Chapter 8
Nanomaterials for Soil Fertilisation and Contaminant Removal

Mrudula Pulimi and Sangeetha Subramanian

Abstract Expanding population and increasing consumption is inducing higher pressure on agricultural resources and food production. Agriculture depends to a large extent on the quality of soil and water resource availability. Soils should ensure water retention, provide sufficient nutrients and not contain any contaminants. However, anthropogenic and natural factors are responsible for the deterioration of soil quality in the form of erosion, loss of water retention capacity and nutrients, and contamination. Large scale use of agrochemicals in the form of fertilisers and pesticides has given rise to increase in the levels of contaminants in soil and ground water. Here we review the application of nanomaterials to improve nutrient quality and to remove soil contaminants. Nanomaterials such as nanoclays, nanozeolites and nanominerals have been used to enhance water retention and as nutrient carriers. These nanomaterials promoted seed germination, plant growth, phosphorus and nitrogen fixation, versus conventional methods. Nanoparticles have also been used for remediating soils contaminated by herbicides, pesticides, organic pollutants and heavy metals. Conventional soil remediation methods such as phytoremediation, thermal treatment and electrokinetic degradation, have been improved using nanoparticles.

Keywords Nanoremediation • Contamination remediation • Soil quality • Sustainable agriculture

M. Pulimi (✉)
Centre for Nanobiotechnology, VIT University, Vellore 632014, Tamilnadu, India
e-mail: pmrudula@vit.ac.in

S. Subramanian
School of Bio Sciences and Technology, VIT University, Vellore 632014, Tamilnadu, India
e-mail: sangeethasubramanian@vit.ac.in

S. Ranjan et al. (eds.), *Nanoscience in Food and Agriculture 1*,
Sustainable Agriculture Reviews 20, DOI 10.1007/978-3-319-39303-2_8

8.1 Introduction

Material with particle size of nanometer ranging between 1 and 100 are considered as nanoparticles and any technology that deals on nanoscale means nanotechnology. The growth of nanotechnology has considerably inflated its application of nanomaterial in different area (Khot et al. 2012). Different engineered carbon based nanomaterial (single and multi-walled carbon nanotubes), metal (quantum dots, nanogold, nanosilver) and metal oxide (titanium oxide, zinc oxide and cesium oxide) based nanomaterial, nano sized polymer material called dendrimers and nano composites material are built for different functional properties. The major advantages of nanomaterial over bulk material include decrease in melting point and surface area, increase in dielectric constant and mechanical strength (Nagi et al. 2012; Maddineni et al. 2015; Dasgupta et al. 2016a, b; Ranjan et al. 2016). In addition, size of nanoparticles enables them to absorb exceptionally on to other material (Nagi et al. 2012; Dasgupta et al. 2015; Ranjan et al. 2014, 2015, 2016). Because of all these unique behaviour and properties, nanoparticles have wider application in textiles, clothing, and cosmetics, pharmaceutical, electronic and paint industry. Also they are widely used for development of health care products and remediation of contaminated environment. In addition to its wider application in major industries, nanomaterials are also applied for the prospects of agriculture in several ways (Jain et al. 2016; Baruah and Dutta 2009; Handford et al. 2014; Sastry et al. 2010; Taghiyari et al. 2015; Dasgupta et al. 2016c). Figure 8.1 represents some of the applications of nanomaterials in different fields.

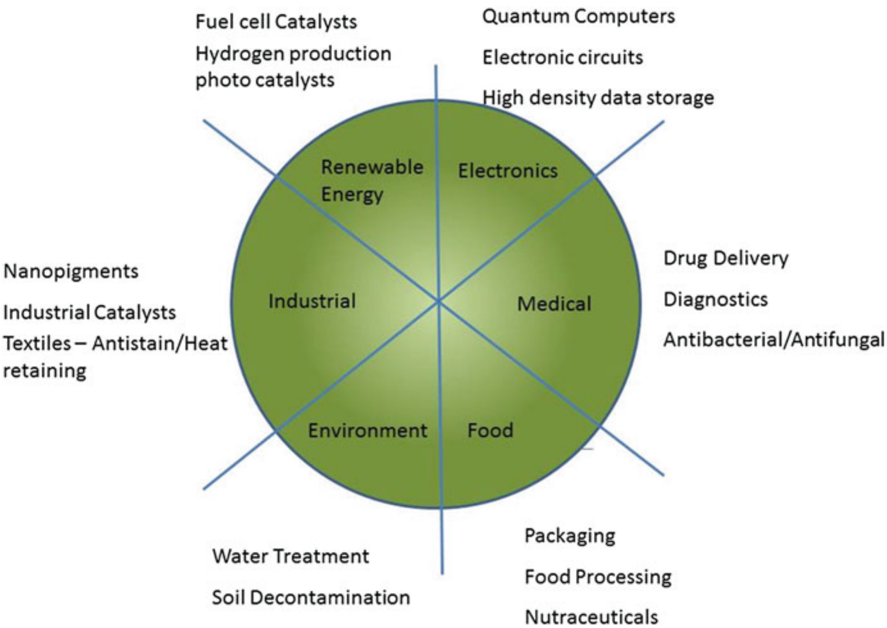

Fig. 8.1 Applications of nanomaterials in various fields

Escalation of human population has led to decrease in productive land to less than 11 % of total earth area (Mermut and Eswaran 2012). With limited availability of resources, development in agriculture has to be attained by increasing the fertility of a soil. Although conventional soil management methods are available, nanotechnology is reported by many researchers currently as an alternate technology for sustainable soil management. Fertility and quality of the agricultural soils primarily depends on quality and quantity of water available, micro and macro nutrients present in the soil. The depletion of nutrient quality in soil is predominantly caused due to man-made or natural soil erosion and accumulation of toxic pollutant in the soil. This paper reviews on application of different nanomaterials for improvement and remediation of soil.

8.2 Soil Amendments

Soil amendments are materials used to improve the physical properties of soil such as water retention capacity, nutrient availability, structure, drainage in order to produce better crop yields. Several soil amendments have been in use historically as fertilizers and soil conditioners. The purpose of fertilizers is to provide adequate nutrients for plant growth. Whereas, soil conditioners have minimum nutrient concentration but are added to enhance the biological, physical or chemical nature of soils. The indiscriminate and ineffective use of soil amendments can lead wastage of nutrients, hence nanotechnology was proposed to enhance the effective use of nutrients. The application of nanotechnology for agriculture includes (i) nanomaterials as enablers for delivery of agrochemicals (ii) sensors to monitor plant stress and soil conditions and (iii) improvement of plant traits against environmental stress and plant diseases. In this review, we will discuss about nanoparticles which are specifically used as nanofertilizer or as carriers for fertilizers. A summary of various types of nanomaterials used as soil amendments is given in Table 8.1.

8.2.1 Nanoclays

Clays are an integral part of soil mainly consisting of phyllo-silicate minerals with varying water retention capacities. Clays offer high surface area and have a net negative charge which helps clays in retaining plant nutrients and act as a pH buffer in soil. Clays lose their plasticity and become brittle when the water content is reduced. Nanoclays are generally prepared from the smectite group of clays which includes montmorillinate. Nanoclays have been extensively used in preparing polymer nanocomposites which have been applied in paints, cosmetics, drug delivery and water treatment. Nano-clay polymer composites have also been used as nutrient carriers for enhancing plant growth and for enhancing the water retention capacity of soils.

Table 8.1 Nanomaterials used as soil amendments

Type of nanomaterial	Purpose	Reference
Polymer nanoclays	Slow release of nitrogen and phosphorus	Sarkar et al (2013, 2014, 2015)
Poly(acrylamide-co-acrylic acid)/$AlZnFe_2O_4$ superabsorbent hydrogel nanocomposite	Water retention	Shahid et al. (2012)
Acid phosphatase immobilized on nanoclays	Phosphorus mineralization	Calabi-Floody et al. (2012)
Phytase immobilized on nanoclays	Phosphorous mineralization	Menezes-Blackburn et al. (2014)
Nanoporous zeolite	Nitrogen release	Manikandan and Subramanian (2014)
Nanocomposite PAAm/methyl cellulose/montmorillonite hydrogel	Carrier for urea	Bortolin et al. (2013)
Nanozeolite based urea	Nitrogen release	Thirunavakkarasu and Subramanian (2014)
Aminopropyltrimethoxysilane-zeolite based urea	Nitrogen release	Hidayat et al. (2015)
Carbon nanoparticles	Water retention	Saxena et al. (2014)
Magnetite (Fe_3O_4)	Growth of ocimum basilicum	Elfeky et al. (2013)
Hydroxyapatite	Growth of chickpea	Bala et al. (2014)
Nano hydroxyapatite	P fertilizer	Montolvo et al. (2015)
Nano-hydroxyapatite	To resist Cd stress in Cd contaminated soils	Li and Huang (2014)
Urea-modified hydroxyapatite nanoparticles encapsulated wood	Slow release N fertilizer	Kottegoda et al. (2011)
Nanosilica	Nutrient	Karunakaran et al. (2013)
Nano silica	Silica availability and biomass content of soil	Rangaraj et al. (2014)
Nano silica	Silica fertilizer	Suriyaprabha et al. (2012)
Mesoporous silica nanoparticles with urea	Urea	Wanyika et al. (2012)
Nano Zn	Growth of pearl millet	Tarafdar et al. (2014)
Zn encapsulated in Mn core shell	Zinc	Yuvaraj and Subramanian (2014)
ZnO nanoparticles	Zinc and phosphorus uptake	Watts-Williams et al. (2014)
Nano iron, phosphorus and potassium	Fertilizer for saffron flowering	Amirnia et al. (2014)
Nitrogen fertilizer and nanocarbon	Nitrogen use in saline-alkaline soils	Fan et al. (2012)
Nano TiO_2	Phosphorus uptake	Hanif et al. (2015)
NanoN_2 chelate; sulfur coated N_2 chelate	Nitrogen release	Zareabyaneh and Bayatvarkeshi (2015)

A series of nanoclay-polymer composite nutrient carriers were prepared by the reaction of different types of clays such as kaolinite, mica and montmorillonite with partially neutralized acrylic acid and acryl amide with N,N-methylene bisacrylamide as a crosslinker and ammonium persulfate as an initiator. Six different types of nanoclays were used with different types of clays with and without amorphous aluminosilicate. Among the different nano-polymer composites, the percentage release of nutrients at 48 h ranged from around 70 % in the polymer/clay (montmorillonite) composite to 90 % in the polymer/clay (kaolinite) composite proving that these nanoclays can be utilised for slow release of nutrients. Further the nanopolymer composites were loaded separately with di-ammonium phosphate and urea solution. Release of phosphorous and total mineral nitrogen from the polymer composites loaded with diammonium phosphate and urea, respectively, were compared with corresponding conventional fertilizer. Release of Phosphorous and Nitrogen were studied independently with a factorial experiment under four types of fertilizer in combination with three types of soils alfisol, inceptisol and vertisol. Cumulative Phosphorus and total mineral Nitrogen recovery significantly increased over conventional fertilizer. The increase in recovery was +88.3 % and +27.3 % for phosphorous and nitrogen respectively with nanomontmoillonite. Higher Recoveries were a result of slow release property of nanopolymers which reduced nutrient losses (Sarkar et al. 2014, 2015).

Nano-sized $AlZnFe_2O_4$/poly (Acrylamide-*co*-acrylic acid) superabsorbent nanocomposite was synthesized and the effects of different levels of nanocomposite were studied to evaluate the moisture retention properties of sandy loam soil. The soil amendment with 0.1, 0.2, 0.3 and 0.4 w/w% of nanocomposite enhanced the moisture retention significantly at field capacity compared to the untreated soil. Seed germination and seedling growth of wheat was found to be notably improved with the application of the nanocomposite. A delay in wilting of seedlings by 5–8 days was observed for nanocomposite-amended soil, thereby improving wheat plant growth and establishment (Shahid et al. 2012).

8.2.2 Nanominerals

Natural zeolites are hydrated aluminosilicates based on an infinite three-dimensional structure of tetrahedrons such as SiO_4, AlO_4, FeO_4 joined by oxygen atoms. Zeolites consist of interconnected channels and cavities of molecular dimensions where cations allowing the ion exchange exist. Zeolite materials allow an introduction of new functional groups through several processes of modification, improving substantially its activity and selectivity on the removal several substances (Inglezakis et al. 2002). Sulphate loaded nano zeolites were prepared and its activity was analysed in a percolation reactor (Thirunavakkarasu and Subramanian 2014). Sulphate release from fertilizer-loaded nanozeolite was available even after 912 h of continuous percolation, whereas sulphate from Ammonium sulphate was exhausted within 384 h.

The effectiveness of micro and nanoporous zeolite as a carrier for urea for slow release of nitrate was investigated by Manikandan and Subramanian (2014). Results revealed that the nitrogen release from the urea blended with nanozeolite (1:1) was up to 48 days while the conventional Zeolite – urea (1:1) mix was up to 34 day and the Nitrogen release ceased to exist in urea within 4 days without the presence of Zeolites.

Growth of Maize on sandy loam soil with and without the presence of porous silica nanoparticles was studied by Suriyaprabha et al. (2012).The increased surface area of silica nanoparticles led to accumulation of nanosilica in the plants and also increased the leaf size thereby leading to larger surface area for photosynthesis. Similarly, the effect of nano Si on growth characteristics of tomato was studied under salinity levels and has delivered promising results in salt tolerance (Haghighi et al. 2012). Using mesoporous silica as carrier for urea for slow release of nitrogen resulted in a fivefold increase in the availability period (Wanyika et al. 2012).

The supplement of the nanoscale hydroxyapatite was found to increase the level of chlorophyll and vitamin C and decrease the level of malondialdehyde in pakchoi plant shoots grown on Cd contaminated soil. The level of antioxidant enzymatic activity in the plant also increased as result of the addition of hydroxyapatite. The results confirmed that nanohydroxyapatite can be applied to reduce the plant uptake of Cd and resist the Cd stress (Li and Wu 2013). Nanohydroxyapatite was evaluated as a potential fertilizer to improve phosphorous availability in comparison with bulk hydroxyapatite and triplesuperphosphate for the growth of wheat (Montalvo et al. 2015). Although nanohydroxyapatite performed better than bulk hydroxyapatite, most likely because of faster dissolution, triplesuperphosphate was still a more efficient phosphorous fertilizer.

8.2.3 Metal and Metal Oxide Nanoparticles

Metal and Metal oxide nanoparticles such as Zinc, Iron, Titanium and their oxides have shown potential in promoting plant growth. Biosynthesized protein encapsulated, crystalline natured nano Zn (15–25 nm) was evaluated as a nanofertilizer for enhancing the growth of pearl millet. Beneficial effects were observed on shoot and root lengths, chlorophyll content leading to a grain yield of 37.7 % over the control without nano Zn (Tarafdar et al. 2014). Release of Zn to the soil using a nano-sized manganese hollow core shell was evaluated in a percolation reactor system. The results showed that the Zn-fortified core shell released Zn for more than 696 h while Zn release ceased after 408 h in $ZnSO_4$-fertilized soil (Yuvaraj and Subramanian 2014).

Beneficial effect of individual nano Fe, P and K on saffron flowering was analysed by Amirnia et al. (2014). Results indicated that nanofertilizers were effective in enhancing the flowering traits of saffron plant. Magnetite (Fe_3O_4) nanoparticles were synthesized and applied as foliar spray and soil additive to basil plant.

Nanoparticles applied were effective in increasing all the measured traits such as chlorophyll content, carbohydrate content, oil content shoot/root length etc. for both foliar spray and soil additive methods (Elfeky et al. 2013).

8.3 Soil Remediants

Anthropogenic activities have led to soil contamination is various parts of the world. Mining, agriculture, Industries, waste disposal are some of the factors which lead to soil pollution. An estimated 3,000,000 potentially contaminated sites are present globally which not only pose risk to human health, ecosystem but also pose a huge economic loss (Singh and Naidu 2012). Common contaminants include petroleum hydrocarbons, chlorinated solvents, persistent organic pollutants, pesticides, inorganics, heavy metals and radioactive constituents (Naidu 2013). Soil remediation methods are well established and have been in use for decades. Remediation technologies could be exsitu or insitu. Table 8.2 gives a summary of the remediation technologies available and the contaminant classes treated.

Nanomaterials with their enhanced reactivity towards contaminants and better mobility could be a potential choice for remediating soils. The application of nanomaterials for mitigating soil pollution includes degradation of pollutants, detection and sensing of pollutants, enhancers for remediation processes. Table 8.3 gives a summary of the research work carried out for evaluating the role of nanoparticles for soil remediation.

Table 8.2 Methods used for soil remediation and the contaminant classes

Method	Contaminant classes
Physical/chemical methods	
Soil vapor extraction	Halogenated and nonhalogenated organic compounds; inorganics; radionuclides; explosives
Stabilization	Halogenated and nonhalogenated organic compounds; hydrocarbons; explosives; inorganics
Chemical oxidation/reduction	Halogenated and nonhalogenated organic compounds; hydrocarbons; explosives; inorganics; radionuclides
Soil washing	Halogenated and nonhalogenated organic compounds; hydrocarbons; explosives; radionuclides
Electrokinetic seperation	Halogenated and nonhalogenated organic compounds; hydrocarbons; explosives; radionuclides; inorganics
Biological treatment	
Bioremediation	Organic compounds; inorganics; radionuclides
Bioventing	Organic compound; explosives; radionuclides; inorganics
Phytoremediation	Halogenated and nonhalogenated organic compound; hydrocarbons; explosives; Radionuclides; inorganics
Thermal treatment	Explosives; radionuclides; inorganics

Table 8.3 Nanoparticles used for soil remediation

Nanoparticles	Purpose	Degradation/ treatment method	Reference
Manganese peroxidase immobilized on nanoclay	Polyaromatics hydrocarbons	Transformation	Acevedo et al. (2010)
Apatite with carboxy methyl cellulose stabilizer	Lead	Immobilization	Liu and Zhao (2013)
Apatite	Atrazine	Dechlorination	Satapanajaru et al. (2008)
Hydroxyapatite	Lead	Immobilization and reduce lead accumulation in plants	Shaheen and Rinklebe (2015)
Hydroxyapatite	Cadmium/lead	Enhance phytoremediation	Wang et al. (2014)
Hydroxyapatite	Cadmium,	Adsorption	Chen et al. (2010)
	Zinc		
	Lead		
	Copper		
Nanosilicone	Lead	Stabilization	Liu et al. (2015)
Carbon black	Copper/zinc	Immobilization	Wang et al. (2009)
Surface modified carbon black	Copper/zinc	Immobilization	Cheng et al. (2014)
Nano Ca/CaO	Radioactive cesium	Ball milling for immobilization	Mallampati et al. (2012, 2013)
Nano zero valent iron	Triethylene	Enhancing phytoremediation by immobilizing triethylene	Martínez-Fernández et al. (2014), (2015)
	Chlorpyrifos	Degradation	Reddy et al. (2013)
	Lead polychlorinated biphenyls		Gao and Zhou (2014)
	Cr (VI)	Electrokinetics and PRB	Shariatmadari et al. (2009)
	DDT	Degradation	El-Temsah et al. (2013)
	Pyrene	Degradation	Chang et al. (2007); Chang and Kang (2009)
		Degradation	Alidokht et al. (2011)
		Degradation	Chrysochoou et al. (2012)
	Molinate	Electrokinetic	Gomes et al. (2014)
	Trichloroethylen	Permeable reactive barrier	Katsenovich and Miralles-Wilhelm (2009)
TiO_2/CeO_2	Cu	Reduce phytotoxicity	Wang et al. (2015)

(continued)

Table 8.3 (continued)

Nanoparticles	Purpose	Degradation/ treatment method	Reference
CMC stabilized nano Pd/Fe	Pentachlorophenil	Electrokinetic reduction	Yuan et al. (2012)
Nanomaghemite and magnetite	Cd, Cu, Pb	Stabilization	Michalkova et al. (2014)
CMC-Pd/nFeO	HCH (pesticides)	Degradation	Singh et al. (2012, 2013)
Nano Ca/CaO	Radioactive cesium	Immobilization by thermal treatment	Mallampati et al. (2015)
Nanomaghemite	Fe/Al/Mn	Immobilization/ phytostabilization	Vitkova et al. (2015)
Fe/Ca/Cao	Cesium	Grinding	Mallampati et al. (2015)
Pd/nFe	Polychrorinatedbiphenyls	Dechlorination	Le et al. (2015)
Nano Ca/CaO	Heavy metals		Mallampati et al. (2013a, b) and Mallampati et al. (2014)
Polyurethene	Phynethrene	Soil washing	Kim et al. (2003, 2004)
ZnO, Al	Heavy metals	Sorption	Mahdavi et al. (2015)
TiO_2	Pyrene	Photocatalytic	Chang et al. (2011)
	Phenanthrene	Photocatalytic	Gu et al. (2012)
MnO_2	Pyrene	Photooxidation	Chang et al. (2011a, b)

8.3.1 Nanomaterials for Contaminant Stabilization

Stabilization techniques effectively reduce the hazard potential of a contaminant by converting it into less soluble, mobile or toxic forms. Stabilization could be done either by physical methods or chemical reactions. The mobility of organic and inorganic compounds can be reduced through various precipitation, complexation, and adsorption reactions. The potential of Fe nano oxide (maghemite and magnetite) and amorphous Mn oxides for stabilizing Cd, Cu and Pb in contaminated soils was investigated by Michálková et al. (2014). Results from batch and column experiments coupled with adsorption tests proved that the amorphous MnO was the most effective treatment for the stabilization of metals in the studied soil samples at the given w/w ratios (1 and 2 %, w/w). Metal stabilization was a result of combined specific adsorption onto the oxide surface together with an increase in soil pH promoting the adsorption of metallic cations. Nano TiO_2 and CeO_2 were utilized to adsorb Cu(II) and mitigate its bioavailability and toxicity to Tobacco plants (Wang et al. 2015a, b). The addition of the nanoparticles along with humic acid resulted in increased the root length by 90 % and 100 % for nano TiO_2 and nano CeO_2 respectively. The results indicated that nanoparticles were successful in reducing the

Cu(II) phytoxicity by reducing the bioavailable soluble Cu(II). The study also reported no phytotooxicity by individual TiO_2 and CeO_2 nanoparticle which makes their usage more amenable.

The effect of nano zero valent iron (nZVI) coated with carboxy methyl cellulose on the degradation of DDT in soil columns was investigated by El-Temsah et al. (2013). Addition of nZVI and subsequent leaching with water led to a reduction in DDT concentrations in soil of almost 50 % compared to controls without nZVI. However the use of nZVI resulted in negative effects on plant growth. It was also observed that the oxidation of nZVI with aging reduces the negative effects of the presence of nanoparticles. Le et al. (2015) developed an integrated remediation system for dechlorination of aroclor 1248 using chemical catalysis and biodegradation. Dechlorination was achieved by treatment with bimetallic nanoparticles Pd/nFe under anoxic conditions. Dechlorination efficiency was 99 %, 92 %, 84 %, and 28 % of tri-, tetra-, penta-, and hexachlorinated biphenyls, respectively. The resulting biphenyl was found to be biodegraded rapidly by *Burkholderia xenovorans* LB400.

8.3.2 Nanomaterials in Thermal Treatment

Thermal treatments for soil remediation include incineration, steam injection and extraction and vitrification. Vitrification is a high temperature process in which organic matter is incinerated and mineral matter is melted and a slag is quickly cooled to obtain the contaminant entrapped in a matrix. Nano Ca/Cao mixtures were used to immobilized radionuclides ^{133} Cesium from contaminated soil through vitrification. The removal efficiency achieved with the nanoparticles was 96 % at 1,200 °C. The investigation results have showed that a certain amount of 133Cs was the entrapped inside new aggregates, produced during the thermal treatment with nCa/CaO (Mallampati et al. 2015a, b).

Thermal desorption of polychlorinated biphenyls in the presence of nZVI was evaluated by Liu et al. (2014). The presence of nZVI gave improved efficiency of desorption at 300 °C. The desorption efficiency was dependent on nZVI concentration and temperature. Nano Zerovalent Iron was also used to enhance thermal degradation of polychlorinated dibenzo-. p-dioxins and dibenzofurans at low temperatures (Lundin et al. 2013).

8.3.3 Nanomaterials for Enhancing Phytoremediation

Phytoremediation is a low cost and effective insitu remediation method for contaminated soil reclamation. Phytoremediation involves uptake, containment, degradation of contaminants by plants. Several reports are available in literature evaluating the effect of nanomaterials for enhancing phytoremediation Gao and Zhu 2014; Wang et al. 2014, 2015) . The effect of nanosilicon on lead toxicity, uptake and accumulation in rice varieties Yangdao 6 and Yu 44 grown on lead contaminated soil was analysed by Liu et al. (2015). The biomass increased by 3.35–11.8 % higher and lead concentration in shoots and grains was reduced by 27–54 % and 21–41 % respectively by adding nanosilicone to lead contaminated soil. The results indicate that nanosilicone was effective in preventing the lead transfer from rice roots to aboveground parts by complexation with lead.

E-waste contaminated soil containing Pb and polychlorobiphenyls was remediated by phytoextraction using Impatiens balsamina in the presence of three different nanozerovalent iron particles – free, vermiculite supported and activated carbon supported zerovalent iron. Free and vermiculite supported nanozero valent iron were found to increase accumulation of Pb in plants and activated carbon supported nano zero valent iron reduced the bioavailability of Pb (Gao and Zhou 2013, 2014).

8.3.4 Nanomaterials for Electrokinetic Remediation

Electrokinetic remediation is an emerging technology which involves application of a low-intensity, direct current through the soil to separate and extract contaminants from soil. The current is applied across electrode pairs that have been implanted in the ground on each side of the contaminated soil. During the process positively charged chemical species, such as metals, ammonium ions, and some organic compounds, move toward the cathode, and negatively charged chemicals, such as chloride, cyanide, fluoride, nitrate, and negatively-charged organic species, migrate toward the anode. Various additives such as surfactants can be added to enhance the remediation process. The combined effect of nanozerovalent iron and electrodialysis of polychlorinated biphenyls (PCB) was evaluated by Gomes et al. (2014a, b). H^+ generated near the anode in electrodialytic chamber solubilized the transition metal from soils which in turn aided in dechlorination of PCB to biphenyl compound (Gomes et al. 2014a, b). Yang and Chang (2011) evaluated the treatment efficiency of combining emulsified nano zerovalent iron and electrokinetic remediation for Trichloroethylene (TCE) on contaminated soil. Electro kinetic remediation enhanced transport of nanoparticles through the soil matrix from anode to cathode chamber. During the transport, hydrophobic TCE diffuses into nano zerovalent iron present in the inner aqueous region through emulsion and becomes dechlorinated.

8.4 Conclusion

Nanotechnology has the potential to provide solutions for better soil management through improving nutrient quality of soil and alleviating soil pollution. Although the efficacy of Nanomaterials as plant growth promoters and remediation agents has been proved, knowledge of the fate and effect of nanomaterials in soil has to be careful considered. Nanomaterials have been reportedly toxic to various organisms

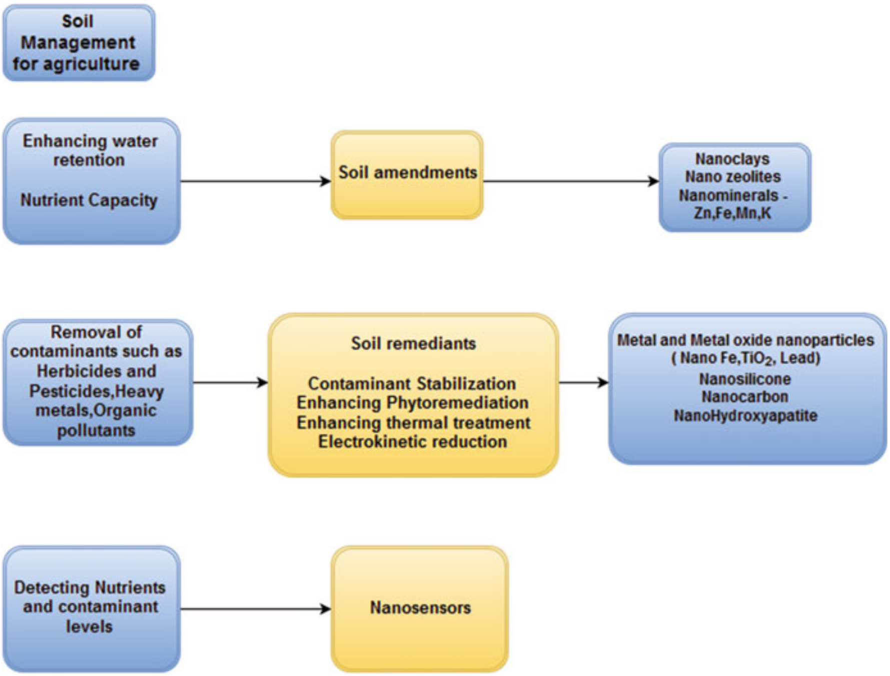

Fig. 8.2 Application of nanomaterials for soil management

and also effect human health (Mukherjee et al. 2014; Zou et al. 2014; Smulders et al. 2015). In this context, any new development involving the application of nanoparticles directly into the environment has to take into consideration the fate, transport and effect on the soil ecosystem, plant toxicity. Several researchers have attempted to understand the fate and transport of nanoparticles (Anjum et al. 2015; Sun et al. 2015) but many more investigations have to be carried out on the stability of the various types of nanoparticles alone and in combination with various contaminants (Fig. 8.2).

References

Acevedo F, Pizzul L, Castillo M, González ME, Cea M, Gianfreda L, Diez MC (2010) Degradation of polycyclic aromatic hydrocarbons by free and nanoclay-immobilized manganese peroxidase from Anthracophyllum discolor. Chemosphere 80(3):271–278. doi:10.1016/j.chemosphere.2010.04.022

Alidokht L, Khataee AR, Reyhanitabar A, Oustan S (2011) Cr(VI) immobilization process in a Cr-spiked soil by zerovalent iron nanoparticles: optimization using response surface methodology. Clean – Soil, Air, Water 39(7):633–640. doi:10.1002/clen.201000461

Amirnia R, BAYAT M, Tajbakhsh M (2014) Effects of nano fertilizer application and maternal corm weight on flowering at some saffron (crocus sativus L.) ecotypes. Turk J Field Crop 19(2):158–168

Anjum NA, Adam V, Kizek R, Duarte AC, Pereira E, Iqbal M., … Ahmad I (2015) Nanoscale copper in the soil-plant system – toxicity and underlying potential mechanisms. Environ Res 138:306–325. doi: 10.1016/j.envres.2015.02.019

Bala N, Dey A, Das S, Basu R, Nandy P (2014) Effect of Hydroxyapatite nanorod on chickpea (Cicer arietinum) plant growth and its possible use as nano-fertilizer. Iran J Plant Physiol 4(3):1061–1069

Baruah S, Dutta J (2009) Nanotechnology applications in pollution sensing and degradation in agriculture: a review. Environ Chem Lett 7(3):191–204. doi:10.1007/s10311-009-0228-8

Bortolin A, Aouada FA, Mattoso LHC, Ribeiro C (2013) Nanocomposite PAAm/methyl cellulose/montmorillonite hydrogel: evidence of synergistic effects for the slow release of fertilizers. J Agric Food Chem 61(31):7431–7439. doi:10.1021/jf401273n

Calabi-Floody M, Velásquez G, Gianfreda L, Saggar S, Bolan N, Rumpel C, Mora ML (2012) Improving bioavailability of phosphorous from cattle dung by using phosphatase immobilized on natural clay and nanoclay. Chemosphere 89(6):648–655. doi:10.1016/j.chemosphere.2012.05.107

Chang Chien SW, Chang CH, Chen SH, Wang MC, Madhava Rao M, Satya Veni S (2011a) Effect of sunlight irradiation on photocatalytic pyrene degradation in contaminated soils by micro-nano size Tio 2. Sci Total Environ 409(19):4101–4108. doi:10.1016/j.scitotenv.2011.06.050

Chang Chien SW, Chang CH, Chen SH, Wang MC, Madhava Rao M, Satya Veni S (2011b) Oxidative degradation of pyrene in contaminated soils by δ-MnO 2 with or without sunlight irradiation. Sci Total Environ 409(19):4078–4086. doi:10.1016/j.scitotenv.2011.06.019

Chang MC, Kang HY (2009) Remediation of pyrene-contaminated soil by synthesized nanoscale zero-valent iron particles. J Environ Sci Health – Part A Toxicol/Hazard Subst Environ Eng 44(6):576–582. doi:10.1080/10934520902784609

Chang MC, Shu HY, Hsieh WP, Wang MC (2007) Remediation of soil contaminated with pyrene using ground nanoscale zero-valent iron. J Air Waste Manag Assoc 57(2):221–227

Chen JH, Wang YJ, Zhou DM, Cui YX, Wang SQ, Chen YC (2010) Adsorption and desorption of Cu(II), Zn(II), Pb(II), and Cd(II) on the soils amended with nanoscale hydroxyapatite. Environ Prog Sustain Energy 29(2):233–241. doi:10.1002/ep.10371

Cheng JM, Liu YZ, Wang HW (2014) Effects of surface-modified nano-scale carbon black on Cu and Zn fractionations in contaminated soil. Int J Phytoremediation 16(1):86–94. doi:10.1080/15226514.2012.759530

Chrysochoou M, Johnston CP, Dahal G (2012) A comparative evaluation of hexavalent chromium treatment in contaminated soil by calcium polysulfide and green-tea nanoscale zero-valent iron. J Hazard Mater 201–202:33–42. doi:10.1016/j.jhazmat.2011.11.003

Dasgupta N, Shivendu R, Deepa M, Chidambaram R, Ashutosh K, Rishi S (2015) Nanotechnology in agro-food: from the field to plate. Food Res Int 69:381–400

Dasgupta N, Shivendu R, Bhavapriya R, Venkatraman M, Chidambaram R, Avadhani GS, Ashutosh K (2016a) Thermal co-reduction approach to vary size of silver nanoparticle: its microbial and cellular toxicology. Environ Sci Pollut Res 23(5):4149–4163. doi:10.1007/s11356-015-4570-z

Dasgupta N, Shivendu R, Patra D, Srivastava P, Kumar A, Ramalingam C (2016b) Bovine serum albumin interacts with silver nanoparticles with a "side-on" or "end on" conformation. Chem Biol Interact 253:100–111. doi:10.1016/j.cbi.2016.05.018

Dasgupta N, Shivendu R, Shraddha M, Ashutosh K, Chidambaram R (2016c) Fabrication of food grade vitamin E nanoemulsion by low energy approach: characterization and its application. Int J Food Prop 19:700–708. doi:10.1080/10942912.2015.1042587

Elfeky SA, Mohammed MA, Khater MS, Osman YAH, Elsherbini E (2013) Effect of magnetite nano-fertilizer on growth and yield of Ocimum basilicum L. Int J Ind Med Plants 46(3):2051–4263

El-Temsah YS, Oughton DH, Joner EJ (2013) Effects of nano-sized zero-valent iron on DDT degradation and residual toxicity in soil: a column experiment. Plant and Soil 368(1–2):189–200. doi:10.1007/s11104-012-1509-8

Fan L, Wang Y, Shao X, Geng Y, Wang Z, Ma Y, Liu J (2012) Effects of combined nitrogen fertilizer and nano-carbon application on yield and nitrogen use of rice grown on saline-alkali soil. J Food, Agric Environ 10(1):558–562

Gao YY, Zhou QX (2013) Application of nanoscale zero valent iron combined with impatiens balsamina to remediation of e-waste contaminated soils. Adv Mater Res 790:73–76

Gao Y, Zhou Q (2014) Effects of three nanoscale zero-valent irons combined with impatiens balsamina on phytoextraction Pb and their mechanism analysis under Pb and PCBs stress. Yingyong Jichu yu Gongcheng Kexue Xuebao/J Basic Sci Eng 22(6):1049–1059. doi:10.16058/j.issn.1005-0930.2014.06.001

Gomes HI, Dias-Ferreira C, Ottosen LM, Ribeiro AB (2014a) Electrodialytic remediation of polychlorinated biphenyls contaminated soil with iron nanoparticles and two different surfactants. J Colloid Interface Sci 433:189–195. doi:10.1016/j.jcis.2014.07.022

Gomes HI, Fan G, Mateus EP, Dias-Ferreira C, Ribeiro AB (2014b) Assessment of combined electro-nanoremediation of molinate contaminated soil. Sci Total Environ 493:178–184. doi:10.1016/j.scitotenv.2014.05.112

Gu J, Dong D, Kong L, Zheng Y, Li X (2012) Photocatalytic degradation of phenanthrene on soil surfaces in the presence of nanometer anatase TiO2 under UV-light. J Environ Sci (China) 24(12):2122–2126. doi:10.1016/S1001-0742(11)61063-2

Haghighi M, Afifipour Z, Mozafarian M (2012) The effect of N-Si on tomato seed germination under salinity levels. J Biol Environ Sci 6(16):87–90

Handford CE, Dean M, Henchion M, Spence M, Elliott CT, Campbell K (2014) Implications of nanotechnology for the agri-food industry: opportunities, benefits and risks. Trends Food Sci Technol 40(2):226–241. doi:10.1016/j.tifs.2014.09.007

Hanif HU, Arshad M, Ali MA, Ahmed N, Qazi IA (2015) Phyto-availability of phosphorus to Lactuca sativa in response to soil applied TiO2 nanoparticles. Pak J Agric Sci 52(1):177–182

Hidayat R, Fadillah G, Chasanah U, Wahyuningsih S, Ramelan AH (2015) Effectiveness of urea nanofertilizer based aminopropyltrimethoxysilane (APTMS)-zeolite as slow release fertilizer system. Afr J Agric Res 10(14):1785–1788

Inglezakis V, Loizidou M, Grigoropoulou H (2002) Equilibrium and kinetic ion exchange studies of Pb 2+, Cr 3+, Fe 3+ and Cu 2+ on natural clinoptilolite. Water Res 36(11):2784–2792

Karunakaran G, Suriyaprabha R, Manivasakan P, Yuvakkumar R, Rajendran V, Prabu P, Kannan N (2013) Effect of nanosilica and silicon sources on plant growth promoting rhizobacteria, soil nutrients and maize seed germination. IET Nanobiotechnol 7(3):70–77. doi:10.1049/iet-nbt.2012.0048

Katsenovich YP, Miralles-Wilhelm FR (2009) Evaluation of nanoscale zerovalent iron particles for trichloroethene degradation in clayey soils. Sci Total Environ 407(18):4986–4993. doi:10.1016/j.scitotenv.2009.05.033

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. doi:10.1016/j.cropro.2012.01.007

Kim JY, Shim SB, Shim JK (2003) Synthesis of amphiphilic polyurethane nanonetwork particles and their application for the soil-washing process. J Appl Polym Sci 87(10):1666–1677. doi:10.1002/app.11610

Kim JY, Shim SB, Shim JK (2004) Comparison of amphiphilic polyurethane nanoparticles to nonionic surfactants for flushing phenanthrene from soil. J Hazard Mater 116(3):205–212. doi:10.1016/j.jhazmat.2004.08.031

Kottegoda N, Munaweera I, Madusanka N, Karunaratne V (2011) A green slow-release fertilizer composition based on urea-modified hydroxyapatite nanoparticles encapsulated wood. Curr Sci (Bangalore) 101(1):73–78

Le TT, Nguyen KH, Jeon JR, Francis AJ, Chang YS (2015) Nano/bio treatment of polychlorinated biphenyls with evaluation of comparative toxicity. J Hazard Mater 287:335–341. doi:10.1016/j.jhazmat.2015.02.001

Li Z, Huang J (2014) Effects of nanoparticle hydroxyapatite on growth and antioxidant system in pakchoi (brassica chinensis L.) from cadmium-contaminated soil. J Nanomater. doi:10.1155/2014/470962

Li Z, Wu Y (2013) Effects of nano particle hydroxyapatite on cadmium bioaccumulation and translocation in pakchoi (Brassia Chinensis) from cadmium polluted soil. Adv Mater Res 652–654:1548–1552

Liu R, Zhao D (2013) Synthesis and characterization of a new class of stabilized apatite nanoparticles and applying the particles to in situ Pb immobilization in a fire-range soil. Chemosphere 91(5):594–601. doi:10.1016/j.chemosphere.2012.12.034

Liu J, Chen T, Qi Z, Yan J, Buekens A, Li X (2014) Thermal desorption of PCBs from contaminated soil using nano zerovalent iron. Environ Sci Pollut Res. doi:10.1007/s11356-014-3226-8

Liu J, Cai H, Mei C, Wang M (2015) Effects of nano-silicon and common silicon on lead uptake and translocation in two rice cultivars. Front Environ Sci Eng. doi:10.1007/s11783-015-0786-x

Lundin L, Moltó J, Fullana A (2013) Low temperature thermal degradation of PCDD/Fs in soil using nanosized particles of zerovalent iron and CaO. Chemosphere 91(6):740–744. doi:10.1016/j.chemosphere.2013.02.021

Maddineni SB, Badal KM, Shivendu R, Nandita D (2015) Diastase assisted green synthesis of size-controllable gold nanoparticles. RSC Adv 5:26727–26733. doi:10.1039/C5RA03117F

Mahdavi S, Afkhami A, Jalali M (2015) Reducing leachability and bioavailability of soil heavy metals using modified and bare Al2O3 and ZnO nanoparticles. Environ Earth Sci 73(8):4347–4371. doi:10.1007/s12665-014-3723-6

Mallampati SR, Mitoma Y, Okuda T, Sakita S, Kakeda M (2012) High immobilization of soil cesium using ball milling with nano-metallic Ca/CaO/NaH 2PO 4: Implications for the remediation of radioactive soils. Environ Chem Lett 10(2):201–207. doi:10.1007/s10311-012-0357-3

Mallampati SR, Mitoma Y, Okuda T, Sakita S, Kakeda M (2013a) Cesium immobilization in soil by ball-milling treatment with nanometallic Ca/CaO additive. J Hazard, Toxicol, Radioact Waste 17(1):2–8. doi:10.1061/(ASCE)HZ.2153-5515.0000151

Mallampati SR, Mitoma Y, Okuda T, Sakita S, Kakeda M (2013b) Total immobilization of soil heavy metals with nano-Fe/Ca/CaO dispersion mixtures. Environ Chem Lett 11(2):119–125. doi:10.1007/s10311-012-0384-0

Mallampati SR, Mitoma Y, Okuda T, Sakita S, Simion C (2014) Simultaneous decontamination of cross-polluted soils with heavy metals and PCBs using a nano-metallic Ca/CaO dispersion mixture. Environ Sci Pollut Res 21(15):9270–9277. doi:10.1007/s11356-014-2830-y

Mallampati SR, Mitoma Y, Okuda T, Simion C, Lee BK (2015a) Dynamic immobilization of simulated radionuclide 133Cs in soil by thermal treatment/vitrification with nanometallic Ca/CaO composites. J Environ Radioact 139:118–124. doi:10.1016/j.jenvrad.2014.10.006

Mallampati SR, Mitoma Y, Okuda T, Simion C, Lee BK (2015b) Solvent-free synthesis and application of nano-Fe/Ca/CaO/[PO<inf>4</inf>] composite for dual separation and immobilization of stable and radioactive cesium in contaminated soils. J Hazard Mater 297:74–82. doi:10.1016/j.jhazmat.2015.04.071

Manikandan A, Subramanian KS (2014) Fabrication and characterisation of nanoporous zeolite based N fertilizer. Afr J Agric Res 9(2):276–284. doi:10.5897/ajar2013.8236

Martínez-Fernández D, Bingöl D, Komárek M (2014) Trace elements and nutrients adsorption onto nano-maghemite in a contaminated-soil solution: a geochemical/statistical approach. J Hazard Mater 276:271–277. doi:10.1016/j.jhazmat.2014.05.043

Martínez-Fernández D, Vítková M, Bernal MP, Komárek M (2015) Effects of nano-maghemite on trace element accumulation and drought response of Helianthus annuus L. in a contaminated mine soil. Water Air Soil Pollut 226(4):101–110. doi: 10.1007/s11270-015-2365-y

Menezes-Blackburn D, Jorquera MA, Gianfreda L, Greiner R, de la Luz Mora M (2014) A novel phosphorus biofertilization strategy using cattle manure treated with phytase-nanoclay complexes. Biol Fertil Soils 50(4):583–592. doi:10.1007/s00374-013-0872-9

Michálková Z, Komárek M, Šillerová H, Della Puppa L, Joussein E, Bordas F, . . . Ettler V (2014) Evaluating the potential of three Fe- and Mn-(nano)oxides for the stabilization of Cd, Cu and Pb in contaminated soils. J Environ Manag 146:226–234. doi: 10.1016/j.jenvman.2014.08.004

Montalvo D, McLaughlin MJ, Degryse F (2015) Efficacy of hydroxyapatite nanoparticles as phosphorus fertilizer in andisols and oxisols. Soil Sci Soc Am J 79(2):551–558. doi:10.2136/sssaj2014.09.0373

Mukherjee A, Pokhrel S, Bandyopadhyay S, Mädler L, Peralta-Videa JR, Gardea-Torresdey JL (2014) A soil mediated phyto-toxicological study of iron doped zinc oxide nanoparticles (Fe at ZnO) in green peas (Pisum sativum L.). Chem Eng J 258:394–401. doi:10.1016/j.cej.2014.06.112

Nagi G, Sanderson R, Hartmann P (2012) Preparation of polystyrene–clay nanocomposites via dispersion polymerization using oligomeric styrene-montmorillonite as stabilizer. Polym Int 61(5):834–843. doi:10.1002/pi.415

Naidu R (2013) Recent advances in contaminated site remediation. Water Air Soil Pollut 224(12):1–11. doi:10.1007/s11270-013-1705-z

Rangaraj S, Gopalu K, Rathinam Y, Periasamy P, Venkatachalam R, Narayanasamy K (2014) Effect of silica nanoparticles on microbial biomass and silica availability in maize rhizosphere. Biotechnol Appl Biochem 61(6):668–675. doi:10.1002/bab.1191

Ranjan S, Nandita D, Arkadyuti RC, Melvin SS, Chidambaram R, Rishi S, Ashutosh K (2014) Nanoscience and nanotechnologies in food industries: opportunities and research trends. J Nanopart Res 16(6):2464. doi:10.1007/s11051-014-2464-5

Ranjan S, Nandita D, Sudandiradoss C, Ramalingam C, Ashutosh K (2015) A novel approach to evaluate titanium dioxide nanoparticle-protein interaction through docking: an insight into the mechanism of action. P Natl A Sci India B. doi:10.1007/s40011-015-0673-z

Ranjan S, Nandita D, Bhavapriya R, Ganesh SA, Chidambaram R, Ashutosh K (2016) Microwave-irradiation-assisted hybrid chemical approach for titanium dioxide nanoparticle synthesis: microbial and cytotoxicological evaluation. Environ Sci Pollut Res. doi:10.1007/s11356-016-6440-8

Reddy AVB, Madhavi V, Reddy KG, Madhavi G (2013) Remediation of chlorpyrifos-contaminated soils by laboratory-synthesized zero-valent nano iron particles: effect of pH and aluminium salts. J Chem. doi:10.1155/2013/521045

Thirunavakkarasu M, Subramanian KS (2014) Surface modified nano-zeolite used as carrier for slow release of sulphur. J Appl Nat Sci 6(1):19–26

Sarkar S, Datta SC, Biswas DR (2013) Using nanoclay polymer composite for efficient delivery of N and P to Pearl Millet grown in a smectite dominant soil in a green house experiment. Clay Res 32(2):102–113

Sarkar S, Datta SC, Biswas DR (2014) Synthesis and characterization of nanoclay-polymer composites from soil clay with respect to their water-holding capacities and nutrient-release behavior. J Appl Polym Sci 131(6). doi: 10.1002/app.39951

Sarkar S, Datta SC, Biswas DR (2015) Effect of fertilizer loaded nanoclay/superabsorbent polymer composites on nitrogen and phosphorus release in soil. Proc Natl Acad Sci India Sect B – Biol Sci 85(2):415–421. doi:10.1007/s40011-014-0371-2

Sastry RK, Rashmi HB, Rao NH, Ilyas SM (2010) Integrating nanotechnology into agri-food systems research in India: a conceptual framework. Technol Forecast Soc Chang 77(4):639–648. doi:10.1016/j.techfore.2009.11.008

Satapanajaru T, Anurakpongsatorn P, Pengthamkeerati P, Boparai H (2008) Remediation of atrazine-contaminated soil and water by nano zerovalent iron. Water Air Soil Pollut 192(1–4):349–359. doi:10.1007/s11270-008-9661-8

Saxena M, Maity S, Sarkar S (2014) Carbon nanoparticles in ‘biochar’ boost wheat (Triticum aestivum) plant growth. RSC Adv 4(75):39948–39954. doi:10.1039/c4ra06535b

Shaheen SM, Rinklebe J (2015) Impact of emerging and low cost alternative amendments on the (im)mobilization and phytoavailability of Cd and Pb in a contaminated floodplain soil. Ecol Eng 74:319–326. doi:10.1016/j.ecoleng.2014.10.024

Shahid SA, Qidwai AA, Anwar F, Ullah I, Rashid U (2012) Improvement in the water retention characteristics of sandy loam soil using a newly synthesized poly(acrylamide-co-acrylic acid)/AlZnFe2O4 superabsorbent hydrogel nanocomposite material. Molecules 17(8):9397–9412. doi:10.3390/molecules17089397

Shariatmadari N, Weng CH, Daryaee H (2009) Enhancement of hexavalent chromium [Cr(VI)] remediation from clayey soils by electrokinetics coupled with a nano-sized zero-valent iron barrier. Environ Eng Sci 26(6):1071–1079. doi:10.1089/ees.2008.0257

Singh B, Naidu R (2012) Cleaning contaminated environment: a growing challenge. Biodegradation 23(6):785–786. doi:10.1007/s10532-012-9590-5

Singh R, Misra V, Mudiam MKR, Chauhan LKS, Singh RP (2012) Degradation of γ-HCH spiked soil using stabilized Pd/Fe0 bimetallic nanoparticles: pathways, kinetics and effect of reaction conditions. J Hazard Mater 237–238:355–364. doi:10.1016/j.jhazmat.2012.08.064

Singh R, Manickam N, Mudiam MKR, Murthy RC, Misra V (2013) An integrated (nano-bio) technique for degradation of γ-HCH contaminated soil. J Hazard Mater 258–259:35–41. doi:10.1016/j.jhazmat.2013.04.016

Smulders S, Larue C, Sarret G, Castillo-Michel H, Vanoirbeek J, Hoet PHM (2015) Lung distribution, quantification, co-localization and speciation of silver nanoparticles after lung exposure in mice. Toxicol Lett 238(1):1–6. doi:10.1016/j.toxlet.2015.07.001

Sun P, Zhang K, Fang J, Lin D, Wang M, Han J (2015) Transport of TiO<inf>2</inf>nanoparticles in soil in the presence of surfactants. Sci Total Environ 527–528:420–428. doi:10.1016/j.scitotenv.2015.05.031

Suriyaprabha R, Karunakaran G, Yuvakkumar R, Prabu P, Rajendran V, Kannan N (2012) Growth and physiological responses of maize (Zea mays L.) to porous silica nanoparticles in soil. J Nanopart Res 14(12):1–14. doi:10.1007/s11051-012-1294-6

Taghiyari HR, Karimi A, Tahir PMD, Choo ADY (2015) Effects of nanotechnology on fluid flow in agricultural and wood-based composite materials. In: Agricultural biomass based potential materials. Springer International Publishing, pp 73–89. doi:10.1007/978-3-319-13847-3_4

Tarafdar JC, Raliya R, Mahawar H, Rathore I (2014) Development of zinc nanofertilizer to enhance crop production in pearl millet (Pennisetum americanum). Agric Res 3(3):257–262. doi:10.1007/s40003-014-0113-y

Vítková M, Komárek M, Tejnecký V, Šillerová H (2015) Interactions of nano-oxides with low-molecular-weight organic acids in a contaminated soil. J Hazard Mater 293:7–14, http://dx.doi.org/10.1016/j.jhazmat.2015.03.033

Wang HW, Wang YJ, Chen JH, Wang SQ, Cheng JM, Zhou DM (2009) Application of modified nano-particle black carbon for the remediation of soil heavy metal pollution. Zhongguo Huanjing Kexue/China Environ Sci 29(4):431–436

Wang F, Wang L, Wang X, Shi Z (2014) Role of immobilization amendments in phytoremediation of Pb-Cd-contaminated soil using tobacco plants. Chin J Environ Eng 8(2):789–794

Wang H, Kim B, Wunder SL (2015a) Nanoparticle-supported lipid bilayers as an in situ remediation strategy for hydrophobic organic contaminants in soils. Environ Sci Tech 49(1):529–536. doi:10.1021/es504832n

Wang Y, Peng C, Fang H, Sun L, Zhang H, Feng J, . . . Shi J (2015) Mitigation of Cu(II) phytotoxicity to rice (Oryza sativa) in the presence of TiO2 and CeO2 nanoparticles combined with humic acid. Environ Toxicol Chem 34(7):1588–1596. doi: 10.1002/etc.2953

Wanyika H, Gatebe E, Kioni P, Tang Z, Gao Y (2012) Mesoporous silica nanoparticles carrier for urea: potential applications in agrochemical delivery systems. J Nanosci Nanotechnol 12(3):2221–2228. doi:10.1166/jnn.2012.5801

Watts-Williams SJ, Turney TW, Patti AF, Cavagnaro TR (2014) Uptake of zinc and phosphorus by plants is affected by zinc fertiliser material and arbuscular mycorrhizas. Plant and Soil 376(1):165–175. doi:10.1007/s11104-013-1967-7

Yang GCC, Chang Y-I (2011) Integration of emulsified nanoiron injection with the electrokinetic process for remediation of trichloroethylene in saturated soil. Sep Purif Technol 79(2):278–284, http://dx.doi.org/10.1016/j.seppur.2011.03.004

Yuan S, Zheng Z, Meng XZ, Chen J, Wang L (2010) Surfactant mediated HCB dechlorination in contaminated soils and sediments by micro and nanoscale Cu/Fe particles. Geoderma 159(1–2):165–173. doi:10.1016/j.geoderma.2010.07.008

Yuan S, Long H, Xie W, Liao P, Tong M (2012) Electrokinetic transport of CMC-stabilized Pd/Fe nanoparticles for the remediation of PCP-contaminated soil. Geoderma 185–186:18–25. doi:10.1016/j.geoderma.2012.03.028

Yuvaraj M, Subramanian KS (2014) Controlled-release fertilizer of zinc encapsulated by a manganese hollow core shell. Soil Sci Plant Nutr. doi:10.1080/00380768.2014.979327

Zareabyaneh H, Bayatvarkeshi M (2015) Effects of slow-release fertilizers on nitrate leaching, its distribution in soil profile, N-use efficiency, and yield in potato crop. Environ Earth Sci. doi:10.1007/s12665-015-4374-y

Zou J, Feng H, Mannerström M, Heinonen T, Pyykkö I (2014) Toxicity of silver nanoparticle in rat ear and BALB/c 3T3 cell line. J Nanobiotechnol 12(1):52–62. doi: 10.1186/s12951-014-0052-6