Chapter 7
Application of Nanotechnology for Sustainable Crop Production Systems

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7.1 Introduction

Nanotechnology is the science of manipulation, control, precision placement, modelling and integration of nanoscale (1–100 nm) substances to form structures, components, devices and systems having new problem-solving properties and functions (Halford 2005; US EPA 2007; Sargent Jr. 2011; Jin 2012). However, the simultaneously colloidal particulate nanoscale (10 to 1000 nm) size can be considered as nanoparticles for application in agriculture and allied disciplines (Nakache et al. 1999; US Department of Agriculture 2002). The versatile use of nanoparticles is linked with their high surface areas and unique physicochemical properties. Therefore, synthesis of a certain dimension of nanoparticles of metallic and nonmetallic compounds/atoms can be used for a certain purpose. Nanomaterials containing an array of nanosized pores have large surface area-to-volume ratios. They have been actively researched and developed due to their potential as catalytic and adsorption materials, offering sites for novel chemical reactions. For example, recently Jiang et al. (2017) synthesized mesoporous rhodium nanoparticles that are two to threefold more efficient as catalytic converter for vehicle (Figs. 7.1 and 7.2).

The European Commission declared the nanotechnology as one of its six “vital empowering technologies” in several industrial sectors (Parisi et al. 2015), such as biotechnology, medicine, electronics, material science and energy sectors, among others (Iqbal et al. 2017), whereas Hornyak et al. (2008) opined that nanotechnology is a convergent and enabling horizontal technology that cuts across all vertical industrial sectors such as agriculture, biotechnology, chemical, recreation/sports, telecommunication, computers/data storage, construction, transportation, health care/pharmaceuticals, aerospace/defence and energy.

It has become a robust technology for the sustainability of agriculture (Sastry et al. 2011; Mukhopadhyay 2014; Prasad et al. 2014). Although the agricultural sector has benefited from many other modern technological innovations, such as hybrid crop cultivars, synthetic fertilizers, genetic engineering and gene editing through biotechnological innovation, the real promise of nanotechnology in agricultural development is yet to be realized at large (Parisi et al. 2015). The potential of application of nanotechnology in climate-resilient and smart agriculture is manifold. Nanomaterials can help reduce the amount of sprayed chemical products by smart delivery of active ingredients, minimize nutrient losses in fertilization (Gogos et al. 2012) and increase yields through optimized water and nutrient management.

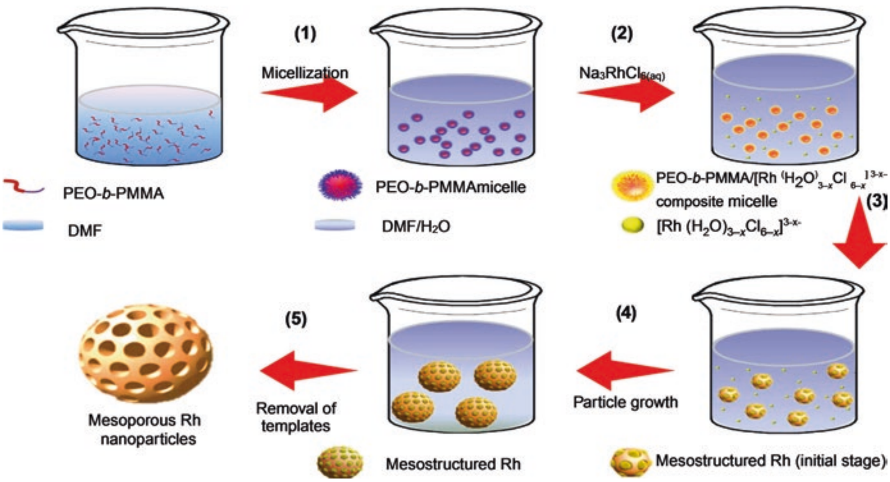

Fig. 7.1 An illustration describing the formation mechanism for mesoporous Rh nanostructures. Mesoporous Rh nanostructures form via chemical reduction on self-assemble polymeric PEO-b-PMMA micelle templates. The PEO-b-PMMA micelles function as a soft template, Na_3RhCl_6 as the Rh precursor, AA as the reducing agent, and DMF/H_2O as the mixed solvent, respectively. The synthetic process has five steps: (1) addition of water causes the PEO-b-PMMA to self-assemble into spherical micelles with a PMMA core and a PEO shell; (2) Na_3RhCl_6 source is dissolved into $Na^{þ}$ and $[Rh(H_2O)_{3-x}Cl_{6-x}]^{(3-x)-}$, and then the aqua complexes interact with the PEO moieties via hydrogen bonding between the PEO and aqua complexes (i.e. the formation of PEO-b-PMMA/$[Rh(H_2O)_{3-x}Cl_{6-x}]^{(3-x)-}$ composite micelles); (3) the Rh species are reduced to form solid Rh nuclei, (4) which coalesce and further grow into mesoporous Rh nanostructures over; and (5) the templates are removed by a solvent extraction method. (Adapted from Jiang et al. 2017 with permission)

The smart use of natural resources such as water, nutrients and chemicals in agricultural sectors by using nanosensors is cost-effective and environment-friendly (Jie et al. 2013; Prasad et al. 2017). Nanomaterials and global positioning systems with satellite imaging, of fields, can help farmers in detecting crop pests and to precisely know the status of stresses such as drought, salinity, flood and soil nutrient deficiencies. These smart materials can detect the presence of viruses (Jhanzab et al. 2015; Manjunatha et al. 2016; Wang and Xie 2018) and other microbial pathogens; increase the use efficiency of water, fertilizer and other agricultural inputs; and thus contribute to reduce the environmental pollution (Prasad et al. 2014; Jhanzab et al. 2015). Nanomaterials, e.g. zeolites and nano-clays, can improve the retention of water or liquid agrochemicals in the soil for their slow release to the plants (Duhan et al. 2017). Nanotechnology-led innovations are also being used in plant improvement and genomic transformation programmes (Torney et al. 2007).

Fertilizers are very important in crop production and contribute 40–50% total yield of field crops (Das and Mandal 2015). However, fertilizer use efficiency seldom increases by 30% in most of the cases. Overuse of fertilizers may cause water and air pollution (Smith 2003; Smith et al. 2006; Bhateria and Jain 2016). Use of

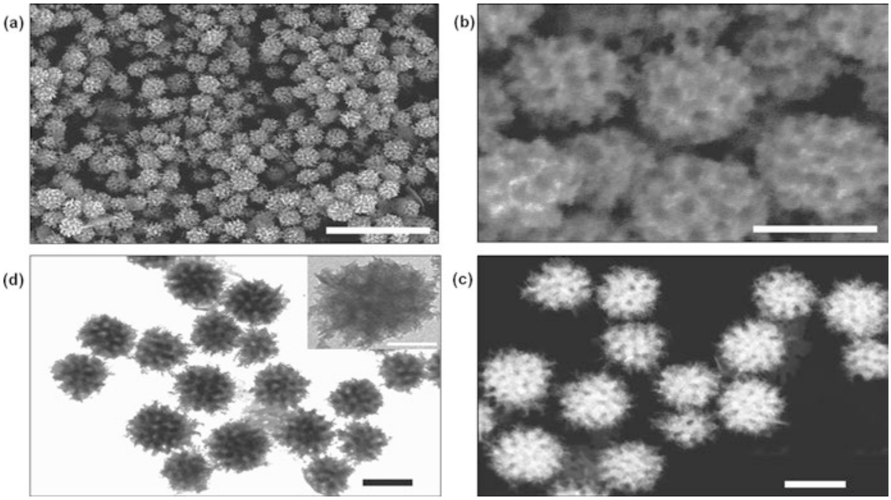

Fig. 7.2 Structural characterization of mesoporous Rh nanoparticles. (**a**) Low-magnification SEM micrograph (scale bar, 500 nm), (**b**) high-magnification SEM micrograph (scale bar, 100 nm), (**c**) TEM micrograph (scale bar, 100 nm), and (**d**) HAADF-STEM micrograph (scale bar, 100 nm) of mesoporous Rh nanoparticles. The inset in c is a high-magnification TEM micrograph of a single mesoporous Rh nanoparticle (scale bar, 50 nm). (Adapted from Jiang et al. 2017 with permission)

nanotechnology for slow release nanofertilizers seems an attractive alternative in changing climate and can also help decrease nitrogen losses through leaching, emissions and long-term soil absorption.

Application of nanoparticles has great scope in developing environmentally sound and cost-effective methods for controlling the plant pathogens (Zargar et al. 2011; Ahmed et al. 2016), insect pests (Park et al. 2006; Scrinis and Lyons 2007; Suman et al. 2010) and weeds (De et al. 2014; Chhipa and Joshi 2016; Pandey et al. 2016). For example, use of nano-silver compounds provided effective control of different fungal pathogens than the commercial fungicides (Ouda 2014). Nanoencapsulation, of insecticides, with nanoparticles may help efficient plant absorption for effective control against insect pests (Park et al. 2006; Scrinis and Lyons 2007; Suman et al. 2010) and weeds (Ali et al. 2014; De et al. 2014; Kumar et al. 2017). Nanocapsules, nanoparticles, nanoemulsions and viral capsids act as smooth carriage systems for controlling disease, insect pest and weed in association with plants (Dimetry and Hussein 2016).

Therefore, the application of nanotechnology is one of the emerging technologies for sustainability of crop production systems to meet the growing food demand of increasing population in the world. In this chapter, recent progress and potential applications of nanotechnology for sustainable crop production systems are discussed. Challenges and constraints in the use of nanotechnology have also been described.

7.2 Nanomaterials for Use in Crop Production Systems

Agonizing deeds of mankind to selfishly deracinate their wants has left Mother Nature under excruciation. Forgetting the consequences that will raise serious issues of global warming and unleash the tears of its weeping in the form of climate change leads to startled natural calamities for which the mankind had never considered for preparation.

A crop production system in general is a precision agricultural approach, where food and fibre produced are concurrently profitable; uses on-farm affordable resources without hampering biodiversity; conserves quality of products, dynamic nature of soil and systemic nutrient density of the available water; and supports energetic rural community (Walters et al. 2016; Duhan et al. 2017). This eco-friendly crop production system could be further supported by the advanced application of nanotechnology-based approach (Duhan et al. 2017). Currently nanotechnological approaches have stigmatized the concept that something is impossible and beyond the reach of mankind. Therefore, this technology has now touched every aspect of life starting from medical to agricultural industry. Among the three most abundantly explored fields, agriculture stands out based on its major requirements to sustain its necessity. Present advancement made in the field of agriculture may majorly improve two basic aspects of agriculture that is soil and productivity apart from universally required water. Nanomaterials for the improvement and sustenance of soil and improvement of crop are generally either of organic (chitosan, polyacrylic acid, clay or zeolite), inorganic (Fe, Zn, SiO_2, TiO_2) or both hybrid origins (polymer-encapsulated carbon nanotubes, nanodiamonds, graphene) (DeRosa et al. 2010; Duhan et al. 2017; Morales-Díaz et al. 2017). These nanomaterials, which are used for the preparation of various forms of nano-based agricultural tools to maintain soil dynamic nature of the soil as well as to improve crop productivity by nanofertilizer and further to protect the crops from biotic stress by nanopesticides, have seriously made an impeccable impact in the sustainable improvement of agricultural research (Chhipa 2017).

7.2.1 Nanofertilizers

The chemical or natural substances, applied to improve soil fertility, are known as fertilizers/biofertilizers (natural) (Dong et al. 2012; Bhardwaj et al. 2014). Nanofertilizer and nanobiofertilizers contain synthetic and natural substances, respectively, and enhance the soil fertility as well as bioavailability more efficiently than the conventional fertilizers (Chhipa 2017). However, to be declared as nanofertilizer, the individual size of the molecules, in dispersed and/or aggregated state, should be $\leq$100 nm, and the bulk size should be closer to 100 nm, and the nano-product should be stable, i.e. the nanofertilizer should retain its nanoscale dimension and intactness during pre- and post-interaction with the soil or the crop.

However, the rate of dissolution and bioactivity are inevitably influenced by the shape. The design of the nanofertilizer where the products are functionalized with certain target agents and/or for control release agents to develop a hybrid product (Dimkpa and Bindraban 2017).

Among the abovementioned features of nanofertilizer, the most spectacular application is the optimization of nutrient use efficiency (NUE), control release of the active substances and no effect on soil biodiversity (Sempeho et al. 2014). These nanofertilizers, based on their biodistribution and nutrient composition, by the plant may be subcategorized into macronutrient nanofertilizers, micronutrient nanofertilizers and nanoparticulate fertilizers (Chhipa 2017).

7.2.1.1 Macronutrient Nanofertilizers

The demand for macronutrients such as calcium (Ca), phosphorus (P), potassium (K), magnesium (Mg) nitrogen (N) and sulphur (S) has increased with the increase in pressure for more food production (Chhipa 2017). This increased demand for food is expected to further increase (FAO 2017). However, application of conventional fertilizer at higher rates, to achieve the target food production level, would be catastrophic. Acclimatization of the soil, resulting from agrochemical residue accumulation, may become an unalterable future. This may further pollute the running water along with it. But alternatively, the situation could be encountered by high-volume-to-surface ratio of nanoparticles, whose increased efficiency to withhold increases number of macronutrients and itself being so less in amount (Liu and Lal 2015; Ditta et al. 2015). For example, a nanofertilizer of Ca- and P-hydroxyapatite nanoparticles was prepared by Liu and Lal (2015) that showed higher increment in soybean seed yield in comparison to conventional fertilizer. Kottegoda et al. (2017) later developed another biocompatible urea functionalized hydroxyapatite nanoparticle which is also a rich source of phosphorus with controlled release of nitrogen. However, nanohybrids of this kind so far were only developed for biomedical applications.

7.2.1.2 Micronutrient Nanofertilizers

The nutrients that are required by the plants in less quantity but are equally important for the plant metabolism such as boron (B), chloride (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni) and zinc (Zn) are termed as micronutrients. Zinc oxide (ZnO) nanoparticles, as nanofertilizer, improved the germination, sugar and protein contents and antioxidant activity in cabbage (*Brassica oleracea* var. *capitata* cv. Acre and *B. oleracea* var. *botrytis*) and tomato (*Lycopersicon esculentum* L. cv. Pusa ruby) (Singh et al. 2013). Askary and coworkers (Askary et al. 2016) investigated the impact of nano-iron fertilizer on the physiology of Madagascar periwinkle (*Catharanthus roseus*) with varying concentrations and found that plant growth, pigment composition and total protein contents were significantly improved (Askary et al. 2016). Similarly, Mahmoodi et al. (2017) evaluated the impact of nano-urea and nano-iron fertilizer along with conventional fertilizer on borage (*Borago officinalis* L.) and concluded that only nano-urea improved plant growth and essential oil yield, whereas nano-iron fertilizer increased number of seeds in plants. But all fertilizers, nano-urea and nano-iron fertilizer and conventional fertilizer, were equally effective in improving plant height.

7.2.1.3 Nanoparticulated Fertilizers

Nanoparticulated fertilizers are different from nanoparticulated systems used for the delivery of essential bioactive compounds to the plant directly or indirectly. In case of fertilizers, these nanoparticulated systems may be bases on carbon, silica, based or other organic polymers. Lahiani et al. (2013) reported that application of multi-walled carbon nanotubes (MWCNTs) improved the seed germination and plant growth and development in barley (*Hordeum vulgare*), soybean (*Glycine max*) and maize (*Zea mays*). Abdel-Aziz et al. (2016) evaluated the efficiency of chitosan nanoparticle (polymeric nanoparticle) encapsulating N, P and K for foliar uptake by wheat (*Triticum aestivum*) grown in sandy soil and found improvement in the harvest index, crop index and mobilization index by nanoparticulated fertilizer in comparison to control, non-fertilized and normal fertilized NPK. McGehee et al. (2017) also reported yield enhancement in hydroponically grown tomato with the application of MWCNT improves the production of fruit.

7.2.2 Nanopesticides

In general, a pesticide should be selectively toxic in its nature to the biotic stressors of the crop plants without any effect on plant itself and the symbiotic flora, fauna as well as humans (Hassall 1965). But the extensive use of these pesticides has led to the serious public concerns and environmental pollution. Bioaccumulation is one of the major concerns of the current generation, which emerged due to biomagnifying of persistent organic pollutants (POPs) soon to be considered as persistent toxic substances (PTS) (Kutz et al. 1991). Development of resistance in the target pests' poses another threat for the continuous use of conventional pesticides (Chareonviriyaphap et al. 2013; Soko et al. 2015). These limitations could be overthrown by the exploitation of nanotechnology in engineering various nano-based pesticides or nanopesticides (Chhipa 2017). Some of the commonly used nanopesticides include nanofungicides, nanoherbicides, nanomolluscicides, nanonematicides and nanoparticulated growth regulators (Guang et al. 2013; Cromwell et al. 2014; Oliveira et al. 2015; Pereira et al. 2017; Antonoglou et al. 2018).

The current interest in the use of nanoparticles as agricultural pesticides is based on the fact that these enhance the efficacy and environment and reduce the cost (Zhao et al. 2017; Fig. 7.3). They also noted that for increasing the formulation

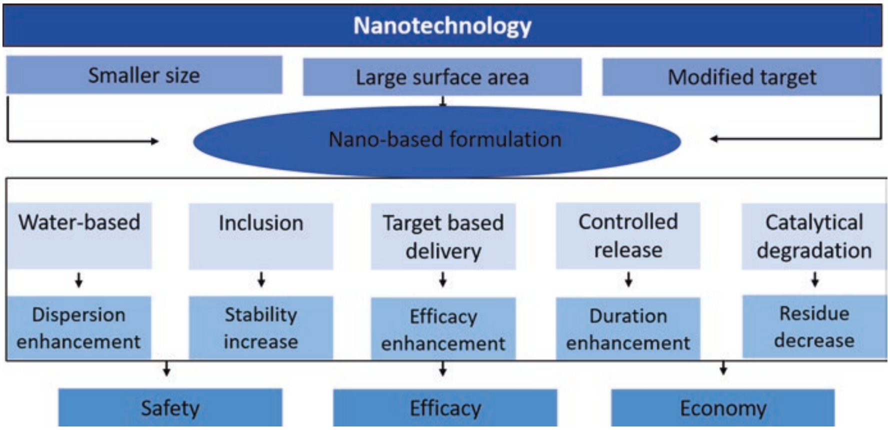

Fig. 7.3 The prospects of nanotechnology where nanopesticides are part. (Adapted from Zhao et al. 2017 with permission)

properties, including water dispersion, chemical stability, targeting adhesion, permeability and controlled release, nanosuspensions, nanoemulsions, nanospheres, nanomicelles and nanocapsules showed great potential, and these are also environmentally sound and eco-friendly (Zhao et al. 2017; Prasad et al. 2019; Fig. 7.4).

Achieving and maintaining environmental sustainability are among the sustainable developmental goals, where efforts to save the environment have been on the spotlight. The use of nanomaterials as agricultural pesticides is based on the underlying nanotechnology that helps to develop systems that protect the environment and plants from hazards by the nano-chemicals. This technology may help attain these objectives through nanocarriers and nanodevices to aid in controlled release and delivery of the content to the targeted site (Huang et al. 2007; Sarlak et al. 2014; Mehrazar et al. 2015). Nanotechnology helps develop nano-based pesticides with controlled release mechanisms (Khot et al. 2012; Mukhopadhyay 2014). The use of nanoparticles in the development of agricultural pesticides may help decrease the residual life in the environment (Karn et al. 2009; Mukhopadhyay 2014; Rani et al. 2017). The most common agricultural nanoparticles are the surfactants and the organic ligands, but various limitations have led to the exploration of other base elements, especially silver (Elek et al. 2010; Du et al. 2011). According to Singh et al. (2013), silica, carbon, silver and aluminium silicate are the potential base ingredients used for the development of nano-pesticides. Use of nanoparticles in pesticide, with less residual life, is illustrated in Fig. 7.5 (Nuruzzaman et al. 2016).

The cellulosic paper and paper-based products are ubiquitous in our daily life. These cellulosic materials may serve as vector of transmission of numerous infectious human diseases (Angelakis et al. 2014). Nano-coating of these useful materials may yield antimicrobial cellulosic paper for safe use and improved packaging materials to enhance shelf life of fruit, vegetables and other agricultural produce. Recently, Islam and co-workers immobilized silver nanoparticles (AgNPs) onto

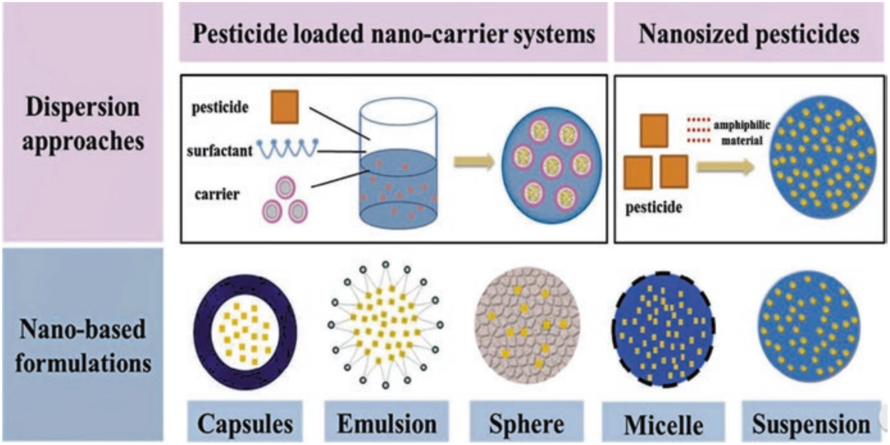

Fig. 7.4 Water-based dispersion pesticide nanoformulation increases the formulation properties. (Adapted from Zhao et al. 2017 with permission)

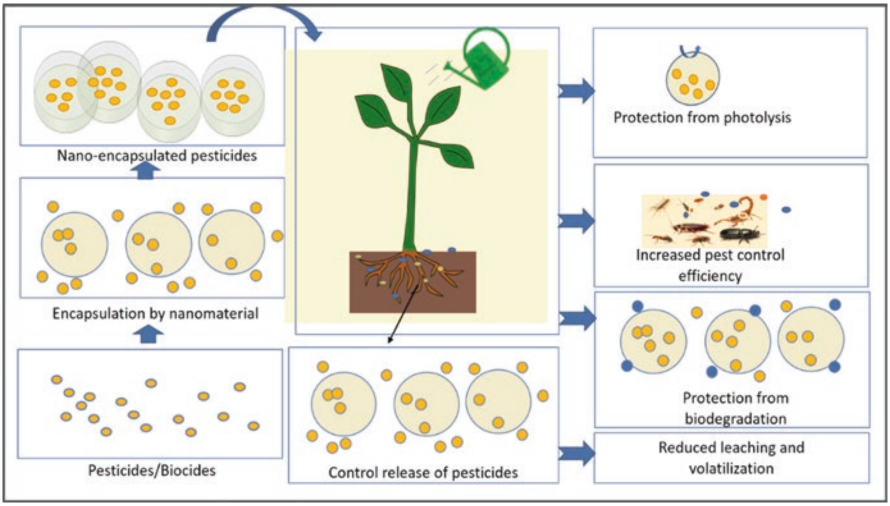

Fig. 7.5 Nanoparticles enable pesticides to reach the targeted areas without biodegrading prematurely. (Adapted from Nuruzzaman et al. 2016 with permission)

dopamine-modified cellulose paper (Fig. 7.6). The AgNP-loaded paper showed excellent antimicrobial activities against some antibiotic-resistant virulent fish pathogenic bacteria such as *Vibrio parahaemolyticus* strains 2A1 and 2A2, *Enterococcus faecalis* strains F1B1 and EF11, *Serratia marcescens* 4 V3 and a disastrous fungal phytopathogen *Magnaporthe oryzae Triticum*. Owing to the high adhesion of the dopamine moiety to nearly all inorganic substances, the novel approach of the preparation of fabricated Ag-DOPA-CP established by Islam et al. (2018; Fig. 7.6) might be extendable to robust immobilization of any other metals

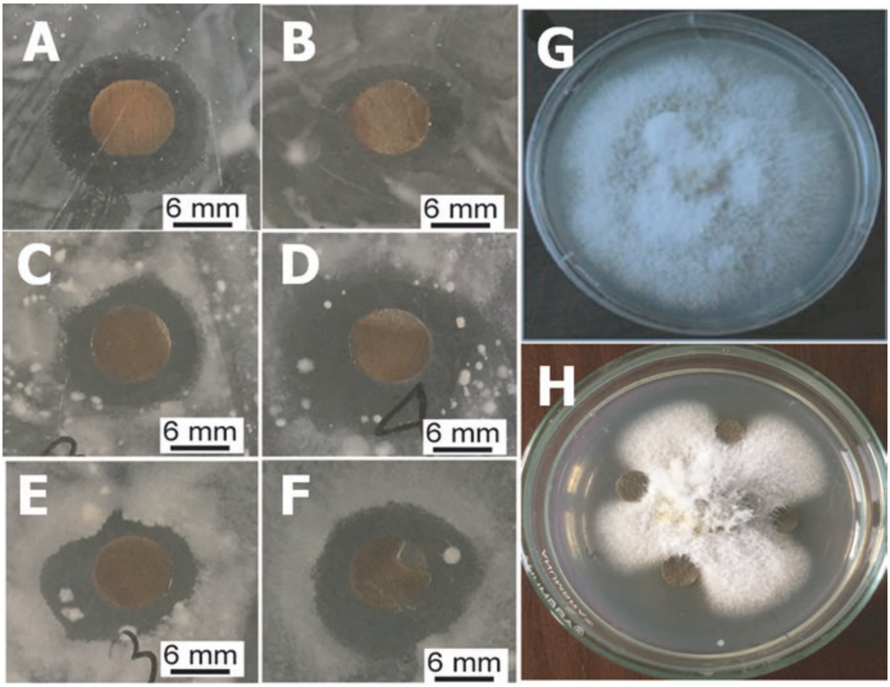

Fig. 7.6 Antimicrobial properties of a synthesized AgNPs anchored papers. (**a**–**f**) Antibacterial activity of Ag-Dopa-CP papers: optical photographs (cropped) of zone of inhibition (ZOI) of Ag-Dopa-CP15m (**a**) and Ag-Dopa-CP8h against *Vibrio parahaemolyticus* strain 2A1 (**b**), *Enterococcus faecalis* strain F1B1 (**c**, **d**) and *Enterococcus faecalis* strain FF11 (**e**, **f**) after 24 h of incubation at 28 °C. (**g**, **h**) Growth of wheat blast fungus *Magnaporthe oryzae Triticum* pathotype without the Ag-Dopa-CP papers (**g**); the growth is strongly inhibited by the Ag-DopaCP15m and Ag-Dopa-CP8h papers (H). (Adapted from Islam et al. 2018 with permission)

and metal oxide nanoparticles onto cellulose paper to explore new applications in numerous paper-based chemical and biological sensors (Ge et al. 2017). The daylight-driven rechargeable antibacterial and antiviral nanofibrous membranes (RNMs) have also been developed by incorporating daylight-active chemicals which can efficiently produce reactive oxygen species (ROS) for controlling bacterial and viral phytopathogens both under dim light and dark conditions (Si et al. 2018). These materials may be used for limited transmission of plant diseases through agricultural equipment for controlling bacterial and viral phytopathogens.

7.2.2.1 Nanofungicides

The fungicides such as cupric salt, dicarboximides, dithiocarbamates, dinitrophenoles, tiabendazoles, triazoles, thiocarbamates and organotin compounds are effective in controlling fungi and protecting fungal diseases. The target specificity of most of the fungicides has yet not been properly determined. However, the mode of action and effect of fungicides on components of the targeted cell membrane, protein translation, DNA replication, signal cascade, metabolic pathways and the phases of cell cycle are known (Yang et al. 2011). The target specificity could be greatly accelerated by amalgamating with nanotechnology. This amalgamation laid the formulation of nanofungicides. Kumar et al. (2016) formulated a nanoform of a commercially available fungicide against *Macrophomina phaseolina* containing 25% trifloxystrobin and 50% tubuconazole. The formulated nanoform had broad spectrum action with an enhanced antifungal activity including malformed hyphae, lysis of the hyphae and malformation of sclerotia in *Macrophomina phaseolina*. Antonoglou et al. (2018) prepared inexpensive Cu-Zn bimetallic nanoparticles against *Saccharomyces cerevisiae* and evaluated their phytotoxicity in phosystem II activity of tomato through chlorophyll fluorescence imaging. They found that the bimetallic nanoformulation had negligible effect on photosystem II of tomato leaf but showed effective antifungal activity against *S. cerevisiae*.

7.2.2.2 Nanoherbicides

Herbicides are substances used in agriculture and landscapes to control unwanted plants. For instance, some of nonselective conventional herbicides include S-ethyl-N, N-dipropyl thiocarbamate, glyphosate, simazine, 4-(2,4-dichlorophenoxy) butyric acid, bromoxynil, diuron, terbacil and hexazinone, whereas 4-dichlorophenoxyacetic acid, paraquat and glyphosate may be categorized as selective herbicides (Rolando et al. 2013). Now the advanced form of herbicides, the nanoherbicides, is slowly taking over the conventional herbicides in laboratory research. For example, a polymeric nanoformulation herbicide consisting of poly(epsilon-caprolactone) and chitosan/tripolyphosphate encapsulating atrazine/paraquat was developed (Grillo et al. 2015). The cytotoxicity and genotoxicity were also determined which showed that the nanoformulation was less toxic than the free herbicides and were much useful in agricultural practices. Similarly, Oliveira et al. (2015) developed poly(epsilon-caprolactone) polymeric nanoparticles loaded with atrazine and determined the post-emergence herbicidal efficiency using mustard greens (*Brassica juncea*). The nanoencapsulated atrazine was more efficient as post-emergence herbicides when applied at lower rate.

7.2.2.3 Nanomolluscicides

To counteract the invasion and damage caused by different species of snails and slugs, various molluscicides including metaldehyde, methiocarb and ferrous phosphate are being used (Abubakar et al. 2017). These commercially available conventional molluscicides have certain limitations such as cost-deficit and nonspecific adverse effect which is the primary concern of the present research and innovation (Coelho and Caldeira 2016). With the advancement of nanotechnology, the hope of developing cost-effective and target-specific nanomolluscicides is no more a dream. Guang et al. (2013) evaluated the toxic effect of green synthesized silver nanoparticles on *Oncomelania hupensis* snails and crucian seedlings. The nanoparticles were toxic to the snails but had negligible toxicity towards crucian seedlings. Omobhude et al. (2017) developed a molluscicidal polymeric nanoparticle of polylactic acid encapsulating curcumine and nisin and tested it against *Biomphalaria pfeifferi*. The nanoformulation was a potent molluscicide in proportion to various stages of development in *B. pfeifferi*.

7.2.2.4 Nanonematicides

There is an urgent need for a novel alternative for the conventional nematicides such as aldicarb, fosthiazate, fenamiphos and oxamyl compounds used to control phytonematodes (Ntalli and Caboni 2012). The toxicity of these nematicides to both human and the environment might also increase due to the increase in expected use (Sánchez-Moreno et al. 2009). The coherent demand for an alternative form of nematicide seems to be positively achieved by an advanced exploration of nanotechnology. The nanonematicide is at the point-blank range of the possible advancement needed to satisfy the urgent demand for novel alternative nematicides. For example, Cromwell et al. (2014) determined the potency of silver nanoparticles against *Maloidogyne graminis* and *M. incognita* in vitro. They demonstrated that the silver nanoparticles are efficient nematicidal. Abdellatif et al. (2016) devised a cutting-edge approach by using green silver nanoparticles as nanonematicide against *M. javanica* infested in tomato and compared the nematicidal efficiency with chemical control of *S. melongena* (Eggplant). They found that the green silver nanoparticles were more effective nematicides in comparison to chemical control of eggplant.

7.2.3 Nanomaterials for Soil Remediation

The transformation of rural areas to urban states is backed up by either establishment of small-scale industries that gradually grows into a setup of mega factories or a multinational corporation, although this transformation hugely benefits to uplift the socioeconomic status of the inhabitants but fails to sustain and conserve the biodiversity. Improper industrial debris disposal severely damages the food chain of the associate floral and faunal community due to contaminated water and soil. Soil and water on the other hand are the basic factor required for sustainable crop production. The contaminants from the water can be precipitate or filtered, but soil on the other side is much more difficult to decontaminate.

Some of the common contaminants sourced from industrial waste include heavy metals such as arsenic (As V, III), lead (Pb), copper (Cu), zinc (Zn), nickel (Ni), cadmium (Cd), radionuclides (uranium and thorium) and organic pollutants such as chlorinated organic compounds (trichloroethylene), petroleum monoaromatics, nitroaromatics and synthetic dyes (Araújoa et al. 2015). The conventional chemical and physical methods available may contribute to secondary contamination due to the use of high quantity of these remediating agents which further poses a limitation for their use (Watson 1996; Yao et al. 2012). On the other hand, the eco-friendly microbial-based soil remediation requires relatively high cost, but outcome may be uncertain (Sharma and Reddy 2004). These drawbacks of conventional chemical-, physical- and microbial-based methods could be eliminated by the utilization of nano-based approaches such as nanofertilizers, nanobiosensors and different nanoremediation processes (Rai et al. 2012; Rizwan et al. 2014; Raliya et al. 2017).

Nanofertilizer, as mentioned above, has immensely influenced the prospect of sustainable agriculture to a greater extent. The serviceability of this novel form of nano-based fertilizer is seen in the form of macronutrient nanofertilizers, micronutrient nanofertilizers and nanoparticulate fertilizers (Chhipa 2017). Under certain nutrient-deficit condition, nanofertilizer of Ca and P hydroxyapatite nanoparticles could be a useful mode of nutrient supply and influence soybean seed yield, and other place nano-urea and nano-iron fertilizer improved growth traits and increased production of essential oil yield of borage (*Borago officinalis* L.) (Liu and Lal 2015; Mahmoodi et al. 2017). A digital/analytical portable device possessing at least a single sensing unit in the nano-dimension which is engineered for monitoring physicochemical variations at locations complicated to reach is regarded as nanosensors (Fraceto et al. 2016). If these digital/analytical portable devices are conjugated to a specific structural feature of single biomolecules such as nucleic acid, protein or carbohydrate, then the devices may also be regarded as nanobiosensors (Yuce and Kurt 2017). Nanobiosensors on the other hand are an exceptional tool for determining the contaminants at a minimum concentration. A nanobiosensor based on grapheme nanoribbon could be used for detection of Mn impurities (Enciu et al. 2014). Salinas et al. (2014) developed a nanosensor for the detection of Ar (argon) by the help of self-assembled monolayers on gold substrate type (III) in an aqueous medium. Nanoremediation is mostly focused on mitigating the impact of harmful contaminants on the environment (Prasad et al. 2017). Specific organic and inorganic compounds such as natural short-ordered aluminosilicate, surface of titanium oxide and humic acids can be coupled with Ni through multiwalled carbon nanotube and serve as an efficient nanobioremediation tool in sustainable agricultural system (Raliya et al. 2013; Prasad et al. 2017).

Industrial wastewater is one of the major sources of contamination of the crop field and waterbodies (Carpenter et al. 1998; Xing et al. 2001; Krishna et al. 2009). Nanoporous carbon has a myriad of application ranging from wastewater purification to gas separation to energy conversion and storage (Diallo and Brinker 2011). Recently, Khan et al. (2018) developed an economically viable and environment-friendly novel strategy for the preparation of nanoporous carbon (NC) from jute. The NC prepared at 800 °C resulted in a high surface area (981 $m^2\ g^{-1}$) associated with the retention of the original fibrous shapes. Industrial application of this novel technology in conversion of jute fibre to the NC would lead to a re-emergence of jute as a black gold in the regional economy.

7.2.4 Nanomaterials for Crop Improvement

Improvement of crops and its production is inversely proportional to the biotic and abiotic stresses. The synthetic pesticides and growth regulators used as a conventional means to mitigate biotic and abiotic stresses further pose additional jeopardy to the sustenance of agriculture. Nanotechnology as previously mentioned can be a verified asset in these conditions. Nanopesticides in the form of nanofungicides, nanoherbicides, nanomolluscicides and nanonematicides are previously been described with example (Guang et al. 2013; Cromwell et al. 2014; Oliveira et al. 2015; Antonoglou et al. 2018). These nano-based products are equipped with a common component that is a nano-based carrier or nanocarrier. Basically, the nanocarriers are categorized as soft and hard nanoparticles (Kah et al. 2018). Polymers, solid lipids and liposomes are considered as soft nanoparticles, and carbon-, silica- and titanium-based nanoparticles and other metallic nanoparticles are considered as hard nanoparticles (Mukhopadhyay 2014; Siafaka et al. 2016; Kah et al. 2018).

In a broad-spectrum nanomaterial-based crop, improvement can also be visualized in various applications such as improved germination of seed and growth of plants, protection of plants from pathogens and precise detection of phytopathogens (Khot et al. 2012; Ismail et al. 2017). Varying doses of silver nanoparticles significantly enhance the rate of seed germination of maize, *Citrullus lanatus* [Thunb.] Matsum. & Nakai (watermelon) and *Cucurbita pepo* L. (pumpkin) by showing slight toxic effect in root elongation of maize (Almutairi and Alharbi 2015). The germination of *Lactuca sativa* (lettuce) seed is also enhanced by the single-capillary electrospraying of TiO_2 nanoparticles (Wu et al. 2014). The nanopriming of *Oryza sativa* L. cv. KDML105 (rice) by a biocompatible silver nanoparticle produced using *Citrus hystrix* D.C. (Kaffir lime) leaf extract significantly improves seed germination and α-amylase activity associated with seedling growth and stimulates upregulation of aquaporin genes (Mahakham et al. 2017). Protection of plants from pathogens have been described above where nanoform of fungicide containing trifloxystrobin and tubuconazole against *Macrophomina phaseolina* and Cu-Zn bimetallic nanoparticles against *Saccharomyces cerevisiae* (Kumar et al. 2016; Antonoglou et al. 2018). Silver nanoparticulated molluscicide against *Oncomelania hupensis* snails and polylactic acid encapsulating curcumin-nisin against *Biomphalaria pfeifferi* (Guang et al. 2013; Omobhude et al. 2017). Crop production could further be enhanced by an efficient detection of the disease. Nanotechnology-based approaches could be the useful tools for this important task. Nano-based biosensors, nanoparticulated systems, nanoimaging and nanopore DNA sequencing tools have tremendously enhanced accuracy, persistence and time duration of pathogen detection and upgradation of high-throughput instrumentation for quality detection of plant pathogens (Khiyami et al. 2014). Recently, quantum dots having versatile surface chemistry, bright fluorescence and negligible photobleaching effect could easily cross plant cell wall pores and might be useful in detection of biotic and abiotic stresses (Wu et al. 2017).

7.3 Effect of Nanomaterials on Soil, Water and Environmental Health and Crop Productivity

7.3.1 Soil, Water and Environmental Health

To meet the growing demand of food for increasing population under the limiting natural resource, agencies and research institutes involved in food security (FAO 2009) are encouraging "sustainable crop intensification". Among the emerging technologies for addressing new challenges in crop production under the changing climate, nanotechnology is emerging as a potential frontier technology to promote sustainable productivity in agriculture. It can be used for remediation of deteriorated environment and also precisely detection of environmental pollutants (Neethirajan and Jayas 2011). Application of nanomaterials such as nanofertilizers, nanopesticides, nanocarriers, nanosensors, nano-packaging and nano-chips is revolutionized in the current agricultural production system. Nanotechnology could promote precision and smooth agriculture and significantly reduce production and postharvest losses in crop production system (Gruere et al. 2013). It is environmentally sound as it can reduce the bulk use of pesticide by adding nano-silver particles to pesticides. The use of nanometal oxides to target soil pathogens and adding metallic nanomaterials such as nanosilicon to increase water uptake efficiency in plants are considered highly promising nanotechnology in agriculture (Servin et al. 2015). The use of synthetic clay nanomineral and zinc oxide nanoparticles for arsenic removal seems useful in water purification device (Clare e al. 2011). The water to be filtered is percolated through a column of hydrotalcite (synthetic clay mineral) (Prasad et al. 2014). The development of a DNA-based nanobiosensor in a polymer to coat fertilizers would release only as much fertilizer as "demanded" by plant root ionic signals (Gautam et al. 2014; Prasad et al. 2014). Similarly, nanoscale zerovalent iron could be remediated pollutants from soil or groundwater and is the most widely used nanomaterials for water purification in the world (Li et al. 2006). Other potential nanomaterials for remediation include nanoscale zeolites, metal oxides, carbon nanotubes and fibres, enzymes, various noble metals (mainly as bimetallic nanoparticles) and titanium dioxide. Nanoparticle filters such as dichorodiphenyltrichloroethane (DDT), endosulfan, malathion and chlor-pyrifos) can be used to remove organic particles and pesticides from water (Pradeep 2012; Bootharaju and Pradeep 2012; Ul-Islam et al. 2012; Thatai et al. 2014).

However, exceptionally, nanoparticles might cause some impulsive contrary effects on agricultural productivity, soil health and ecosystem (Brumfiel 2003; Service 2003; Zhang 2003; Kelly 2004). The applied nanoparticles will gather over time in soils and water environment (Boxall et al. 2007; Gottschalk et al. 2009). Some nanoparticles such as fertilizers and pesticides may flow into food chain through the environmental systems that threaten human health and ecosystem (Zhao et al. 2017). Hence, for avoiding the risk, investigation might be established on safety and risk assessments of nanopesticides. Investigation related to the toxic effect of nanoparticles and the interaction between nanoparticles and plants will provide a theoretical basis of knowledge for the development of nanopesticides for sustainable implementation of nanotechnology in agriculture (Zhao et al. 2017), while nanopesticides can accelerate the catalytic degradation of toxic residues as well as reduce the pesticides residual effect on the soil and water environment through introducing biodegradable carriers' material and adding photocatalysts (Pierluigi et al. 2003; Zhao et al. 2017; Fig. 7.7).

7.3.2 *Crop Productivity*

Efficient crop productivity is a direct result of proper management of plant growth under diverse physiological and biological stresses. Nanomaterials may have strong impact on the management and sustenance of plant growth under biotic and abiotic stresses. The effect of applied nanomaterials varies based on stress condition, quantity and the type of nanometerials used (Siddiqui et al. 2015). For example, soft/organic nanomaterials such as polymer and solid lipid nanoparticles and metallic nanoparticles and carbon-, silica- and titanium-based nanoparticles are considered hard/inorganic nanoparticles being evaluated for their use in sustainable agriculture (Kah et al. 2018).

The insecticidal activity of polycaprolactone and polylactic acid nanosphere loaded with ethiprole had better penetration in comparison to reference formulation (Boehm et al. 2003). With growing knowledge of nanoscience, stimulation and

Fig. 7.7 Nanopesticides accelerate the catalytic degradation of toxic residues as a biosafety. (Adapted from Zhao et al. 2017 with permission)

control of nanoparticulated system based on the targets are quite possible (Gogos et al. 2012). While reviewing the controlled release efficiency of imidacloprid (1-(6 chloro-3-pyridinyl methyl)-N-nitro imidazolidin-2-ylideneamine) encapsulated in polyethylene glycol, Sekhon (2014) inferred that these were quite effective against *Melanagromyza sojae* Zehntmer and *Bemisia tabaci* Gennadius. Lipid-based nanometerials can also be effective in sustainable crop production systems (Naseri et al. 2015). Two herbicides, namely, atrazine and simazine, encapsulated by solid lipid nanomaterial were effective against wild radish (*Raphanus raphanistrum*) in maize with no adverse effect on the crop (de Oliveira et al. 2015).

Hard/inorganic nanoparticles are equally important in crop production systems. The silicon dioxide (SiO_2) nanoparticles can help improve seed germination, plant growth and yield formation in tomato, Olgan larch (*Larix olgensis*) and maize. These nanoparticles also stimulated the seed germination of tomato and squash and antioxidant system (Siddiqui et al. 2015). Carbon-based nanomaterials are more extensively used for disease treatment and diagnostics in animals. But recently they are also being used in crop production. Many molecules such as nano-onions, nanohorns, nano-cones, nanodots, nanotubes, nano-beads, nanofibres, nanodiamonds, fullerenes and graphene are included under the family of carbon nanomaterials (Mukherjee et al. 2016). The interaction of nanomaterials with bioactive compounds results in altered gene expression, DNA damage and increased oxidative damage (Zaytseva and Neumann 2016). However, certain carbon-based materials such as *s*-multiwalled carbon nanotube (*s*MWCNT) may improve seed germination by induction of perforation of the seed coat in *Salvia macrosiphon*, peppers (*Capsicum annuum*) and tall fescue (*Festuca arundinacea*) (Pourkhaloee et al. 2011; Zaytseva and Neumann 2016). Thus, application of nanomaterials has great scope for improvement in crop productivity; however, some nanomaterials may have toxic effects on nontargeted organisms. Therefore, a cautious selection of nanomaterials with specific action is needed for a sustainable crop production.

7.4 Constraints in the Use of Nanotechnology in Crop Production Systems

Every new technology has some limitations of its use. One of the constraints of using nanomaterials in agriculture is nanotoxicity. Although many nanomaterials have shown high promise as nanopesticides, a large proportion of them showed toxicity to the nontargeted organisms. The fate and dispersion/transport of synthesized nanoparticles in the environment critically depend on plants which are an indispensable constituent of our ecosystem (Xingmao et al. 2010). It has also been speculated that plant uptake and bioaccumulation of nanoparticles may also alter gene expression, DNA damage and increased oxidative damage (Xingmao et al. 2010; Zaytseva and Neumann 2016). Therefore, specificity of the activity of nanomaterials is a prerequisite of its larger use in agriculture and environment.

The probable mechanism of emergence of nanotoxicity in plants may initiate from low degradation rate and prolonged adherence of the nanoparticle to the shoot through nanopesticides or root through nanofertilizer. In root, the nanoparticles first must reach vascular tissue (xylem) making their way through thick cell wall and plasma membrane of epidermal layer in order to be properly dispersed throughout plant system (Xingmao et al. 2010). One of the important foci of research is to understand the mode of action of the nanomaterials and explore their effects on nontargeted organisms. Another important focus of research is the application method of nanoparticles as pesticide which is still challenging and could be supplemented with a sophisticated method for developing broad spectrum nanocarriers. Active ingredients with a wide range of efficiency determine intrinsic factors like rate degradation of nanocarriers in the environment. This could determine the rate of releasing of active ingredients and availability of active ingredients for their pesticidal effect (Kah et al. 2018).

Nanofertilizer as macronutrient nanofertilizers, micronutrient nanofertilizers and nanoparticulate fertilizers are currently experimented for their use, and some of them are already in the market (Chhipa 2017). Recently, it has been observed that nanofertilizer shows low mobility and low rate of degradability (Kah et al. 2018). This stagnancy may further lead to deposition of the nano-based micronutrients, the excess of which may lead to nanoaccumulation and nanotoxicity (Chhipa 2017; Kah et al. 2018). These constraints could be mitigated when more advanced form of nanoformulations, like functionalized or tuned nanocarriers, will be used. These carriers could be triggered by control release of the nanoparticulated systems which is achieved either by intracellular (pH, ATP, GSH, enzyme, glucose and H_2O_2) or exogenous (temperature, light, magnetic field, ultrasound and electricity) stimuli (Song et al. 2017). These forms of nanocarriers are already more extensively used and evaluated in the biomedical sciences for various serious and life-threatening diseases. By regulating and modulating certain synthesis parameters, these nanocarriers might be used for sustainable agricultural developments. But the agricultural research using these concepts is scanty; therefore, further detailed and extensive research is essential requirement to develop more efficient nanoformulation for sustainable agricultural development.

7.5 Conclusion and Future Research Thrusts

Nanotechnology has contributed a lot in electronics, energy generation, drug delivery, and disease diagnosis. This technology has great scope and application for sustainable climate resilient and smart crop production systems as well. The nanomaterials can be used to develop nanofertilizers, nanopesticides, nanocarriers, nanosensors, nano-packaging and nano-chips to improve the crop productivity and resource use efficiency through significant reduction in production cost and postharvest losses. The use of nanomaterials may help reduce the amount of sprayed agrochemicals by smart delivery of active ingredients, minimize nutrient losses in fertilization and increase yields through optimized water and nutrient management. Using nanosensors in the application of water, nutrients and chemicals may help further reduce production cost and environmental concerns. Nanomaterials may also be used for the improvement of soil water retention. Nanotechnology-led innovations are also being used in plant improvement and genomic transformation programs. Nonetheless, like other synthetic agrochemicals, unwise and indiscriminate use of nanomaterials may have deleterious impacts on the environment. Therefore, research-based, wise application of nanotechnology is needed for sustainability of environment and crop production systems.

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References

Abdel-Aziz HMM, Hasaneen MNA, Omer AM (2016) Nano chitosan-NPK fertilizer enhances the growth and productivity of wheat plants grown in sandy soil. Span J Agric Res 14(1):e0902. https://doi.org/10.5424/sjar/2016141-8205

Abdellatif KF, Abdelfattah RH, El-Ansary MSM (2016) Green nanoparticles engineering on root-knot nematode infecting eggplants and their effect on plant DNA modification. Iran J Biotechnol 14(4):250–259

Abubakar A, Bala AY, Singh K (2017) Plant molluscicides and their modes of action: a review. Int J Sci Res Technol 2(1):37–49

Ahmed S, Ahmad M, Swami BL, Ikram S (2016) A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: a green expertise. J Adv Res 7(1):17–28

Ali MA, Rehman I, Iqbal A, Din S, Rao AQ, Latif A, Samiullah TR, Azam S, Husnain T (2014) Nanotechnology, a new frontier in agriculture. Adv Life Sci 1(3):129–138

Almutairi ZM, Alharbi A (2015) Effect of silver nanoparticles on seed germination of crop plants. Int J Nucl Quantum Engg 9(6):594–598

Angelakis E, Azhar EI, Bibi F, Yasir M, Al-Ghamdi AK, Ashshi AM, Elshemi AG, Raoult D (2014) Paper money and coins as 772 potential vectors of transmissible disease. Future Microbiol 9(773):249–261

Antonoglou O, Moustaka J, Adamakis ID, Sperdouli I, Pantazaki AA, Moustakas M, Dendrinou-Samara C (2018) Nanobrass CuZn nanoparticles as foliar spray nonphytotoxic fungicides. ACS Appl Mater Interfaces 10(5):4450–4461

Araújoa R, Castrob ACM, Fiúza A (2015) The use of nanoparticles in soil and water remediation processes. Mater Today: Proceed 2:315–320

Askary M, Amirjani MR, Saberi T (2016) Comparison of the effects of nano-iron fertilizer with iron-chelate on growth parameters and some biochemical properties of *Catharanthus roseus*. J Plant Nutr 40(7):974–982

Bhardwaj D, Ansari MW, Sahoo RK, Tuteja N (2014) Biofertilizers function as key player in sustainable agriculture by improving soil fertility, plant tolerance and crop productivity. Microbiol Cell Fact 13:66. https://doi.org/10.1186/1475-2859-13-66

Bhateria R, Jain D (2016) Water quality assessment of lake water: a review. Sust Water Resour Manage 2(2):161–173

Boehm AL, Martinon I, Zerrouk R, Rump E, Fessi H (2003) Nanoprecipitation technique for the encapsulation of agrochemical active ingredients. J Microencapsul 20(4):433–441

Bootharaju MS, Pradeep T (2012) Understanding the degradation pathway of the pesticide, chlorpyrifos by noble metal nanoparticles. Langmuir 28(5):2671–2679
Boxall AB, Tiede K, Chaudhry Q (2007) Engineered nanomaterials in soils and water: how do they behave and could they pose a risk to human health? Nanomedicine 2:919–927
Brumfiel G (2003) Nanotechnology: a little knowledge. Nature 424:246–248
Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN, Smith VH (1998) Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol Appl 8(3):559–568
Chareonviriyaphap T, Bangs MJ, Suwonkerd W, Kongmee M, Corbel V, Ngoen-Klan R (2013) Review of insecticide resistance and behavioural avoidance of vectors of human diseases in Thailand. Parasitol Vectors 6:280. https://doi.org/10.1186/1756-3305-6-280
Chhipa H (2017) Nanofertilizers and nanopesticides for agriculture. Environ Chem Lett 15(1):15–22
Chhipa H, Joshi P (2016) Nanofertilisers, nanopesticides and nanosensors in agriculture. In: Ranjan S, Dasgupta N, Lichtfouse E (eds) Nanoscience in food and agriculture, vol 1. Sustainable Agriculture Reviews. Springer, Cham, pp 247–282
Coelho P, Caldeira R (2016) Critical analysis of molluscicide application in schistosomiasis control programs in Brazil. Infect Dis Poverty 5:57. https://doi.org/10.1186/s40249-016-0153-6
Clare N, Linda A, Guillaume G (2011) Agricultural, food, and water nanotechnologies for the poor: opportunities, constraints, and role of the consultative group on international agricultural research. The International Food Policy Research Institute, Washington, DC
Cromwell WA, Yang J, Starr JL, Jo YK (2014) Nematicidal effects of silver nanoparticles on root-knot nematode in bermudagrass. J Nematol 46(3):261–266
Das DK, Mandal M (2015) Advanced technology of fertilizer uses for crop production. In: Sinha S, Pant KK, Bajpai S (eds) Fertilizer technology, vol 1. Synthesis. Studium Press LLC, Houston, pp 19–67
De A, Bose R, Kumar A, Mozumdar S (2014) Targeted delivery of pesticides using biodegradable polymeric nanoparticles. Springer, New Delhi
DeRosa MC, Monreal C, Schnitzer M, Walsh R, Sultan Y (2010) Nanotechnology in fertilizers. Nat Nanotechnol 5(2):91. https://doi.org/10.1038/nnano.2010.2
Diallo M, Brinker CJ (2011) Nanotechnology for sustainability: environment, water, food, minerals, and climate. In: Roco MC, Hersam MC, Mirkin CA (eds) Nanotechnology research directions for societal needs in 2020. Springer, Dordrecht, pp 221–259
Dimetry NZ, Hussein HM (2016) Role of nanotechnology in agriculture with special reference to pest control. Int J Pharm Technol Res 9:121–144
Dimkpa CO, Bindraban PS (2017) Nanofertilizers: new products for the industry? J Agric Food Chem 66(26):6462–6473
Ditta A, Arsha M, Ibrahim M (2015) Nanoparticles in sustainable agricultural crop production: applications and perspectives. In: Siddiqui M, Al-Whaibi M, Mohammad F (eds) Nanotechnology and plant sciences. Springer, Cham, pp 55–75
Dong W, Zhang X, Wang H, Dai X, Sun X, Qiu W, Yang F (2012) Effect of different fertilizer application on the soil fertility of paddy soils in red soil region of southern China. PLoS One 7(9):e44504. https://doi.org/10.1371/journal.pone.0044504
Du W, Sun Y, Ji R, Zhu J, Wu J, Guo H (2011) TiO_2 and ZnO nanoparticles negatively affect wheat growth and soil enzyme activities in agricultural soil. J Environ Monitor 13(4):822–828
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
Elek N, Hoffman R, Raviv U, Resh R, Ishaaya I, Magdassi S (2010) Novaluron nanoparticles: formation and potential use in controlling agricultural insect pests. Coll Surfaces A: Physicochem Engg Aspects 372(1–3):66–72
Enciu D, Toader A, Ursu I (2014) Magnetic field nanosensor based on Mn impurities. Incas Bulletin 6(2):51–60
FAO (2017) The future of food and agriculture – trends and challenges. Food and Agriculture Organization, Rome

FAO (Food and Agriculture Organization) (2009). Sustainable crop production intensification. Available at http://www.fao.org/agriculture/crops/core-themes/theme/spi/scpi-home/framework/sustainable-intensification-in-fao/en/. Accessed 27 July 2018

Fraceto LF, Grillo R, de Medeiros GA, Scognamiglio V, Rea G, Bartolucci C (2016) Nanotechnology in agriculture: which innovation potential does it have? Front Environ Sci 4:20. https://doi.org/10.3389/fenvs.2016.00020

Gautam RK, Mudhoo A, Lofrano G, Chattopadhyaya MC (2014) Biomass-derived biosorbents for metal ions sequestration: adsorbent modification and activation methods and adsorbent regeneration. J Environ Chem Engg 2(1):239–259

Ge S, Zhang L, Zhang Y, Lan F, Yan M, Yu J (2017) Nanomaterials-modified cellulose paper as a platform for biosensing applications. Nanoscale 9(13):4366–4382

Gogos A, Knauer K, Bucheli TD (2012) Nanomaterials in plant protection and fertilization: current state, foreseen applications, and research priorities. J Agric Food Chem 60(39):9781–9792

Gottschalk F, Sonderer T, Scholz RW, Nowack B (2009) Modelled environmental concentrations of engineered nanomaterials (TiO_2, ZnO, ag, CNT, fullerenes) for different regions. Environ Sci Technol 43:9216–9222

Grillo R, Oliveira HC, Lima R, Fraceto LF (2015) Polymeric nanoparticles as carrier systems for herbicides. J Nanomed Nanotechnol 6(4). https://doi.org/10.4172/2157-7439.S1.022

Gruere G, Narrod C, Abbott L (2013) Agriculture, food, and water nanotechnologies for the poor opportunities and constraints. International Food Policy Research Institute (IFPRI), Washington, DC

Guang XY, Wang JJ, He ZG, Chen GX, Ding L, Dai JJ, Yang XH (2013) Molluscicidal effects of nano-silver biological molluscicide and niclosamide. Zhongguo Xue Xi Chong Bing Fang Zhi Za Zhi 25(5):503–505

Hassall KA (1965) Pesticides: their properties, uses and disadvantages: part I: general introduction; insecticides and related compounds. British Vet J 121(3):105–118

Halford B (2005) Nano dictionary. Chem Engg News 83(15):31

Hornyak GL, Dutta J, Tibbals HF, Rao AK (2008) Introduction to nanoscience and nanotechnology. CRC Press, Boca Raton, p 1640. https://doi.org/10.1201/9781420047806

Huang J, Li Q, Sun D, Lu Y, Su Y, Yang X, Wang H, Wang Y, Shao W, He N, Hong J (2007) Biosynthesis of silver and gold nanoparticles by novel sundried *Cinnamomum camphora* leaf. Nanotechnology 18(10):105104. https://doi.org/10.1088/0957-4484/18/10/105104

Iqbal M, Li C, Jiang B, Hossain MSA, Islam MT, Henzie J, Yamauchi Y (2017) Tethering mesoporous Pd nanoparticles to reduced graphene oxide sheets forms highly efficient electrooxidation catalysts. J Mater Chem A 5:21249–21256

Ismail M, Prasad R, Ibrahim AIM, Ahmed ISA (2017) Modern prospects of nanotechnology in plant pathology. In: Nanotechnology (eds. Prasad R, Kumar M, Kumar V), Springer Nature Singapore Pte Ltd. 305–317

Islam MS, Akter N, Rahman MM, Shi C, Islam MT, Zeng H, Azam MS (2018) Mussel-inspired immobilization of silver nanoparticles toward antimicrobial cellulose paper. ACS Sustain Chem Engg 6(7):9178–9188

Jin R (2012) The impacts of nanotechnology on catalysis by precious metal nanoparticles. Nanotechnol Rev 1(1):31–56

Jhanzab HM, Razzaq A, Jilani G, Rehman A, Hafeez A, Yasmeen F (2015) Silver nano-particles enhance the growth, yield and nutrient use efficiency of wheat. Int J Agron Agri Res 7(1):15–22

Jiang B, Li C, Dag O, Abe H, Takei T, Imai T, Hossain MSA, Islam MT, Wood K, Henzie J, Yamauchi Y (2017) Mesoporous metallic rhodium nanoparticles. Nat Commun 8:15581. https://doi.org/10.1038/ncomms15581

Jie H, Jose RP, Jorge LG (2013) Nanomaterials in agricultural production: benefits and possible threats? Sustainable nanotechnology and the environment: advances and achievements. American Chemical Society, USA, pp 73–90

Kah M, Kookana RS, Gogos A, Bucheli TD (2018) A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. Nat Nanotechnol 13:677–684

Karn B, Kuiken T, Otto M (2009) Nanotechnology and in situ remediation: a review of the benefits and potential risks. Environ Health Persp 117(12):1813. https://doi.org/10.1289/ehp.0900793
Khan JH, Lin J, Young C, Matsagar BM, Wu KC, Dhepe PL, Islam MT, Rahman M, Shrestha LK, Alshehri SM, Ahamad T (2018) High surface area nanoporous carbon derived from Bangladeshi jute. Mater Chem Phys 216(1):491–495
Khiyami MA, Almoammar H, Awad YM, Alghuthaymi MA, Abd-Elsalam KA (2014) Plant pathogen nanodiagnostic techniques: forthcoming changes? Biotechnol Biotechnol Equip 28(5):775–785
Khot LR, Sankaran S, Maja JM, Ehsani R, Schuster EW (2012) Applications of nanomaterials in agricultural production and crop protection: a review. Crop Prot 35:64–70
Kelly KL (2004) Nanotechnology grows up. Science 304:1732–17345
Kottegoda N, Sandaruwan C, Priyadarshana G, Siriwardhana A, Rathnayake UA, Arachchige DMB, Kumarasinghe AR, Dahanayake D, Karunaratne V, Amaratunga GA (2017) Urea-hydroxyapatite nanohybrids for slow release of nitrogen. ACS Nano 11(2):1214–1221
Krishna AK, Satyanarayanan M, Govil PK (2009) Assessment of heavy metal pollution in water using multivariate statistical techniques in an industrial area: a case study from Patancheru, Medak District, Andhra Pradesh, India. J Hazard Mater 167(1–3):366–373
Kumar GD, Natarajan N, Nakkeeran S (2016) Antifungal activity of nanofungicide Trifloxystrobin 25% + Tebuconazole 50% against *Macrophomina phaseolina*. Afr J Microbiol Res 10(4):100–105
Kumar M, Shamsi TN, Parveen R, Fatima S (2017) Application of nanotechnology in enhancement of crop productivity and integrated pest management. In: Prasad R, Kumar M, Kumar V (eds) Nanotechnology. Springer, Singapore, pp 361–371
Kutz FW, Wood PH, Bottimore DP (1991) Organochlorine pesticides and polychlorinated biphenyls in human adipose tissue. Rev Environ Contam Toxicol 120:1–82
Lahiani MH, Dervishi E, Chen J, Nima Z, Gaume A, Biris AS, Khodakovskaya MV (2013) Impact of carbon nanotube exposure to seeds of valuable crops. ACS Appl Mater Interf 5(16):7965–7973
Li XQ, Elliott DW, Zhang WX (2006) Zero-valent iron nanoparticles for abatement of environmental pollutants: materials and engineering aspects. Crit Rev Solid State Mater Sci 31(4):111–122
Liu R, Lal R (2015) Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. Sci Total Environ 514:131–139
Mahakham W, Sarmah AK, Maensiri S, Theerakulpisut P (2017) Nanopriming technology for enhancing germination and starch metabolism of aged rice seeds using phytosynthesized silver nanoparticles. Sci Rep 7:8263. https://doi.org/10.1038/s41598-017-08669-5
Mahmoodi P, Yarnia M, Amirnia R, Tarinejad A, Mahmoodi H (2017) Comparison of the effect of nano urea and nono iron fertilizers with common chemical fertilizers on some growth traits and essential oil production of *Borago officinalis* L. Dairy Vet Sci J 2(2):555585. https://doi.org/10.19080/JDVS.2017.02.555585
Manjunatha SB, Biradar DP, Aladakatti YR (2016) Nanotechnology and its applications in agriculture: a review. J Farm Sci 29(1):1–13
McGehee DL, Lahiani MH, Irin F, Green MJ, Khodakovskaya MV (2017) Multiwalled carbon nanotubes dramatically affect the fruit metabolome of exposed tomato plants. ACS Appl Mater Interfaces 9(38):32430–32435
Mehrazar E, Rahaie M, Rahaie S (2015) Application of nanoparticles for pesticides, herbicides, fertilisers and animals feed management. Int J Nanopart 8(1):1–9
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 8:13001. https://doi.org/10.1088/2043-6254/8/1/013001
Mukhopadhyay SS (2014) Nanotechnology in agriculture: prospects and constraints. Nanotechnol Sci Appl 7:63–71

Mukherjee A, Majumdar S, Servin AD, Pagano L, Dhankher OP, White JC (2016) Carbon nanomaterials in agriculture: a critical review. Front Plant Sci 7:172. https://doi.org/10.3389/fpls.2016.00172

Nakache E, Poulain N, Candau F, Orecchioni AM, Irache JM (1999) Biopolymer and polymer nanoparticles and their biomedical applications. In: Nalwa HS (ed) Handbook of nanostructured materials and nanotechnology. Academic Press, New York, p 3461

Naseri N, Valizadeh H, Zakeri-Milani P (2015) Solid lipid nanoparticles and nanostructured lipid carriers: structure, preparation and application. Adv Pharm Bull 5(3):305–313

Neethirajan S, Jayas DS (2011) Nanotechnology for the food and bioprocessing industries. Food Bioproc Technol 4(1):39–47

Ntalli NG, Caboni P (2012) Botanical nematicides: a review. J Agric Food Chem 60(40):9929–9940

Nuruzzaman M, Rahman MM, Liu Y, Naidu R (2016) Nanoencapsulation, nano-guard for pesticides: a new window for safe application. J Agric Food Chem 64(7):1447–1483

de Oliveira JL, Campos EVR, da Silva CMG, Pasquoto T, Lima R, Fraceto LF (2015) Solid lipid nanoparticles co-loaded with simazine and atrazine: preparation, characterization, and evaluation of herbicidal activity. J Agric Food Chem 63(2):422–432

Oliveira HC, Stolf-Moreira R, Martinez CBR, Grillo R, de Jesus MB, Fraceto LF (2015) Nanoencapsulation enhances the post-emergence herbicidal activity of atrazine against mustard plants. PLoS One 10(7):e0132971. https://doi.org/10.1371/journal.pone.0132971

Omobhude ME, Morenikeji OA, Oyeyemi OT (2017) Molluscicidal activities of curcumin-nisin polylactic acid nanoparticle on *Biomphalaria pfeifferi*. PLoS Negl Trop Dis 11(8):e0005855. https://doi.org/10.1371/journal.pntd.0005855

Ouda SM (2014) Antifungal activity of silver and copper nanoparticles on two plant pathogens, *Alternaria alternata* and *Botrytis cinerea*. Res J Microbiol 9(1):34–42

Pandey S, Giri K, Kumar R, Mishra G, Rishi RR (2016) Nanopesticides: opportunities in crop protection and associated environmental risks. Proceed Nat Acad Sci India Sec B Biol Sci 2016:1–22

Parisi C, Vigani M, Rodríguez-Cerezo E (2015) Agricultural nanotechnologies: what are the current possibilities? Nano Today 10(2):124–127

Park HJ, Kim SH, Kim HJ, Choi SH (2006) A new composition of nanosized silica-silver for control of various plant diseases. Plant Pathol J 22:25–34

Pereira AES, Sandoval-Herrera IE, Zavala-Betancourt SA, Oliveira HC, Ledezma-Pérez AS, Romero J, Fraceto LF (2017) γ-Polyglutamic acid/chitosan nanoparticles for the plant growth regulator gibberellic acid: characterization and evaluation of biological activity. Carbohydr Polym 157:1862–1873

Pierluigi C, Robert ES, John EC (2003) Phenylpyrazole insecticide photochemistry, metabolism and GABAergic action: ethiprole compared with fipronil. J Agri Food Chem 51:7055–7061

Pourkhaloee A, Haghighi M, Saharkhiz MJ, Jouzi H, Doroodmand MM (2011) Carbon nanotubes can promote seed germination via seed coat penetration. Seed Technol 33:155–169

Pradeep T (2012) Noble metal nanoparticles for water purification: a critical review. Thin Solid Films 517(24):6441–6478

Prasad R, Kumar V, Prasad KS (2014) Nanotechnology in sustainable agriculture: present concerns and future aspects. Afr J Biotechnol 13(6):705–713

Prasad R, Bhattacharyya A, Nguyen QD (2017) Nanotechnology in sustainable agriculture: recent developments, challenges, and perspectives. Front Microbiol 8:1014. https://doi.org/10.3389/fmicb.2017.01014

Prasad R, Kumar V, Kumar M, Choudhary D (2019) Nanobiotechnology in Bioformulations. Springer International Publishing (ISBN 978-3-030-17061-5) https://www.springer.com/gp/book/9783030170608

Rai V, Acharya S, Dey N (2012) Implications of nanobiosensors in agriculture. J Biomater Nanobiotechnol 3:315–324

Rani M, Shanker U, Jassal V (2017) Recent strategies for removal and degradation of persistent and toxic organochlorine pesticides using nanoparticles: a review. J Environ Manag 190:208–2022

Raliya R, Tarafdar JC, Gulecha K, Choudhary K, Ram R, Mal P, Saran RP (2013) Scope of nanoscience and nanotechnology in agriculture. J Appl Biol Biotechnol 1:41–44
Raliya R, Saharan V, Dimkpa C, Biswas P (2017) Nanofertilizer for precision and sustainable agriculture: current state and future perspectives. J Agric Food Chem 66(26):6487–6503
Rizwan MD, Singh M, Mitra CK, Morve RK (2014) Eco-friendly application of nanomaterials: Nanobioremediation. J Nanopart 431787(7). https://doi.org/10.1155/2014/431787
Rolando CA, Garrett LG, Baillie BR, Wat MS (2013) A survey of herbicide use and a review of environmental fate in New Zealand planted forests. New Zealand J Forest Sci 43:17. https://doi.org/10.1186/1179-5395-43-17
Sánchez-Moreno S, Alonso-Prados E, Alonso-Prados JL, García-Baudín JM (2009) Multivariate analysis of toxicological and environmental properties of soil nematicides. Pest Manag Sci 65(1):82–92
Sargent Jr JF (2011) Nanotechnology and environmental health and safety: issues for consideration. CRS Report for Congress, Congressional Research Service, 7-5700, www.crs.gov, RL34614, p 37
Sarlak N, Taherifar A, Salehi F (2014) Synthesis of nanopesticides by encapsulating pesticide nanoparticles using functionalized carbon nanotubes and application of new nanocomposite for plant disease treatment. J Agric Food Chem 62(21):4833–4838
Salinas S, Mosquera N, Yate L, Coy E, Yamhure G, González E (2014) Surface plasmon resonance nanosensor for the detection of arsenic in water. Sens Transducers 183(12):97–102
Sastry RK, Rashmi HB, Rao NH (2011) Nanotechnology for enhancing food security in India. Food Policy 36(3):391–400
Scrinis G, Lyons K (2007) The emerging nano-corporate paradigm: nanotechnology and the transformation of nature, food and Agri-food systems. J Sci Food Agric 15:22–44
Sekhon BS (2014) Nanotechnology in Agri-food production: an overview. Nanotechnol Sci Appl 7:31–53
Sempeho SI, Kim HT, Mubofu E, Hilonga A (2014) Meticulous overview on the controlled release fertilizers. Adv Chem 363071:16. https://doi.org/10.1155/2014/363071
Servin A, Elmer W, Mukherjee A, De La Torre-Roche R, Hamdi H, White JC, Bindraban P, Dimkpa C (2015) A review of the use of engineered nanomaterials to suppress plant disease and enhance crop yield. J Nanopart Res 117(2):92. https://doi.org/10.1007/s11051-015-2907-7
Service RF (2003) Nanomaterials show signs of toxicity. Science 300:243
Singh NB, Amist N, Yadav K, Singh D, Pandey JK, Singh SC (2013) Zinc oxide nanoparticles as fertilizer for the germination, growth and metabolism of vegetable crops. J Nanoeng Nanomanuf 3:353–364
Sharma HD, Reddy KR (2004) Geo-environmental engineering: site remediation, waste containment, and emerging waste management technologies. Wiley, Hoboken
Si Y, Zhang Z, Wu W, Fu Q, Huang K, Nitin N, Ding B, Sun G (2018) Daylight-driven rechargeable antibacterial and antiviral nanofibrous membranes for bioprotective applications. Sci Adv 4(3):eaar5931. https://doi.org/10.1126/sciadv.aar5931
Siafaka PI, Okur NU, Karavas E, Bikiaris DN (2016) Surface modified multifunctional and stimuli responsive nanoparticles for drug targeting: current status and uses. Int J Mol Sci 17(9):1440. https://doi.org/10.3390/ijms17091440
Siddiqui MH, Al-Whaibi MH, Firoz M, Al-Khaishany MY (2015) Role of nanoparticles in plants. In: Siddiqui MH, Al-Whaibi MH, Firoz M (eds) Nanotechnology and plant sciences. Springer, Switzerland, p 303
Smith VH (2003) Eutrophication of freshwater and coastal marine ecosystems a global problem. Environ Sci Pollut Res 10(2):126–139
Smith VH, Joye SB, Howarth RW (2006) Eutrophication of freshwater and marine ecosystems. Limnol Oceanogr-Meth 51(1–2):351–355
Soko W, Chimbari MJ, Mukaratirwa S (2015) Insecticide resistance in malaria-transmitting mosquitoes in Zimbabwe: a review. Infect Dis Poverty 4:46. https://doi.org/10.1186/s40249-015-0076-7

Song Y, Li Y, Xu Q, Liu Z (2017) Mesoporous silica nanoparticles for stimuli-responsive controlled drug delivery: advances, challenges, and outlook. Int J Nanomedicine 12:87–110
Suman PR, Jain VK, Varma A (2010) Role of nanomaterials in symbiotic fungus growth enhancement. Curr Sci 99:1189–1191
Thatai S, Khurana P, Boken J, Prasad S, Kumar D (2014) Nanoparticles and core–shell nanocomposite based new generation water remediation materials and analytical techniques: a review. Microchem J 116:62–76
Torney F, Trewyn BG, Lin VSY, Wang K (2007) Mesoporous silica nanoparticles deliver DNA and chemicals into plants. Nat Nanotechnol 2(5):295. https://doi.org/10.1038/nnano.2007.108
Ul-Islam M, Khan T, Park JK (2012) Nanoreinforced bacterial cellulose–montmorillonite composites for biomedical applications. Carbohydr Polym 4:1189–1197
US (EPA) Environmental Protection Agency (2007) Nanotechnology white paper. EPA, Washington, DC. http://www.epa.gov/osainter/pdfs/nanotech/epa-nanotechnologywhitepaper-0207.pdf. Accessed 26 June 2018
US Department of Agriculture (2002) Nanoscale science and engineering for agriculture and food systems. United States Department of Agriculture, National Planning Workshop, November 18–19, 2002, Washington, DC
Wang X, Xie H (2018) A review on applications of remote sensing and geographic information systems (GIS) in water resources and flood risk management. Water 10(5):608. https://doi.org/10.3390/w10050608
Watson JG (1996) Physical/chemical treatment of organically contaminated soils and sediments. J Air Waste Manage Assoc 46(10):993–1003
Walters JP, Archer DW, Sassenrath GF, Hendrickson JR, Hanson JD, Halloran JM, Vadas P, Alarcon VJ (2016) Exploring agricultural production systems and their fundamental components with system dynamics modelling. Ecol Model 333(10):51–65
Wu SG, Huang L, Head J, Ball M, Tang YJ, Chen D-R (2014) Electrospray facilitates the germination of plant seeds. Aerosol Air Qual Res 14:632–641
Wu H, Santana I, Dansie J, Giraldo JP (2017) *In vivo* delivery of nanoparticles into plant leaves. Curr Protoc Chem Biol 9(4):269–284
Xing G, Cao Y, Shi S, Sun G, Du L, Zhu J (2001) N pollution sources and denitrification in water bodies in Taihu Lake region. Sci China Ser B: Chem 44(3):304–314
Xingmao M, Geiser-Lee J, Deng Y, Kolmakov A (2010) Interactions between engineered nanoparticles ENPs and plants: Phytotoxicity, uptake and accumulation. Sci Total Environ 408:3053–3061
Yang C, Hamel C, Vujanovic V, Gan Y (2011) Fungicide: modes of action and possible impact on non-target microorganisms. ISRN Ecol 130289:8. https://doi.org/10.5402/2011/130289
Yao Z, Li J, Xie H, Yu C (2012) Review on remediation technologies of soil contaminated by heavy metals. Procedia Environ Sci 16:722–729
Yuce M, Kurt H (2017) How to make nanobiosensors: surface modification and characterisation of nanomaterials for biosensing applications. RSC Adv 7:49386. https://doi.org/10.1039/C7RA10479K
Zargar M, Hamid AA, Bakar FA, Shamsudin MN, Shameli K, Jahanshiri F (2011) Green synthesis and antibacterial effect of silver nanoparticles using *Vitex negundo* L. Molecules 16(8):6667–6676
Zaytseva O, Neumann G (2016) Carbon nanomaterials: production, impact on plant development, agricultural and environmental applications. Chem Biol Technol Agric 3:17. https://doi.org/10.1186/s40538-016-0070-8
Zhang W (2003) Environmental technologies at the nanoscale. Environ Sci Technol 7:103–108
Zhao X, Cui H, Wang Y, Sun C, Cui B, Zeng Z (2017) Development strategies and prospects of nano-based smart pesticide formulation. J Agric Food Chem 66(26):6504–6512