Nanoagrotechnology for Soil Quality, Crop Performance and Environmental Management

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Jeyabalan Sangeetha, Devarajan Thangadurai, Ravichandra Hospet, Etigemane Ramappa Harish, Prathima Purushotham, Mohammed Abdul Mujeeb, Jadhav Shrinivas, Muniswamy David, Abhishek Channayya Mundaragi, Shivasharana Chandrabanda Thimmappa, Suresh Basavaraj Arakera, and Ram Prasad

Abstract

Nanotechnology is emerging as the key enabling technology that contributes to increased crop production with special emphasis on soil protection with environmental sustainability. Increasing worldwide food security and challenging climatic conditions are the key components for encouraging the scientific community to focus on accelerating the growth of nanoagrotechnology. Last few decades immensely contributed to the field of agriculture; technological innovations by

J. Sangeetha
Department of Environmental Science, Central University of Kerala, Kasaragod, Kerala 671316, India

D. Thangadurai (✉) • R. Hospet • P. Purushotham • A.C. Mundaragi
Department of Botany, Karnatak University, Dharwad, Karnataka 580003, India
e-mail: drthanga.kud@gmail.com

E.R. Harish • J. Shrinivas • M. David
Department of Zoology, Karnatak University, Dharwad, Karnataka 580003, India

M.A. Mujeeb • S.C. Thimmappa
Department of Microbiology and Biotechnology, Karnatak University, Dharwad, Karnataka 580003, India

S.B. Arakera
Department of Marine Biology, Karnatak University PG Centre, Karwar, Karnataka 581303, India

R. Prasad
Amity Institute of Microbial Technology, Amity University, Noida, Uttar Pradesh 201303, India

R. Prasad et al. (eds.), *Nanotechnology*, DOI 10.1007/978-981-10-4573-8_5

several hybrid varieties, synthetic chemical compounds and advanced techniques of biotechnology are an integral part of this achievement. The present decade emerged as the "decade of nanoagrotechnology", as a new origin of agricultural developments through most groundbreaking scientific finding in the field.

Keywords
Aptamers • Carbon nanotube • Pesticides • Fertilizers • Agrochemicals • Smart dust technology

5.1 Introduction

In recent years, the use of nanotechnology has created massive interest in the field of agriculture (Kuzma and Verhage 2006; Renton 2006; Chaudhry et al. 2008; Chinnamuthu and Boopathi 2009; Huyghebaert et al. 2010; Naidoo and Kistnasamy 2015). Although internationally there is no unified definition approved (Lövenstam et al. 2010), nanotechnology widely used to obtain products measures the scales less than 100 nm in one dimension. The scale having lesser range comprises larger surface area and volume ratio; the organic and inorganic properties of substance fundamentally differ due to larger substances present in corresponding materials (Aziz et al. 2015; Prasad et al. 2016). Oftenly, nanomaterials exhibit variations in thermodynamic, magnetic and optical properties in smaller quantity when compared to bulk materials (Schnettler et al. 2013). Literally, this property leads to development of new prospects in all sectors. A wide array of nanotechnology-based applications were developed in agriculture to overcome limitations such as packaging quality, food safety and processing technology (Doyle 2006; Garber 2006; Nord 2009; Yada 2009; Miller 2010; Neethirajan and Jayas 2010; Prasad et al. 2014; Prasad 2016) and also to promote sustainable agriculture to produce better-quality food products throughout the world (Larkins et al. 2008; Gruère 2011; Prasad et al. 2017a). Interesting applications include the use of nanoporous zeolites to improve fertilizers efficiency, nanosensors to measure soil quality and smart dust tools for fertilizer delivery (Chinnamuthu and Boopathi 2009; Guillaume 2012). For food and water safety, tremendous research projects are underway, nanosilver or nanoclay products have been developed for improved water filtration and nanosensors are being developed to detect and help track food pathogens (Chinnamuthu and Boopathi 2009; Gruère 2011; Prasad et al. 2014). In agricultural industries, certain nanomaterials such as nanoparticles (NPs), nanoclays (NCs) and nanoemulsions (NEs) are used. A number of methods are available for their synthesis and have many applications in the agrifood sector. NPs are unique in its nature, where the physicochemical properties depend on its surface characteristics. Thus, the chemical compound determines only the chemical composition and purity of the component, whereas, the nanomaterials demand comprehensive characterization of the compound.

One amongst the many challenges of agriculture is to optimize production and minimize losses in the field as well as during transport and storage (Khater 2011).

The main loss in the cultivation is due to the action of insects and pests that can be prevented by insecticides obtained naturally from plants or minerals and the use of nanotechnological tools for the production of new formulations (Khater 2011; Gogos et al. 2012; Forim et al. 2013). Control-release system is designed to enhance the target specificity, regulating the action of active ingredients and to reduce its residual criteria (Risch and Reineccius 1995; De Oliveira et al. 2014). Nanotechnology has shown tremendous progress in the formulation of nanocompounds to improve the stability and effectiveness (Ghormade et al. 2011; Perlatti et al. 2013). Hence, such byproducts help to release the active compound to the respective site, and it provides ability to release molecules to the site of action. They can also help to minimize undesirable toxic effects on nontarget organisms, as well as improve physicochemical stability and prevent degradation of the active agent by microorganisms (Gogos et al. 2012; Perlatti et al. 2013). The fertility of the soil is maintained by the release and carrier systems, designed to control the diffusion, erosion, swelling or mixture of these (Pothakamuri and Barbosa-Cánovas 1995; Arifin et al. 2006; Tramon 2014), depending upon the mass-transfer system involved. Many different matrices can be used to produce nanostructured systems, including biodegradable polymers, and a variety of preparation techniques have been reported (Gogos et al. 2012; Perlatti et al. 2013; Prasad et al. 2017b). Nanotechnology, the phenomenal development in terms of environmental protection and risk management, thus holds promise for cleanup of hazardous waste. Rather than this, nanotechnology implies smart device for detecting the location of pathogens and to apply fertilizers for prevention of diseases, which disturbs the yield (Bergeson 2010). Nanosensors are innovative technique for detecting bacterial, viral and fungal pathogens in plants (Baac et al. 2006; Boonham et al. 2008; Yao et al. 2009; Chartuprayoon et al. 2010). Fluorescent silica nanoparticles were used by Yao et al. (2009) in addition to that antibody for diagnosing *Xanthomonas axonopodis* pv. *vesicatoria*, which is responsible for the bacterial spot disease in a Solanaceae member; it is the significant nanoparticle for detection of pathogens. Similarly, nano-gold-based immunosensors were used by Singh et al. (2010) – surface plasmon resonance (SPR) which recognizes Karnal bunt (*Tilletia indica*) disease in wheat. In spite of this, researchers have designed the SPR sensor for detection of plant disease, and it helps in seed certification and obtaining plant quarantine in wheat crops. Nano-chips, type of nanosensors known for its rapid diagnosis of pathogens and prevention of diseases, includes fluorescent oligo-probes for hybridization detection, which is well known for its sensitivity and particularly in detecting variation in single nucleotide of several microbes (López et al. 2009).

Major impacts on the environment are due to the exploitation of nanoscience and nanotechnology. To overcome most of environmental cleanup problems, the newly emerged environmental remediation technology represented by nanoscale particles helps to provide low cost-effective solutions. For *in situ*, the modified Fe nanoparticles provide large surface density, reactivity and enormous flexibility. Nanoscale iron particles are used to transform or eliminate environmental pollutants such as chlorinated compounds, organochlorine pesticides and PCBs (Zhang 2003). Modified Fe nanoparticles are catalyzed for synthesizing and for the enhancement of speed and efficacy of remediation; hence, this modified Fe particles have several advantages such as effective transformation of bulk environmental pollutants, cost-effectiveness and less toxicity. Recently, researchers have developed nanoscale iron particles for reduction and catalyzation of the environmental pollutants including chlorinated organic compound and heavy metal ions. Chlorinated contaminants can be dechlorinated completely within the water and soil-water slurries rapidly. For instance, with a nanoscale Pd and Fe particle dose at 6.25 gL^{-1}, all chlorinated compounds were reduced to below detectable limits. Ethane was the major product in all tests. Greater than 99% removal was achieved with nanoscale iron particle in 24 h. Many pesticides that are persistent in aerobic environments are more readily degraded under reducing conditions. Zerovalent iron (ZVI) is used as a chemical reductant for the application of such techniques (Tratnyek and Johnson 2006; Garner and Keller 2014). For the removal of heavy metals ions from the polluted waters, "magnetic" bacteria seem to be useful (e.g. Ag, Hg, Pb, Cu, Zn, Sb, Mn, Fe, As, Ni, Al, Pt, Pd and Ru). With the presence of magnetic ions such as iron sulphide, heavy metals were precipitated onto bacterial cell walls, by making the bacterial cell sufficiently magnetized for removal from suspension by magnetic separation protocol. Some of the bacteria were able to synthesize iron sulphide, which may act as adsorbent for many metallic ions. Synthesis of mesoporous magnetic nanocomposite particle can be used for the removal of harmful agents present in the environment. This new technique employs molecular templates for coating nanoparticles of magnetite with that of mesoporous silica.

Currently, nanotechnology is widely used in agriculture and environmental cleanup; still it requires qualitative analysis for the assessment of toxicity and behavioural changes in the environmental systems, as well as to gain long-lasting bioavailability and durability.

5.2 Nanotechnology for Production and Protection of Crop Plants

Nanotechnology is one of the encouraging fields of interdisciplinary research. It promotes a wide array of possibilities in scientific areas like electronics, pharmaceuticals, medicine and agriculture. The recent approaches in the development of nanotechnology with biotechnology remarkably expanded the potential applications of nanoparticles in various fields of agriculture. Applications include insect pest control through the effective formulations of nanomaterial-based insecticides and pesticides, nanoparticle-mediated gene transfer in plants for the production of insect pest-resistant varieties, increase of agricultural outputs using bio-conjugated nanoelements in a steady release of water and nutrients and use of nanoparticles in making various kind of biosensors, which could help for remote sensing devices needed for site-specific crop management (Bhattacharyy et al. 2016a, b). Nanomaterials like metal-, metal-oxide- and carbon-based polymers and nanomaterials of biocomposites are being well developed (Nair et al. 2010). Their types include single-walled and multi-walled carbon nanotubes and silver, aluminium, gold, copper, silica, titanium dioxide, cerium oxide, zinc and zinc oxide nanoparticles. A wide application of these nanomaterials were observed in environmental remediation, water purification, water treatment, food processing, industrial and household needs, pharmaceutical purposes and smart sensor development (Jain 2005; Chau et al. 2007; Wei et al. 2007; Byrappa et al. 2008; Gao and Xu 2009; Qureshi et al. 2009; Zhang and Webster 2009; Lee et al. 2010; Bradley et al. 2011). The focused applications in these areas have well contributed to the improvement of agricultural production and protection (Bouwmeester et al. 2009; Emamifar et al. 2010; Nair et al. 2010; Sharon et al. 2010).

The demand for food and global population growth has led to optimizing agricultural production with minimizing losses (Khater 2011). The harmful effects of pests and insects are the major cause of crop losses, which can be minimized by way of applying natural botanicals as well as by implicating nanotechnology (Khater 2011; Gogos et al. 2012; Forim et al. 2013). Hence, there are a number of research works which are ongoing particularly on the effective and eco-friendly use of nanotechnologies in the agriculture field. Nanotechnology offers great promise in overcoming problems related to environmental impacts and target specificity of pest and insecticide and optimizing quality product yields. Nanotechnological formulation is applied to optimize the stability and effectiveness of various natural products (Ghormade et al. 2011; Perlatti et al. 2013). These nanoformulations offer the capacity to release the active compound to the particular organism and further provide controlled release of molecules at the specific site of action and also minimize the toxic effects on nontargeted organisms, as well as improve physicochemical stability and prevent degradation of the active compounds by microorganisms (Duran and Marcato 2013; Perlatti et al. 2013). Effective application of nanomaterials as fertilizer has been noticed (Raliya and Tarafdar 2013). Various nanoparticle compounds, for the most part, carbon-based nanomaterials and metal-based nanoparticles, have been utilized for their assimilation, accumulation, translocation and, more importantly, impacts on development and advancement of crop plants (Nair et al. 2010; Rico et al. 2011; Sekhon 2014). The acceptable morphological effects include improved germination rate and percentage, the vegetative biomass of seedlings and length of root and shoot. The enhanced physiological parameters observed as improved nitrogen metabolism and photosynthetic activity by metal-based nanoparticles in few crops, including soybean (Agrawal and Rathore 2014), peanut (Giraldo et al. 2014) and spinach (Zheng et al. 2005; Linglan et al. 2008), were reported. The existence of magnetic fluid in the maize seeds pertains a significant improvement in the nucleic acid level because of the regeneration reactions occurring in plant metabolism (Racuciu et al. 2009). Magnetic nanomaterials coated with that of tetramethylammonium hydroxide help to accelerate chlorophyll-a level in maize (Racuciu and Creanga 2006). In pumpkin application of iron oxide found to improve root elongation, and that ascribed to the iron cessation (Wang et al. 2011). Nanopesticides are one of the upcoming effective tools used to solve the problems of non-nanoparticles (Sasson et al. 2007). It covers a wide variety of quality nanoproducts; some of them are getting good marketing popularization also. Hence, some of the nanoformulations combine along with many polymers, the surfactants and certain nanoparticles in nanometer size. In the development of agro-compounds for crop protection, the scarcity of water solubility is observed to be one of the major limiting factors. Microencapsulation is a versatile technique for water-repellent pesticides for delivery of active components (Ragaei and Sabry 2014; Sekhon 2014). Organic polymers often used in the production of nanoparticle have been reported (Perlatti et al. 2013).

Nanomaterials serve similarly as additives and active constituents (Gogos et al. 2012). The controlled-release (CR) formulations of imidacloprid produced from polyethylene glycol and aliphatic acids through encapsulation show better control than that of commercial formulations against epidemic pests of soybean (whitefly and stem fly) (Sekhon 2014). The poly-amphiphilic polymer-based formulation exhibits potential performance for determining yellow mosaic virus transmitted through whitefly and stem fly incidence (Sekhon 2014). In addition to this, some of the improved CR formulations recorded increased yield over the control and commercial formulation (Adak et al. 2012a, b). The CR formulations along with imidacloprid and carbofuran examined as one of the efficient pests against the leafhopper and to the aphid when compared to any other conventional formulations. The residue of imidacloprid and carbofuran in the soil and potato tuber was not seen during the period of harvesting in any of the formulations (Kumar et al. 2011). Nanoparticles including iron oxide, gold, polymeric nanoparticles and silver particles are used as nanopesticides. Various concepts of nanoparticle formulation, effects, characterization and their applications in plant pest control are observed (Al-Samarrai 2012).

The potential use of nanoparticle in insect pest management has been successfully documented (Bhattacharyya et al. 2010, 2016a, b). In the control of polyphagous pest, *Helicoverpa armigera*, notable application of nanoparticles has been reported (Vinutha et al. 2013). Synthesized silver nanoparticles reveal excellent mosquito larvicidal and antilice activity (Jayaseelan et al. 2011; Ragaei and Sabry 2014; Sekhon 2014). Nanoencapsulation helps to promote the gradual release of chemical compounds for a distinct host for the management of insect pest by releasing some of the activities such as diffusion, biodegradation and osmotic pressure (Vidyalakshmi et al. 2009). The acceptable application of amorphous nanosilica as a pesticide has been found in several agricultural findings (Barik et al. 2008). Nanocopper is a modified nanoparticle which is suspended in water and used in a known compound, Bouisol, as fungicide for some grape varieties and other fruit crops. Because of mutagenesis, viral capsids could be changed to achieve several elements like the production of some enzymes and nucleic acids to act against parasites (Perez-de-Luque and Rubiales 2009). Nanoparticles with silver at 100 mg/kg restrain growth of mycelium and germination of conidia on cucurbits and inhibit the growth rate of powdery mildew in pumpkins (Lamsal et al. 2011). As one of the elite nanopesticides, silver nanoparticles show a significant application in agriculture practices (Afrasiabi et al. 2012). Treatment of mulberry leaves affected by grasserie disease is done by application of the ethanolic suspension of hydrophobic alumina-silicate nanoparticles, which has remarkably minimized the viral load (Goswami et al. 2010). DNA-tagged gold nanoparticles are powerful for *Spodoptera* *litura* and hence considered as a functional component for integrated pest management (Chakravarthy et al. 2012).

Antifungal activities of silica-silver nanoparticles against *Botrytis cinerea*, *Colletotrichum gloeosporioides* and *Rhizoctonia solani* (Park et al. 2006), silver nanoparticles against *Fusarium oxysporum* and *Aspergillus flavus* (Aziz et al. 2016) and polymer-based copper nanocomposites against pathogenic fungi have been well documented (Cioffi et al. 2004). Copper nanoparticles found in soda-lime glass powder expressed effective antimicrobial activity against gram-positive and negative bacteria (Esteban-Tejeda et al. 2009). Weed control is an essential part of enriching the productivity of any crop, and effective use of nanoherbicides seems to be an economically important substitute. The nano-silicon carrier consisting diatom frustules has been utilized for delivery of herbicides and pesticides in crop plants (Lodriche et al. 2013). The effective activity of fungicidal sulphur nanoparticles on two phytopathogens, *Venturia inaequalis* that is accountable for the apple scab disease and *Fusarium solani* responsible for early blight in tomato leaf, was reported (Rao and Paria 2013). For minimizing undesirable pest populations, the application of pheromones is one of the promising eco-friendly management to gain crop quality, for example, nanogel produced from pheromone called methyl eugenol. A detrimental pest for several of fruit crops, *Bactrocera dorsalis*, is effectively managed by the use of nanogelled pheromone (Bhagat et al. 2013). Scientists observed prominent effectiveness of nanoparticles with alumina as insecticide against two insect pests, *Rhyzopertha dominica* and *Sarocladium oryzae*. These pests are considered as major insect pests in preserved food supplies. Hence, compared to commercially available insecticides, nanostructured alumina can offer reliable and cost-effective substitute for control of insect pests (Stadler et al. 2012). The most notable use of nanofertilizers in crop production makes very innovative and effective initiation to boost the agricultural yields (Sekhon 2014).

As an alternative for conventional mode of fertilizer, nanofertilizer provides a new way for the release of nutrients into the soil by the slow and controlled way, thus minimizing autrification and water pollution (Naderi and Abedi 2012). Effect of titanium dioxide (TiO_2) nanoparticles on maize exhibits considerable change in growth (Moaveni and Kheiri 2011). In an experiment, titanium dioxide and silicon dioxide (SiO_2) nanoparticles enhance the nitrate reductase activity in soybeans to strengthen plant absorption ability (Lu et al. 2002). Researchers have found environmentally sustainable nano-organic iron-chelated fertilizer (Iran Nanotechnology Initiative Council 2009). Nanofertilizers exhibit various unique features like increased production yield, improved photosynthesis activity and an ability of ultrahigh absorption which leads to significant expansion of leaves in crop plants (Singh et al. 2016). The moderate application of nanofertilizer in agricultural practices not only enhances the crop quality but also increases the efficacy of the soil compounds, thereby minimizing the utilization of chemical fertilizers (Naderi and Danesh 2013; Sekhon 2014).

Nanotechnology is considered to be one of the potential sources for crop protection and production system. Use of nanotechnology could be a promising way for enhancing agricultural production. With the results of the maximum output of crop yield by using the minimum amount of fertilizer, inputs make it more farmer friendly. There are several approaches for the development of improved nanoformulation of agrochemicals; in the meantime, issues related to biosafety and interaction with plant, soil and environment clearly need improvement.

5.3 Nanosensors for Monitoring Soil Conditions and Environmental Stresses

Nanotechnology provides details of compound in a nanoscale range, based on its physical, organic and inorganic properties (Sadik et al. 2009). Continuous use of chemical fertilizers adversely affects the soil microbes and microfauna, and the plants, which further leads toxicity. The cost of nanofertilizers is economically low in price, and it requires a lesser amount when compared to chemical fertilizers. The main cause for improper yield was due to uptake of nitrogen, which is identified by the farmers, recently. Currently, a sensing device is utilized to overcome certain environmental issues. To rectify the disturbances to soil microbes comprises few assays, but it holds some limitations, such as, time consuming with high price to perform analysis; to avoid such issues sensing device is used, which displays the exact image on conditions of the field (Tothill 2001). Sensing devices are used to monitor the variations or effects, which are caused by several pesticides, insecticides and inorganic fertilizers; it also monitors the physical properties of soil, such as pH of soil, humidity and the growth conditions of crop plant, stem, fruit and even root, and instantly it can monitor the toxicity. Typically, sensors are human friendly; it helps in detection and it cautions farmers to carry out proper measures, which have to be taken before rather than acting for an effect later (Rameshaia et al. 2015).

5.3.1 Carbon Nanotube

Nanotubes are composed of carbon molecules and are cylindrical in shape with slight variation in terms of wall construction. This kind of multi-layered carbon nanotubes has played a major role in agricultural sector to obtain maximized growth and to improve germination and water uptake and enhance the nutrient uptake from the soil. Along with this, the implementation of several ranges of carbon nanotubes exhibits better yield with the presence of an external Fe supplement, and Ca ion helps in maintaining the quality of yield (Tiwari et al. 2014). This multi-layered carbon nanotubes with the concentration of 50 μg/ml were used to some crops like maize, wheat, peanut and garlic and gave better result by increasing the length of root and shoot, to allow the seeds to imbibe at time of germination, to enhance the growth and to obtain a well-characterized root system (Srivastava and Rao 2014). Addition of C nanotubes helps in retaining water content in plants and increasing the production rate vigorously to that of lesser amount of nanomaterials like 50 μg/ml; researchers have stressed the use of fullerene to increase the productivity of tomato, which is a phenomenal work in the agricultural sector (Husen and Siddiqi 2014).

5.3.2 Nanoaptamers

Aptamers are single-stranded nucleic acids, which bind to the pre-targeted molecules with high affinity, that fix into the target molecules to form three-dimensional molecules to produce exact bonding of the substance in vitro selection method (Tai-Chia and Chih-Ching 2009). Those kinds of sensors give accurate measurement to identify plant pathogens and resistance of crops and to enhance productivity rate. Photoluminescence, present in sensor, helps in signalling, without disturbing the cell; it helps to obtain the proper regulation of the system, i.e. insulin-binding aptamer designed to assess light extinctions from a specific region to get the signal. Luminescent assay technique is one of the promising aptamer sensors for the assessment of toxic content in food (McKeague et al. 2011) specifically to identify herbicide and pesticidal properties (atrazine and malachite green).

5.3.3 Smart Dust Technology

For monitoring of environmental hazards and energy usage, smart dust technology is developed; it almost detects everything in the surroundings like monitoring the temperature and tracking the traffic. The technology gains popularity due to its unique way of regulating the system. This tool is usually monitored with the help of computer network wirelessly; they are distributed in the field to perform the tasks, and the device is undetectable due to small-size transducers regardless of location of the sensor (Bawankar et al. 2012). The devices consist of micro-sized electrochemical sensors in the system. However, this sensor has promising result and great potential for sensing the environmental variations, automation and computing, but it still has few limitations such as impact on environment, toxicity and how far this will be helpful in the field of agriculture, health and environment (Rameshaiah et al. 2015).

5.3.4 Wireless Sensors

Wireless sensors hold a strong proof that, to monitor the activities, there is no need to be at the location where the process takes place. A wireless technology is designed for the same purpose; it not only requires point-to-point arrangements but also the amount field trials estimated. Those types of sensors maintain an increase in the growth of plants crops by constant monitoring of soil and environmental conditions. Such kind of sensors maintains optimal growth of the crop plants by continuously monitoring the soil and environmental conditions. Closed-circuit television (CCTV) is installed and used in the agricultural fields to cattle monitoring, rainwater harvesting and water quality checking. The data obtained from the CCTV can be stored and analyzed for future purposes.

5.4 Nanocapsules for Efficient Delivery of Pesticides, Fertilizers and Agrochemicals

Agroforestry ecosystems are greatly governed by interactions between biotic and abiotic components (Mittler 2006). Biotic factors such as crop plants, weeds (34%), insect pests (18%), disease-causing pathogens and nematodes (16%) had negative impacts on agricultural production (Patterson et al. 1999; Oerke 2006). In order to overcome this issue, agrochemical was developed, and its uses were randomly increased in the wake of green revolution. Agrochemicals are the inorganic chemical substances, which include fertilizers, pesticides, hormones, and other chemical growth agents that are intended to increase productivity rate by preventing crop loss during or after harvesting (Aktar et al. 2009). The green revolution brought inorganic synthetic chemicals, organic and inorganic pesticides, hybrid seeds and new irrigation technique made much more impact on agriculture sector in terms of yield and resistant well. Now the times have been changed – as the green revolution is not as green as it was earlier – it has now become a curse to environment and nontarget organisms, due its improper delivery of agrochemicals and management (Pepper 2011). Since the agrochemicals that were found have broad-range toxics and have detrimental effect on nontarget organism that reside in both terrestrial and aquatic ecosystems, it was needed to replace these agrochemicals and to develop an effective and more environmentally friendly agrochemical delivery system with the help of precision farming practices and effective application of nanotechnology to agriculture.

5.4.1 Targeted Delivery of Agrochemicals Using Nanotechnology

In recent times, nanotechnology emerged as a potential tool in the field of material science, biological science, chemical science, engineering sciences and space science (Nair et al. 2010; Rai and Ingle 2012). From the last decade, its uses and benefits are enormous in the field of agricultural science (Scott et al. 2003) by enhancing the agricultural productivity with replacing conventional agricultural practices (Ghormade et al. 2011; Gogos et al. 2012; Khot et al. 2012; Rai and Ingle 2012). Safe application of conventional agrochemicals is a major concern, due to a number of problems associated with them. For example, >90% of applied agrochemicals are lost and unable to reach the target area; it may be influenced by a number of factors including techniques used, physicochemical properties of agrochemicals and environmental conditions (Mogul et al. 1996; Perlatti et al. 2013). The losses are due to emission, leaching, evaporation, degradation due to photolysis, hydrolysis and by microorganisms. In addition to their loss, it may cause pollution to the environment and toxicity to nontarget organism (van den Berg et al. 1999; Bedos et al. 2002; Nuruzzaman et al. 2016).

The conventional agrochemical practices are replaced by various nano-based formulations that are similar to conventional formulations developed by several scientists to overcome such issues with improved features. These include increased rate of solubility, stability, permeability, biodegradability, improved nutrient use efficiency and decreased rate of agrochemical spreading with uniform dispersion (Kah et al. 2013; Kah 2015). These nano-based formulations contain nanomaterials which can work as carrier material for agrochemicals and exhibited useful properties such as stability, solubility, stiffness and crystallinity and may release efficient dosage of water and nutrients for the purpose of pest detection; management resulted in better agricultural yield (Bordes et al. 2009).

For specific applications of agrochemicals, researchers have possessed several kinds of nano-based insecticides, and fertilizers, for improving agrochemical activities, simultaneously by retaining the environmental impact to a minimum. Most of these formulations include the structures having the nanometer range with minimum amount of pesticide ingredient, along with the precised nanopore network with surfactant. Such nano-based products have long desired goal to manage the agricultural inputs and to reduce the impact of modern agriculture (Kah 2015).

5.4.2 Nano-based Pesticides in Agriculture

Conventional pesticide practices are replaced by microemulsion formulation method for the first time by the method developed by Schulman et al. (1959) and commercially available in the 1970s (Fanger 1974). Nanocapsules disperse the agrochemicals in uniform spherical droplets of either oil or water in an appropriate continuous phase. These have very low surface tension, cost-effective approach, droplet in size and clear, transparent and thermodynamically stable dispersion of oil water and stabilized by interfacial film of surfactant frequently in combination with cosurfactant (Lawrence and Rees 2000; De et al. 2014). Later, several researchers encapsulate pesticide by using variety of cost-effective materials with larger surface area, higher stability and solubility and easily biodegradable nanomaterials such as polymer-based nanomaterials, block polymers, solid lipid nanoparticles, inorganic porous nanomaterials, nanoclays and layered double hydroxides forming different types of nanomaterials such as nanocapsules for herbicides, nanospheres, micelles, nanogels, liposomes and inorganic nanocages (Perez-de-Luque and Rubiales 2009; Kah et al. 2013; Nuruzzaman et al. 2016).

5.4.3 Nano-based Fertilizer Efficiency in Agriculture

Commonly used fertilizers may enhance the agricultural yield, but the availability of nutrients present in sprayed agrochemicals is not fully accessible to plants, of this about 40–70% of nitrogen, 80–90% of phosphorus and 50–90% of potassium contents were lost (Subramanian et al. 2015). The lost chemicals may reach environment through leaching, drift, runoff and evaporation and become fixed in soil and contribute to air, water and soil pollution and may disturb the soil mineral balance and to decrease soil fertility (Solanki et al. 2015). To minimize these pollution and nutrient losses, smarty delivery systems are developed by using nanomaterials (Mukal et al. 2009; Nair et al. 2010). Such nanostructured fertilizers could increase the efficacy of nutrients by using various mechanisms, such as targeted delivery and controlled release so that it could spray the respective constituents in response to environmental impacts and biological requirement. Solanki et al. (2015) revealed that they help to increase the crop productivity rate by increasing the germination in seed, growth of seedlings, net photosynthetic rate, nitrogen metabolism and carbohydrate and protein synthesis in the respective plant crop (Chen and Yadav 2011; Subramanian et al. 2015). The data reveals that the nanofertilizers used against the crops to reach the optimum requirement are just a ppm level per acre; this technology is economically reasonable, and it is safe for living beings and is eco-friendly in nature.

5.5 Improving Plant Traits Against Environmental Stresses Using Nanotechnology

Recent developments in plant biotechnology have revolutionized the agricultural sector to overcome environmental stresses, including cold, drought, diseases and salinity, due to increasing global population, and to meet the food requirements agricultural intensification has adopted with wide usage of harmful chemical pesticides. On contrary, the modern agriculture practices have been facing several challenges that need to be addressed immediately. The extensive use of inorganic pesticides and fertilizers has raised concerns over major populations that they have severe adverse effects on environment and health of animals. Though in recent past, several technologies such as nanotechnology and genetically engineering have been developed to overcome these constraints; however, they have been not implemented into the field clearly indicating that risk assessment is not yet been evaluated. Global warming is another major abiotic stress factor that has a negative impact on the plant growth and crop productivity. Due to which, soil microorganisms are adversely affected, wherein natural enzymes are destroyed. Subsequently, uptake of macro- and micronutrients affected hence more and more fertilizers poured into the agriculture fields for better crop yield (Nair et al. 2010). Several abiotic stresses such as drought, water deficit and high salinity result in decreased crop productivity; Nanotechnology is an emerging field of science that could solve these problems with ease. It also aids in monitoring and delivering deficient nutrients, including the fertilizers and pesticides at the specific affected part of the plant, thus increasing and improving the overall plant growth and crop yield. Several nanoparticles have been evaluated for its effect on germination, seed growth, nutrient efficiency and uptake of fertilizers. Recent advancements in instrumentation technology have aided in evaluation and monitoring the behaviour of nanoparticles in plants. Several studies indicate that nanoparticles enhance the biological activity (Khan et al. 2016).

The potential applications of nanotechnology in agricultural sciences are increasing day by day, and it has been studied in various streams including production, protection and improvement of crops. During the last two decades, several studies highlighted the potential applications of nanoparticles against plant stress;

nanoparticles such as zinc oxide (Torabian et al. 2016), silicon (Qados and Moftah 2015), titanium oxide (Hong et al. 2005; Gao et al. 2006; Jaberzadeh et al. 2013), copper (Adhikari et al. 2012), silver (Yin et al. 2012; Hojjat 2016) and carbon nanotubes (Pourkhaloee et al. 2011) have shown promising role in overcoming the plant environment stress-related problems (Monica and Cremonini 2009).

Soluble phosphates are extensively used in agriculture as fertilizers, and their uncontrolled usage has resulted in eutrophication, and on the contrary, other phosphates are not effective in fulfilling deficiency. Recent study suggests that synthetic apatite nanoparticle enables the availability of phosphorus to crops with limited or less adverse effect on environment. Furthermore, the use of apatite nanoparticles as a phosphorous fertilizer can be beneficial; also, their report indicated an up to 32.6% and 20.4% increase in soybean crop yield when compared to conventional phosphorous fertilizer usage (Liu and Lal 2014; Raliya et al. 2016). More recent studies on the zinc oxide NPs on mung bean indicated that there was a significant increase in uptake of phosphate utilization and biosynthesized zinc oxide improved plant phenology including stem height and root volume. Jaberzadeh et al. (2013) research group recommended that application of titanium dioxide NPs at 0.02% concentration on wheat has increased the plant growth including gluten and starch content under water-deficit stress.

Cold stress causes loss of water content and seepage of solutes from the cell leading to deprived growth and seed germination, subsequently affecting crop yield. Application of nanoparticles such as selenium, titanium oxide and silicon oxide in combination with short chilling treatment has known to be beneficial with increased growth and physiological activities (Hawrylak-Nowak et al. 2010; Mohammadi et al. 2013; Azimi et al. 2014; Hasanpour et al. 2015; Kohan-Baghkheirati and Geisler-Lee 2015).

In recent past, several research groups are evaluating the potential applications and risks of silicon NPs in plants. Silicon increases drought resistance in plants and improves water-deficit stress tolerance (Pei et al. 2010), and it stimulates the root elongation and the physiological activity (Currie and Perry 2007; Epstein 2009; Ashkavand et al. 2015). Its deficiency has been shown to have abnormalities in plant structure when compared with silicon-rich counterparts; furthermore, silicon-deficient plants are more susceptible to biotic and abiotic stresses (Rafi et al. 1997; Ma 2004; Gao et al. 2005). Suriyaprabha et al. (2012) analyzed maize seeds treated with naturally synthesized (from rice husk) silica NPs. They reported that there was significant increase in germination percentage and root growth upon nano-SiO_2 treatments. A recent report on hawthorn seedlings suggests that silicon NPs were tended to be critical for physiological and biochemical functions under drought stress conditions (Ashkavand et al. 2015). Iron, titanium oxide and silver NPs are few amongst others that have been studied against drought stress conditions in safflower (Zareii et al. 2014), flax (Aghdam et al. 2016) and ajwain (Seghatoleslami et al. 2015), respectively.

Another study demonstrated that application of analcite nanoparticles to soil successfully enhanced seed germination, seedling growth and photosynthetic activity against drought conditions (Zaimenko et al. 2014). To overcome the salinity stress, nanosilica was applied to tomato seeds; application of silicon NPs had minimized the potential harm to the seed germination and root length under high salinity (Haghighi et al. 2012; Haghighi and Pessarakli 2013). Application of nano-silicon on plants such as lentils, sunflower and safflower has been reported (Sabaghnia and Janmohammadi 2014, 2015). Foliar application of nano-silicon on safflower gave positive results (Janmohammadi et al. 2016); foliar application of zinc oxide nanoparticles increased plant growth, CO_2 assimilation rate and chlorophyll content of *Helianthus annuus* L., under salt stress (Torabian et al. 2016). Nevertheless, several previous studies have shown the negative impacts of metal oxide nanoparticles on plant growth, seed germination and environment, thus causing phytotoxicity, cytotoxicity and genotoxicity (Lin and Xing 2008; AshaRani et al. 2009; Musante and White 2010; Goix et al. 2014; Ko and Kong 2014).

The distinct properties such as the size and surface charge of the nanoparticles enhance their easy penetration into cell membranes and targeted delivery of the materials. Several reports suggest that lower concentrations of NPs have a positive effect. On contrary, NPs applied at higher concentration have shown negative effect and cause cytotoxicity and lead to generation of reactive oxygen species. Many reports have cautioned the use of certain nanoparticles that may pose risk to environment and animals.

In conclusion, nanoparticles improve tolerance in plants towards several abiotic stresses. The mechanisms involved in the regulation and resistance have not been well understood, or the reports are scarce. Hence, further systematic investigations are necessary at the molecular level to understand the role and significance of nanoparticles at subcellular level. Suitable biosensor techniques have to be adopted to control the activities of nanoparticles and to evaluate and characterize stress inhibitors and stress inducer.

5.6 Nanotechnology and Its Applications in Water Conservation

From the perspective of necessity, water is considered as next oil. Pure potable water is depleting rapidly across the globe, affecting as many as 1.2 billion people every year (Montgomery and Elimelech 2007). In principle, unlike oil, water is a renewable natural resource which only confines to the cycle of evaporation, condensation and precipitation. Given the fact that out of 10^{18} gallons of fresh water on earth, the rate of its consumption exceeds its replenishment back into the cycle (Schoen et al. 2010). Scientists have already concluded that demand may exceed supply in just another two decades (Kim et al. 2010). Two main causes of scarcity of potable water across the globe are technical boundaries in distribution of water from centralized purification facility to the site of its consumption, and pollution and contamination of soft water bodies through natural and anthropogenic activities, which makes water unusable. Although, natural water cycles are capable of purifying itself, these cycles are not fast enough to effectively clean up the contaminated sites. On the other hand, traditional water purification processes are however being used in purification and supply of clean drinking water and have their own limitations. These limitations are due to centralized purification units consuming a large amount of energy and space. Moreover, there are poor supply channels from the site of purification to the site of consumption.

Nanotechnology, on the other hand, has promising solutions for addressing the issue of water purification in an efficient manner. The strategy includes on-site purification (minimizing cost of transportation and technical limitations with centralized purification units). Due to their unique physical properties and large surface area, nanomaterials have peculiar functionalities. Such unique functional attributes of nanomaterials are useful to develop novel materials like membranes, adsorption materials and catalysts for water treatment processes (Gehrke et al. 2015).

Membrane filters are pressure-driven channels across a semi-permeable membrane where particle matters larger than 0.5 nm are rejected back, which means particle impurities lesser than 0.5 nm still pass through membrane barriers. Nanofiltration membranes, on the other hand, are characterized by their charge-based selection and repulsion property and allow only water molecules to pass through membranes (Jagadevan et al. 2012; Sharma and Sharma 2012; Qu et al. 2013). These nanofilters prove useful in purification of ground hard water. Nanofilters can also be used in desalination of seawater where conventional membrane filters are cost intensive.

Nanoparticles have a larger surface area and, hence, are appropriate candidates for adsorption of many organic compounds. Any solid material which is used to adsorb gases or dissolved impurities which are in close physical contact are adsorbents. Traditional adsorbents such as activated carbon particle system may require regular backwash because of chock formation within or amongst carbon particles (Pan and Xing 2008). Nano-adsorbents have high specific surface area for many organic and inorganic pollutants like micropollutants and heavy metals. Due to their nanoparticle size, these systems do not chock and require less maintenance regimes.

Traditional biological process of water treatment to nullify the effect of organic and microbial pollution through oxidation demands large amount of infrastructure and energy. However, the use of catalyst to breakdown complex organic molecules is an emerging field with larger scope of practical application. Photocatalysis, on the other hand, is an advanced oxidation process for mitigating the organic toxic pollution from wastewater (Friedmann et al. 2010). According to several studies published (Fujishima et al. 2008; Gaya and Abdullah 2008; Chong et al. 2010), suspended complex organic wastes in water can be degraded by making use of photocatalysts. It is due to their well-known particle properties, low toxicity and cost efficiency. Titanium oxide (TiO) nanoparticle is one of the most frequently used photocatalyst to date (Qu et al. 2013). TiO nanoparticles, when irradiated with UV light with appropriate wavelength (200–300 nm) range, become photo-excited. This will immediately follow formation of electron hole pair triggering a chain reaction of oxido-reduction reactions. Increase in rate of reaction will only make degradation of heavy decomposable substances easier.

Nanotechnology, although, newly emerging and reliable technology for application in wastewater treatment, has its unforeseen limitations. Commercialization of nanomaterials for water treatment procedures strongly depends on its eco-toxic potentials on aquatic fauna. Many studies to ascertain toxicological endpoints, pathways of biotransformation and impact on life cycle of these nanoparticles on aquatic ecosystem have been carried out (EPA 2010; Clemente et al. 2011; Asghari et al. 2012). Apart from toxicological point of view, efficiency of nanoparticles in certain processes like catalytic system poses question marks. Generally, during tertiary water treatment processes, micropollutants like antibiotics and other suspended organic particles are removed in polishing processes. Whereas, ultraviolet radiation is only efficient about 5% of that of sunlight making its efficiency low in terms of industrial scales (Asghari et al. 2012). Nevertheless, nanotechnology in terms of emerging field of science has many more favourable and cost-efficient applications in wastewater treatments such that limitations in this field can be oversighted for now.

5.7 Conclusion and Future Perspectives

Nanotechnology is an emerging trend to contribute increased crop production with special emphasis on soil protection with environmental sustainability. This includes important technologies such as nanobiotechnology which are giving rise to a number of applications with more environmentally efficient outcomes in the areas of energy production, consumer goods, agricultural crops and information and communication technologies, which have the potential to address major environmental concerns or help to adapt to changing environmental conditions (e.g. due to climate change).

Research works on agricultural nanotechnology development and its applications have been progressing with hope for solutions to several environmental and agricultural problems. Due to its extremely small size, nanomaterial with its uncommon physical, chemical and biological properties, which are very distinct from their bulk materials and individual compounds, was accepted to be much compelling and safe.

Nanomaterials are showing most promising results in crop protection, soil improvement, disease diagnosis, plant breeding, water purification and soil conservation by acting as smart delivery systems for nutrients and other agrochemicals, indicators of soil and plant health and chelators to remove toxic substances from the soil.

In spite of these tremendous potentials and claims from academic institutions, small entrepreneurs and large-scale industries for patents on nanomaterials, no new nanomaterial-based products have reached the market. High initial investment is one of the major barriers to the production of large-scale nanomaterials for field applications. Another difficulty is regulatory issues and public opinion to release these nanomaterials to be tested at open and multicentre agricultural field trials, pointing its nanosize and lack of insights for its biological risk and physiological target sites.

Future challenges for the further development and field level application of this potential technology are designing methods for large-scale and cost-effective production of nanomaterials and formulating integrated robust top-down and bottom-up procedures to assess the hazards of nanomaterials to humans and other non-target organisms in the environment.

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