality production from crops avoiding any pest attack (Duhan et al. 2017). Nanotechnology can also lead the way to effectively deliver genes or sequence molecule to achieve higher efficiency in plant breeding programs.

Pest control

The application of nanotechnology can be realized in several fields like pest control and nutrient supply through application of pesticides and fertilizers as effective and less-contaminating nanoformulations. The carcinogenic and cytotoxic nature of traditional pesticides makes them hazardous for the ecosystem. The recent development of nanosensor devices such as platinum NPs/carbon nitride nanotubes nanocomposite for detection of atrazine (Yola and Atar 2017) and core–shell type NPs/2D hexagonal boron nitride nanosheets for determination of cypermethrin (Atar and Yola 2018) has created easier and cost effective method for pesticide detection. Nanosilver has been studied for agricultural application to fight against pathogens (Yasur and Rani 2013).

Fertilizer

In agriculture, use of nanofertilizers for micronutrients (Zn, Se etc.) supply is rapidly advancing (Duhan et al. 2017). Further, nanotechnology-driven nanosensing devices may be developed so as to know real-time data of water and nutrient availability and crop growth. Carbon nanotubes (CNTs) and mesoporous silica nanoparticles (MSNs) have been applied in the delivery of desired chemicals to seeds and crops. Their main features include a large surface area, pore volume and highly ordered pores (Patil et al. 2011). Another research target is to develop nanofertilizers in such a way that they may release nutrients "in the quantity and at the time" as and when required by plants.

Plant growth regulator

The research need to understand mechanistic aspects of NPs uptake through roots or leaves, root to shoot and shoot to root transport and distribution to various tissues. This would pave way for utilization of a nanoformulation, fertilizer or pesticide, appropriately in soil or as foliar spray. Nanoparticles may be used as suspension or may be incorporated into a matrix (clay, zeolite, chitosan). The effects of NPs on organisms and environment are dependent on size of NPs, their shapes (aggregation), chemical properties (element(s) making up the NPs), mobility in the environment (Morales-Díaz et al. 2017), plant species in consideration, exposure duration and mode of exposure and environmental conditions. The uptake of NPs by a plant and mobility within the plant depend on the shapes and size of NPs as well as on its chemical properties. Inside plants, NPs bring about several changes that result into positive physiological and growth changes of plants. The expression of stress responsive genes is altered and metabolic pathway and enzymatic activities are fine-tuned upon NPs supply. There are reports of changes in synthesis, and functions of ethylene in the presence of Ag NPs that led to either positive (growth improvement) or negative (altered plant–microbe interaction) changes. Water permeability of seeds and other membranes inside the plants has been found to improve upon application of NPs like Au, CuO and TiO_2. The improved functioning of nitrogen metabolism and photosynthesis has been noticed by TiO_2 NPs leading to enhanced growth of studied plants (Yang et al. 2006) (Table 1). Although there is steady rise in the use of NPs in agriculture sector and more and more research is going on that would further increase this use. However, it must be kept in mind the fate and behavior of NPs in the environment, their interaction with crop plants, microbes, and persons, their subsequent movement through the food chain and ultimate effects on animal and human consumers should be evaluated in depth. This would ensure safe and sustainable use of NPs in near future.

Nanomaterial toxicity to crops

Absorption and uptake of nanomaterial

Although NPs used to study plants responses vary in size, the dimension for effective plant uptake and movement is reported to range from 40 to 50 nm (Corredor et al. 2009; Larue et al. 2012; Koo et al. 2015). Further, the effect of

Table 1 Supplementation of nanoparticles changes physiological and biochemical activities in plants

Plants	Nanoparticles	Size (nm)	Treatments	Exposure time (days)	Physiological/biochemical activities	References
Brassica juncea L.	Fe_3O_4 NPs	80–110	500 mg L^{-1}	4	Reducing As toxicity; sulfur-related gene transcripts increased	Praveen et al. (2018)
Ricinus communis L.	Ag NPs	> 100	2000 mg L^{-1}	7	Enhanced enzymatic activity of ROS enzymes and phenolic content	Yasur and Rani (2013)
Triticum aestivum	Fe_3O_4 NPs	6.8	2000 mg L^{-1}	5	Reduce heavy metals uptake and mitigate their toxicity	Konate et al. (2017)
Vicia faba	TiO_2 NPs	25	0.01–0.03%	35	Increased shoot length, leaf area and root dry weight; increased the enzymatic activities and levels of soluble sugars, amino acids	Abdel Latef et al. (2018)
Solanum lycopersicum	$CoFe_2O_4$ NPs	17	62.5, 125, 250 and 500 mg L^{-1}	15	Increased root and shoot length	López-Moreno et al. (2016)
Lycopersicon esculentum	TiO_2 NPs	16	0.05–0.20 g L^{-1}	7	Net photosynthetic rate, conductance to H_2O and transpiration rate, Regulation of photosystem	Qi et al. (2013)
Trigonella foenum-graecum L.	Ag-NPs	8–21	200 µL	5	Role of enhancement of both plant growth and diosgenin synthesis.	Jasim et al. (2017)
Arabidopsis thaliana	CeO_2 NPs	10–30	250 ppm	25	Increased plant biomass	Ma et al. (2013)
Gossypium hirsutum L.	ZnO NPs	2–54	25, 50, 75, 100, and 200 mg L^{-1}	21	Increased biomass, photosynthetic pigments and proteins; decreased level of MDA, protective role against oxidative damage.	Venkatachalam et al. (2017)
Spinacia oleracea	TiO_2 NPs	4–6	0.25%	20–45	The improved functioning of nitrogen metabolism, photosynthesis; enhanced plant growth	Yang et al. (2006)
Cucumis sativus	ZnO NPs	10	400 mg kg^{-1}	10	Micronutrients (Cu, Mn and Zn), increased starch content	Zhao et al. (2014)

coating or encapsulating material on the uptake and movement of NPs cannot be neglected. There are variations among plant species too and different plants would therefore take up variable amounts of NPs in a given exposure time and concentrations (Larue et al. 2012). The movement of NPs inside the plants can be symplastic (between cells through plasmodesmata, sieve plates) or apoplastic (cell walls, extracellular spaces, xylem vessels) or a mix of both (Sattelmacher 2001; Roberts and Oparka 2003; Wang et al. 2012). Symplastic movement of NPs may occur once NPs cross plasma membrane via one of the several processes like endocytosis (Etxeberria et al. 2006), pore formation (Wong et al. 2016), via carrier proteins (Nel et al. 2009), plasmodesmata (Roberts and Oparka 2003) and ion channels (Schwab et al. 2015). Foliar uptake of NPs occurs after the cuticle is crossed either via diffusion through cuticle (lipophilic NPs) or by stomata (hydrophilic NPs) (Eichert et al. 2008). NPs may accumulate in different tissues and organs, some in edible parts of plants (grains and fruits) and others in non-edible parts (leaves and flowers) (Servin et al. 2013; Koo et al. 2015).

Toxicity to crops

NPs may themselves cause toxicity to plants after uptake or it may be due to release of toxic ions from NPs degradation. Nanoparticles may negatively affect plant growth, germination, biomass and root and leaf growth when present in excess (Shen et al. 2010; Hong et al. 2014). The adverse biochemical reactions of NPs include increased production of ROS due to the presence of extra electrons or due to interaction of NPs with biomolecules causing oxidative stress (Valavanidis et al. 2009), effects on water uptake and transport in plants, effects on metabolic pathways and photosynthesis (Wang et al. 2016a, b). Upon treatment with 200 mg L^{-1} of CeO_2 and CuO_2 NPs, changes in photosynthetic parameters were observed in cucumber (Hong et al. 2016). Further, transcriptome changes in response to NPs and DNA degradation have also been noticed (Shen et al. 2010; Kumari et al. 2011). Genotoxic effects including chromosomal aberrations and micronuclei formation, DNA fragmentation were observed in *Nicotiana tabacum* and *A. cepain* response to TiO_2 NPs (Ghosh et al. 2010). Zhu et al. (2013) compared the toxicity of three nanometal oxides, CuO_2, CdO_2, and TiO_2 and found CuO_2 to be the most cytotoxic that also induced DNA damage with 8-hydroxy-2′-deoxyguanosine (8OHdG) formation, while TiO_2 was the least toxic. Hong et al. (2014) analyzed cucumber (*Cucumis sativus*) plants for toxicity nano ceria ($n$$CeO_2$) during aerial exposure route and found that Ce uptake led to changes in enzymatic profile of plants. Ma et al. (2015) reported that phytotoxicity of CeO_2 nanoparticles to cotton plants was through destruction of chloroplasts and vascular bundles and also by changing absorption of nutrients (Zn, Mg, Fe, and P). It has been found that growth cycle changes upon exposure to *n*CeO to barley with decrease in the leaf area, tiller number, and also in spikes per plant. Further, leaf growth and chlorophyll levels indicated improved performance of plants (Table 2).

Detoxification mechanism in crops induced by nanomaterial

An important toxicity mechanism of nanoparticles is enhanced production of ROS, which affects normal physiological redox regulated functions. Due to their small size, NPs have larger surface and hence greater surface reactivity as compared to bulk size counterparts. This results in a greater induction of ROS by nanoparticles.

Antioxidants play an important role in regulating ROS levels and thus preventing the damages. These include both enzymatic and non-enzymatic antioxidants. Superoxide dismutases (SODs), peroxidases (POD), and catalases (CAT) are some of the important antioxidant enzymes while glutathione (GSH), ascorbate, phenolics constitute major non-enzymatic antioxidants. The exposure of NPs has also been associated with changes in antioxidant levels. A study on castor bean (*Ricinus communis*) seeds with exposure to silver nanoparticles reported an increased ROS production and associated stimulation of antioxidants (Yasur and Rani 2013). The toxicity of silver nanoparticles in *Arabidopsis thaliana* has been associated to disturbance to the balance of oxidant and antioxidant systems, and water homeostasis and also to photosynthesis through effects on thylakoid membrane and chlorophyll content (Qi et al. 2013). Effects of CuO nanoparticles on *A. thaliana* showed that released Cu ions from CuO nanoparticles were the cause of toxicity (Tang et al. 2016). An increase in SOD activity has been observed in some studies (Chen et al. 2016) upon exposure to ~ 1000 mg/L of NiO nanoparticles and in rice (Ma et al. 2016) under 250 mg L^{-1} CeO_2 nanoparticles exposure. Servin et al. (2013) studied the responses to TiO_2 nanoparticles in cucumber and found induction of CAT but no effect on APX activity. The effects of neodymium(III) oxide nanoparticles in pumpkin found increased SOD and POD activities but decreased CAT and APX activities (Chen et al. 2016). Rico et al. (2013) observed that the 500 mg L^{-1} of CeO_2 nanoparticles affected the levels of thiols and ascorbate negatively and hence resulted in increased membrane damage and photosynthetic stress in rice. It has been found that nanoparticles (e.g., CeO_2 and In_2O_3) can affect the expression of genes of sulfur assimilation pathway enzymes and hence modulate GSH biosynthesis in Arabidopsis (Ma et al. 2013). Servin et al. (2013) reported significant increase in CAT activity upon exposure to 250–750 mg L^{-1} of TiO NPs, but no effect was observed in APX activity.

Threats of Nanotechnology

The applications of nanoparticles in various sectors are envisaged and therefore huge growth in the production of NPs has taken place (Piccinno et al. 2012). However, this is despite the fact that the information about further fate of NPs after application is still not fully elucidated. It is widely understood that the present level of NPs contamination is not dangerous (Johnson and Park 2012). The present estimated output of NPs (SiO_2, TiO_2, FeO_2, AlO_2, ZnO_2, and CeO_2) is 270,000 metric tons/year (Medina-Velo et al. 2017). Still this may not be neglected that NPs concentrations may reach beyond safe limits very soon (Nicolodi and Gianello 2014).

Nanotechnology has its own advantages and disadvantages (Bhushan 2007) (Table 3). Because NPs are very different from their everyday counterparts, their adverse effects cannot be derived from the known toxicity of the macro-sized material. This poses significant issues for addressing the health and environmental impact of free nanoparticles. The presence of NPs in the environment is both due to natural sources and anthropogenic production. Nanoparticles reach to the soil via atmospheric deposition and rain, and via

Table 2 Physiological and biochemical changes in plants under nanoparticles stress

Plants	Nanoparticle	Size (nm)	Treatments	Biochemical activities	References
Phaseolus vulgaris	CeO_2 NPs	10–30	0, 250, 500, 1000, and 2000 mg L^{-1}	NPs application induced membrane damage	Salehi et al. (2018)
Romaine lettuce	Nano-CeO_2	16.5	0–2000 mg kg^{-1}	POD was increased, oxidative stress, increased nitrate-N level in shoots, inhibited the biomass production	Zhang et al. (2017)
Allium cepa	ZnO NPs	< 100	25, 50, 75, and 100 g mL^{-1}	Mitotic index decreased with the increase of pycnotic cell TBARS increase	Kumari et al. (2011)
Cucumber sativus	TiO_2 NPs	27	0–750 mg kg^{-1}	CAT was increased	Servin et al. (2013)
Triticum aestivum	CuO NPs	< 50	3, 10, 30, 300 mg kg^{-1}	Inhibition of root elongation; exposure resulted in root hair proliferation and shortening of the zones of division and elongation	Adams et al. (2017)
Cucumis sativus	*n*CeO_2 and *n*CuO NPs	> 50	50 mg L^{-1} 200 mg L^{-1}	Reduced fruit firmness	Hong et al. (2016)
Arabidopsis	ZnO NPs	< 50	200 and 300 mg L^{-1}	reduced Arabidopsis growth; inhibition of the expression of chlorophyll synthesis genes and photosystem structure genes	Wang et al. (2016a, b)
Arabidopsis thaliana	CeO_2 NPs	10–30	250 and 1000 mg L^{-1}	CAT, SOD, POD and APX were significantly enhanced, GT and GR were also increased treatment	Ma et al. (2016)
Cucurbita maxima	Nd_2O_3 NPs	30–45	100 mg L^{-1}	Inhibition plants growth and the necessary elements uptake was hampered	Chen et al. (2016)
Arabidopsis	CuO NPs	30–50	10, 20 mg L^{-1}	Root damage; ROS generation in root tips; up-regulation of oxidative stress-related genes	Tang et al. (2016)
Capsicum annuum L.	Ag NPs	–	0.01, 0.05, 0.1, 0.5 and 1 mg L^{-1}	Decrease in plant growth	Vinković et al. (2017)
Egeria densa and *Juncus effusus*	Ag NPs	> 50	450 mg	some injury and stress to aquatic plants Antioxidant activity increased	Yuan et al. (2018)

Table 3 Possible impacts of nanoparticles on society. *Source*: Maheshwari et al. (2011)

	Positive impacts	Negative impacts
Relevance to developing nation	Pure and hygienic water, Environmental Remediation, economical medicines and other goods	A nanotechnology partition among rich and poor nations
Surveillance and collection of data	Improved trade and service delivery	Compromised privacy
Defense	Improved early warning indication for threats and enhanced defense potential	Increase in personal and national security risks
Biotechnological approach	Advancement in drug delivery system and disease treatment	Health threat, too invasive

direct supply in agricultural fields. In the soil, NPs continue to buildup due to low mobility of NPs in soil and this is why NPs are present in higher concentrations in soil than that in air and water (Gottschalk and Nowack 2011). The NP-based nanofertilizers may act as source of NPs contamination in soil, water and air. The NPs in soil are taken up by plants and may also enter microbes. Within the plants, NPs move through plants to reach up to shoot and to various organs and tissues. Through microbes and plants, NPs continue to travel through food chain via protozoans, fish and insects etc. and may finally reach to humans. Hazards and risks of nanoparticles include increased production of ROS, DNA damage, genotoxic effects, damages to organs and tissues in humans, effects on growth and yield of crop plants and negative impacts on beneficial bacteria in the environment. The potential effects of nanoparticles on human health and environment should be evaluated before they are widely marketed.

The potential threats to health of people should be understood thoroughly. There are several potential entry routes for NPs into the body. They can be inhaled, swallowed, absorbed through skin or get deliberately injected during medical procedures. The behavior of NPs inside the organism is one of the big issues that need to be resolved. This behavior is a function of size, shape and surface reactivity of nanoparticles with the surrounding tissue (Bhushan 2007). Cytotoxicity can be caused by the particles being contaminated by harmful or poisonous products. The chances of such contamination increase as nanoparticles are being manufactured on a large scale.

Due to the continuous production of NPs during the last few decades, they are inevitably being released or end up in the environment. Nevertheless, little is known about the potential impacts of NPs on the environment even though in some cases chemical composition, shapes and size have been shown to contribute to the toxicological effects (Khan et al. 2017). Researchers have discovered that silver nanoparticles used in socks only to reduce foot odor are being released in the wash with possible negative consequences. Silver nanoparticles, which are bacteriostatic, may then destroy beneficial bacteria which are important for breaking down organic matter in waste treatment plants or farms (Sonal et al. 2007).

Keeping in mind the above-mentioned threats of NPs, the development of NPs for pharmacology, therapeutics and diagnostics, agriculture and cosmetics etc. must proceed in tandem with assessment of their toxicological and environmental side effects (Rehna and Siddique 2018). Regulatory bodies such as the Environmental Protection Agency and the Food and Drug Administration in the U.S. or the Health & Consumer Protection Directorate of the European Commission have started dealing with the potential risks posed by nanoparticles. So far, neither engineered NPs nor the products and materials that contain them are subject to any special regulation regarding production, handling or labeling (Bhushan 2007).

Conclusion

Despite several studies available on the fate and behavior of NPs and their toxic impacts, the holistic knowledge on the subject is largely missing. Micro- and nanoplastics are emerging as environmental contaminants of great scale with presence in almost all the environmental matrices. The fate and behavior of nanoplastics need to be studied upon. Further studies need to focus on using several exposure concentrations, durations and mode of exposure, and apply simulated field conditions or perform experiments in real field conditions. A standard set of parameters need to be defined to assess toxic impacts of various NPs on different plants and in varying environmental conditions. Mendonça et al. (2017) has advocated the use of certain representative species of animals at different trophic level to perform standard set of experiments to obtain required data in future so that regulatory guidelines may be established and the use of NPs can be safely monitored and regulated.

The cost of NPs should be kept within the reach of common public especially in case of NPs to be used in agriculture sectors. The NPs for medical industry can be costly and can be affordable. However, for large-scale agricultural usage by the poor farmers, NPs cost should be kept as low as possible. The future research must emphasize on reaping the benefits of technology keeping cost constraints and requirements in mind. Presently, major focus has therefore shifted on development of NPs through natural processes or from natural products like chitosan and chitin from crustaceans exoskeleton and alginate (from brown algae).

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References

Abdel Latef AAH, Srivastava AK, El-sadek MSA, Kordrostami M, Tran LSP (2018) Titanium dioxide nanoparticles improve growth and enhance tolerance of broad bean plants under saline soil conditions. Land Degrad Dev 29(4):1065–1073

Adams J, Wright M, Wagner H, Valiente J, Britt D, Anderson A (2017) Cu from dissolution of CuO nanoparticles signals changes in root morphology. Plant Physiol Biochem 110:108–117

Atar N, Yola ML (2018) Core–shell nanoparticles/two-dimensional (2D) hexagonal boron nitride nanosheets with molecularly imprinted polymer for electrochemical sensing of cypermethrin. J Electrochem Soc 165(5):H255–H262

Awasthi G, Kumar A, Awasthi KK, Singh AP, Srivastva S, Vajpayee P, Mishra K, Tripathi RD (2016) Green synthesis of nanoparticles: an emerging phyotechnology. In: Singh R, Kumar S (eds) Green technologies and environmental sustainability. Springer, Berlin, pp 339–363

Bakshi M, Singh HB, Abhilash PC (2014) The unseen impact of nanoparticles: more or less? Curr Sci 106:350–352

Bhushan B (2007) Nanotechnology: a boon or bane? AIP Conf Proc 929:250–253

Chen G, Ma C, Mukherjee A, Musante C, Zhang J, White JC, Dhankher OP, Xing B (2016) Tannic acid alleviates bulk and nanoparticle Nd_2O_3 toxicity in pumpkin: a physiological and molecular response. Nanotoxicology 10(9):1243–1253

Corredor E, Testillano PS, Coronado MJ, González-Melendi P, Fernández-Pacheco R, Marquina CI et al (2009) Nanoparticle penetration and transport in living pumpkin plants: in situ subcellular identification. BMC Plant Biol 9:45–55

Duhan JS, Kumar R, Kumar N, Kaur P, Nehra K, Duhan S (2017) Nanotechnology: the new perspective in precision agriculture. Biotechnol Rep 15:11–23

Eichert T, Kurtz A, Steiner U, Goldbach HE (2008) Size exclusion limits and lateral heterogeneity of the stomatal foliar uptake pathway for aqueous solutes and water-suspended nanoparticles. Physiol Plant 134(1):151–160

Etxeberria E, Gonzalez P, Baroja-Fernandez E, Romero JP (2006) Fluid phase endocytic uptake of artificial nano-spheres and fluorescent quantum dots by sycamore cultured cells: evidence for the distribution of solutes to different intracellular compartments. Plant Signal Behav 1:196–200

Ghosh M, Bandyopadhyay M, Mukherjee A (2010) Genotoxicity of titanium dioxide (TiO_2) nanoparticles at two trophic levels: plant and human lymphocytes. Chemosphere 81:1253–1262

Gladkovaa MM, Terekhovaa VA (2013) Engineered nanomaterials in soil: sources of entry and migration pathways. Mosc Univ Soil Sci Bull 68(3):129–134

Göde C, Yola ML, Yılmaz A, Atar N, Wang S (2017) A novel electrochemical sensor based on calixarene functionalized reduced graphene oxide: application to simultaneous determination of Fe(III), Cd (II) and Pb(II) ions. J Colloid Interface Sci 508:525–531

Gottschalk F, Nowack B (2011) The release of engineered nanomaterials to the environment. Environ Monit Assess 13(5):1145–1155

Gupta VK, Yola ML, Atar N, Ustundağ Z, Solak AO (2013a) A novel sensitive Cu(II) and Cd(II) nanosensor platform: graphene oxide terminated *p*-aminophenyl modified glassy carbon surface. Electrochim Acta 112:541–548

Gupta VK, Yola ML, Qureshi MS, Solak AO, Atar N, Üstündağ Z (2013b) A novel impedimetric biosensor based on graphene oxide/gold nanoplatform for detection of DNA arrays. Sens Actuators B Chem 188:1201–1211

Hema S, Thambiraj S, Shankaran DR (2018) Nanoformulations for targeted drug delivery to prostate cancer: an overview. J Nanosci Nanotechnol 18(8):5171–5191

Hillie T, Hlophe M (2007) Nanotechnology and the challenge of clean water. Nature Nanotechnol 2:663–664

Hong J, Peralta-Videa JR, Rico C, Sahi S, Viveros MN, Bartonjo J, Zhao L, Gardea-Torresdey JL (2014) Evidence of translocation and physiological impacts of foliar applied CeO_2 nanoparticles on cucumber (*Cucumis sativus*) plants. Environ Sci Technol 48(8):4376–4385

Hong J, Wang L, Sun Y, Zhao L, Niu G, Tan W, Rico CM, Peralta-Videa JR, Gardea-Torresdey JL (2016) Foliar applied nanoscale and microscale CeO_2 and CuO alter cucumber (*Cucumis sativus*) fruit quality. Sci Total Environ 563–564:904–911

Jasim B, Thomas R, Mathew J, Radhakrishnan EK (2017) Plant growth and diosgenin enhancement effect of silver nanoparticles in fenugreek (*Trigonellafoenum graecum* L.). Saudi Pharm J 25(3):443–447

Jiang W, Mashayekhi H, Xing B (2009) Bacterial toxicity comparison between nano-and micro-scaled oxide particles. Environ Pollut 157(5):1619–1625

Johnson AC, Park B (2012) Predicting contamination by the fuel additive cerium oxide engineered nanoparticles within the United Kingdom and the associated risks. Environ Toxicol Chem 31(11):2582–2587

Khan I, Saeed K, Khan I (2017) Nanoparticles: properties, applications and toxicities. Arab J Chem. https://doi.org/10.1016/j.arabjc.2017.05.011

Khandelwal A, Joshi R (2018) Synthesis of nanoparticles and their application in agriculture. Acta Sci Agric 2(3):10–13

Konate A, He X, Zhang Z, Ma Y, Zhang P, Alugongo GM, Rui Y (2017) Magnetic (Fe_3O_4) nanoparticles reduce heavy metals uptake and mitigate their toxicity in wheat seedling. Sustainability 9(5):790

Koo Y, Wang J, Zhang Q, Zhu H, Chehab EW, Colvin VL et al (2015) Fluorescence reports intact quantum dot uptake into roots and translocation to leaves of *Arabidopsis thaliana* and subsequent ingestion by insect herbivores. Environ Sci Technol 49:626–632

Kumari M, Khan SS, Pakrashi S, Mukherjee A, Chandrasekaran N (2011) Cytogenetic and genotoxic effects of zinc oxide nanoparticles on root cells of *Allium cepa*. J Hazard Mater 190:613–621

Larue C, Veronesi G, Flank AM, Surble S, Herlin-Boime N, Carrière M (2012) Comparative uptake and impact of TiO_2 nanoparticles in wheat and rapeseed. J Toxicol Environ Health A 75:722–734

Li Y, Niu J, Shang E, Crittenden J (2014) Photochemical transformation and photoinduced toxicity reduction of silver nanoparticles in the presence of perfluorocarboxylic acids under UV irradiation. Environ Sci Technol 48(9):4946–4953

Lobo AO, Marciano FR, Regiani I, Matsushima JT, Ramos SC, Corat EJ (2011) Influence of temperature and time for direct hydroxyapatite electrodeposition on superhydrophilic vertically aligned carbon nanotube films. J Nanomed Nanotechnol 6:277

López-Moreno ML, Avilés LL, Pérez NG, Irizarry BÁ, Perales O, Cedeno-Mattei Y, Román F (2016) Effect of cobalt ferrite ($CoFe_2O_4$) nanoparticles on the growth and development of *Lycopersicon lycopersicum* (tomato plants). Sci Tot Environ 550:45–52

Ma C, Chhikara S, Xing B, Musante C, White JC, Dhankher OP (2013) Physiological and molecular response of *Arabidopsis thaliana* (L.) to nanoparticle cerium and indium oxide exposure. ACS Sustain Chem Eng 1(7):768–778

Ma C, Rui Y, Liu S, Li X, Xing B, Liu L (2015) Phytotoxic mechanism of nanoparticles: destruction of chloroplasts and vascular bundles and alteration of nutrient absorption. Sci Rep 5:11618

Ma C, Liu H, Guo H, Musante C, Coskun SH, Nelson BC, White JC, Xing B, Dhankher OP (2016) Defense mechanisms and nutrient displacement in *Arabidopsis thaliana* upon exposure to CeO_2 and In_2O_3 nanoparticles. Environ Sci Nano 3(6):1369–1379

Maheshwari R, Singh P, Chauhan AK, Rani B (2011) Nanotechnology: a boon or bane. Int Res J Pharm 2(12):108–113

Medetalibeyoğlu H, Manap S, Yokuş ÖA, Beytur M, Kardaş F, Akyıldırım O, Özkan V, Yüksek H, Yola ML, Atar N (2018) Fabrication of Pt/Pd nanoparticles/polyoxometalate/ionic liquid nanohybrid for electrocatalytic oxidation of methanol. J Electrochem Soc 165(5):F338–F341

Medina-Velo IA, Peralta-Videa JR, Gardea-Torresdey JL (2017) Assessing plant uptake and transport mechanisms of engineered nanomaterials from soil. MRS Bull 42:379–383

Mendonça MCP, Rizoli C, Ávila DS, Amorim MJB, de Jesus MB (2017) Nanomaterials in the environment: perspectives on in vivo terrestrial toxicity testing. Front Environ Sci 5:71

Morales-Díaz AB, Ortega-Ortíz H, Juárez-Maldonado A, Cadenas-Pliego G, González-Morales S, Benavides-Mendoza A (2017) Application of nanoelements in plant nutrition and its impact in ecosystems. Adv Nat Sci Nanosci Nanotechnol 8(1):013001

Nel A, Xia T, Madler L, Li N (2006) Toxic potential of materials at the nano level. Science 311:622–627

Nel AE, Mädler L, Velegol D, Xia T, Hoek EM, Somasundaran P et al (2009) Understanding biophysicochemical interactions at the nano-bio interface. Nat Mater 8:543–557

Nicolodi M, Gianello C (2014) Understanding soil as an open system and fertility as an emergent property of the soil system. Sustain Agric Res 4(1):94

Nowack B, Bucheli TD (2007) Occurrence, behavior and effects of nanoparticles in the environment. Environ Pollut 150:5–22

Onac C, Alpoguz HK, Yola ML, Kaya A (2018) Transport of melamine by a new generation of nano-material membranes containing carbon nanotubes and determination with surface plasmon resonance. Innov Food Sci Emerg Technol 45:467–470

Patil A, Chirmade UN, Trivedi V, Lamprou DA, Urquart A, Douroumis D (2011) Encapsulation of water insoluble drugs in mesoporous silica nanoparticles using supercritical carbon dioxide. J Nanomed Nanotechnol 2:111

Pérez-de-Luque A (2017) Interaction of nanomaterials with plants: what do we need for real applications in agriculture? Front Environ Sci 5:12

Piccinno F, Gottschalk F, Seeger S, Nowack BJ (2012) Industrial production quantities and uses of ten engineered nanomaterials in Europe and the world. J Nanopart Res 14:1109

Praveen A, Khan E, Perwez M, Sardar M, Gupta M (2018) Iron oxide nanoparticles as nano-adsorbents: a possible way to reduce arsenic phytotoxicity in indian mustard plant (*Brassica juncea* L.). J Plant Growth Reg 37(2):612–624

Qi M, Liu Y, Li T (2013) Nano-TiO_2 improve the photosynthesis of tomato leaves under mild heat stress. Biol Trace Elem Res 156(1–3):323–328

Rehna VJ, Siddique A (2018) Risk evaluation and exposure hazards of engineered nanomaterials: a survey. Am J Eng Res 7(1):235–245

Rico CM, Hong J, Morales MI, Zhao L, Barrios AC, Zhang JY, Peralta-Videa JR, Gardea-Torresdey JL (2013) Effect of cerium oxide nanoparticles on rice: a study involving the antioxidant defense system and in vivo fluorescence imaging. Environ Sci Technol 47(11):5635–5642

Roberts AG, Oparka KJ (2003) Plasmodesmata and the control of symplastic transport. Plant Cell Environ 26:103–124

Roco MC (2003) Nanotechnology: convergence with modern biology and medicine. Curr Opin Biotechnol 14(3):337–346

Salehi H, Chehregani A, Lucini L, Majd A, Gholami M (2018) Morphological, proteomic and metabolomic insight into the effect of cerium dioxide nanoparticles to *Phaseolus vulgaris* L. under soil or foliar application. Sci Total Environ 616:1540–1551

Sattelmacher B (2001) The apoplast and its significance for plant mineral nutrition. New Phytol 149:167–192

Schwab F, Zhai G, Kern M, Turner A, Schnoor JL, Wiesner MR (2015) Barriers, pathways and processes for uptake, translocation and accumulation of nanomaterials in plants—critical review. Nanotoxicology 10:257–278

Servin AD, Morales MI, Castillo-Michel H, Hernandez Viezcas JA, Munoz B, Zhao L, Nunez JE, Peralta-Videa JR, Gardea Torresdey JL (2013) Synchrotron verification of TiO_2 accumulation in cucumber fruit: a possible pathway of TiO_2 nanoparticle transfer from soil into the food chain. Environ Sci Technol 47:11592–11598

Shang E, Li Y, Niu J, Zhou Y, Wang T, Crittenden JC (2017) Relative importance of humic and fulvic acid on ROS generation, dissolution, and toxicity of sulfide nanoparticles. Water Res 124:595–604

Shen CX, Zhang QF, Li J, Bi FC, Yao N (2010) Induction of programmed cell death in *Arabidopsis* and rice by single-wall carbon nanotubes. Am J Bot 97:1602–1609

Sonal S, Prabhakar V, Aneesh T, Sabitha M (2007) Nanomedicine: promise of the future in disease management. Internet J Nanotechnol 2(2):1–6

Tang Y, He R, Zhao J, Nie G, Xu L, Xing B (2016) Oxidative stress-induced toxicity of CuO nanoparticles and related toxicogenomic responses in *Arabidopsis thaliana*. Environ Pollut 212:605–614

Valavanidis A, Vlachogianni T, Fiotakis C (2009) 8-Hydroxy-2′-deoxyguanosine (8-OHDG): a critical biomarker of oxidative stress and carcinogenesis. J Environ Sci Health Part C 27:120–139

Venkatachalam P, Priyanka N, Manikandan K, Ganeshbabu I, Indiraarulselvi P, Geetha NN, Muralikrishna K, Bhattacharya RC, Tiwari M, Sharma N, Sahi SV (2017) Enhanced plant growth promoting role of phycomolecules coated zinc oxide nanoparticles with P supplementation in cotton (*Gossypium hirsutum* L.). Plant Physiol Biochem 110:118–127

Vinković T, Novák O, Strnad M, Goessler W, Jurašin DD, Parađiković N, Vrček IV (2017) Cytokinin response in pepper plants (*Capsicum annuum* L.) exposed to silver nanoparticles. Environ Res 156:10–18

Wang Z, Xie X, Zhao J, Liu X, Feng W, White JC et al (2012) Xylem- and phloem-based transport of CuO nanoparticles in maize (*Zea mays* L.). Environ Sci Technol 46:4434–4441

Wang P, Menzies NW, Dennis PG, Guo J, Forstner C, Sekine R, Lombi E, Kappen P, Bertsch PM, Kopittke PM (2016a) Silver nanoparticles entering soils via the wastewater–sludge–soil pathway pose low risk to plants but elevated Cl concentrations increase Ag bioavailability. Environ Sci Technol 50(15):8274–8281

Wang X, Yang X, Chen S, Li Q, Wang W, Hou C, Gao X, Wang L, Wang S (2016b) Zinc oxide nanoparticles affect biomass accumulation and photosynthesis in *Arabidopsis*. Front Plant Sci 6:1243

Wong MH, Misra RP, Giraldo JP, Kwak SY, Son Y, Landry MP et al (2016) Lipid exchange envelope penetration (LEEP) of nanoparticles for plant engineering: a universal localization mechanism. Nano Lett 16:1161–1172

Yang F, Hong F, You W, Liu C, Gao F, Wu C, Yang P (2006) Influence of nano-anatase TiO_2 on the nitrogen metabolism of growing spinach. Biol Trace Elem Res 110(2):179–190

Yasur J, Rani PU (2013) Environmental effects of nanosilver: impact on castor seed germination, seedling growth, and plant physiology. Environ Sci Pollut Res 20(12):8636–8648

Yola ML, Atar N (2014) A novel voltammetric sensor based on gold nanoparticles involved in *p*-aminothiophenol functionalized multi-walled carbon nanotubes: application to the simultaneous determination of quercetin and rutin. Electrochim Acta 119:24–31

Yola ML, Atar N (2017) A review: molecularly imprinted electrochemical sensors for determination of biomolecules/drug. Curr Anal Chem 13(1):13–17

Yola ML, Atar N (2018) Phenylethanolamine A (PEA) imprinted polymer on carbon nitride nanotubes/graphene quantum dots/core-shell nanoparticle composite for electrochemical PEA detection in urine sample. J Electrochem Soc 165(2):H1–H9

Yola ML, Atar N, Üstündağ Z, Solak AO (2013) A novel voltammetric sensor based on *p*-aminothiophenol functionalized graphene oxide/gold nanoparticles for determining quercetin in the presence of ascorbic acid. J Electroanal Chem 698:9–16

Yola ML, Eren T, Atar N (2014) Molecularly imprinted electrochemical biosensor based on Fe@Au nanoparticles involved in 2-aminoethanethiol functionalized multi-walled carbon nanotubes for sensitive determination of cefexime in human plasma. Biosens Bioelectron 60:277–285

Yola ML, Eren T, Atar N (2016) A molecular imprinted voltammetric sensor based on carbon nitride nanotubes: application to determination of melamine. J Electrochem Soc 163(13):B588–B593

Yuan L, Richardson CJ, Ho M, Willis CW, Colman BP, Wiesner MR (2018) Stress responses of aquatic plants to silver nanoparticles. Environ Sci Technol 52(5):2558–2565

Zhang P, Ma Y, Liu S, Wang G, Zhang J, He X, Zhang J, Rui Y, Zhang Z (2017) Phytotoxicity, uptake and transformation of nano-CeO_2 in sand cultured romaine lettuce. Environ Pollut 220:1400–1408

Zhao L, Peralta-Videa JR, Rico CM, Hernandez-Viezcas JA, Sun Y, Niu G, Servin A, Nunez JE, Duarte-Gardea M, Gardea-Torresdey JL (2014) CeO_2 and ZnO nanoparticles change the nutritional qualities of cucumber (*Cucumis sativus*). J Agric Food Chem 62(13):2752–2759

Zhu X, Hondroulis E, Liu W, Li CZ (2013) Biosensing approaches for rapid genotoxicity and cytotoxicity assays upon nanomaterial exposure. Small 9(9–10):1821–1830

Zhu B, Xia X, Xia N, Zhang S, Guo X (2014) Modification of fatty acids in membranes of bacteria: implication for an adaptive mechanism to the toxicity of carbon nanotubes. Environ Sci Technol 48(7):4086–4095

Zhu B, Xia X, Zhang S, Tang Y (2018) Attenuation of bacterial cytotoxicity of carbon nanotubes by riverine suspended solids in water. Environ Pollut 234:581–589