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REVIEW ARTICLE

Recent trends in nanomaterials applications in environmental monitoring and remediation

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Abstract Environmental pollution is one of the greatest problems that the world is facing today, and it is increasing with every passing year and causing grave and irreparable damage to the earth. Nanomaterials, because of their novel physical and chemical characteristics, have great promise to combat environment pollution. Nanotechnology is being used to devise pollution sensor. A variety of materials in their nano form like iron, titanium dioxide, silica, zinc oxide, carbon nanotube, dendrimers, polymers, etc. are increasingly being used to make the air clean, to purify water, and to decontaminate soil. Nanotechnology is also being used to make renewable energy cheaper and more efficient. The use of nanotechnology in agriculture sector will reduce the indiscriminate use of agrochemicals and thus will reduce the load of chemical pollutant. While remediating environment pollution with nanomaterials, it should also be monitored that these materials do not contribute further degradation of the environment. This review will focus broadly on the applications of nanotechnology in the sustainable development with particular emphasis on renewable energy, air-, water-, and soil-remediation. Besides, the review highlights the recent developments in various types of nanomaterials and nanodevices oriented toward pollution monitoring and remediation.

Keywords Nanoparticles · Pollutants · Nanosensors · Sustainable development · Solar cell · Nanocides

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Introduction

Technological progress brought by industrial revolution and highly efficient capitalist business practices is probably the main cause of fathomless exploitation of natural resources. Ever expanding human population and urbanization have stretched the use of natural resources to the maximum and ultimately this overuse of natural resources is leading to nature's degradation. Today, the air is filled up with numerous pollutants like carbon monoxide, chlorofluorocarbons, volatile organic compounds, hydrocarbons, and nitrogen oxides. Water and soil are contaminated with arsenic, heavy metals, and chlorinated compounds. Sewage water, industrial effluents, indiscriminate use of pesticides, fertilizers, and oil spills are some of the major reasons for water and soil degradation.

As contaminants are mostly found as mixtures, there is a need for technologies that are capable of monitoring, recognizing, and treating such small amount of contaminants in air, water, and soil. In this context, we need a technology which can sense, reduce, prevent, and treat environment contamination. Nanotechnology has the potential to provide sustainable solution to the global challenges related to protecting water, soil, and providing cleaner air. Nanoscience allows designing and manipulating materials at the atomic and molecular level. These materials can be fabricated with specific functionalities that can recognize a particular pollutant within a mixture. The small size of nanoparticles (NPs), together with their high surface-to-volume ratio, can lead to very sensitive detection. These novel properties of NPs will allow developing highly miniaturize, accurate, and sensitive pollution-monitoring devices (nanosensors) to detect pollutants in air and water (Mohammadian et al. 2013; Zhang et al. 2012a, b). Many researchers have fabricated different NPs which actively interact with a pollutant and decompose it in less toxic substance (Kanel et al. 2006; Li and Zhang 2007; Celebi et al. 2007).

Nanotechnology can also be used to reduce production of harmful wastes in manufacturing process by reducing the amount of material used and by employing less toxic compounds. If we consider the agriculture sector, precision farming and development of slow release pesticide (Cao et al. 2005), fertilizers are expected to reduce soil and water pollution by these harmful chemicals. Nanotechnology can provide more cost-efficient and cost-effective water treatment and desalination technologies, and enable the development of renewable energy sources, including highly efficient solar energy conversion systems (Wang et al. 2013; Wallentin et al. 2013). From the very beginning, the National Nanotechnology Initiative (NNI) in the USA had the aim to maintain industrial sustainability by significant reductions in materials and energy use, reducing sources of pollution, and increasing opportunities for recycling, and these were documented as an important goal of the NNI in the 1999 Nanotechnology Research Directions Report (Roco 2001). In this review, we have highlighted and discussed the application of nanotechnology to combat air and water pollution in particular (Table 1). Application of nanotechnology in soil treatment, sustainable agriculture, and production of renewable energy is also reviewed (Table 1). Application of different nanomaterials in environmental remediation, monitoring, and efficient renewable energy production is summarized in Fig. 1.

Remediation of air pollution

Nanotechnology can be used to clean the air in several ways. One is through the use of nanocatalysts with increased surface area for gaseous reactions. These catalysts transform harmful vapors from cars and industrial plants into harmless gases. Catalysts currently in use include a nanofiber catalyst made of manganese oxide NP that removes volatile organic compounds from industrial smokestacks. Gold NP has promising catalytic activity in converting highly toxic CO to CO_2. Chen and Goodman hypothesized that the quantum size effect of gold NP is responsible for the oxidation of highly toxic CO into CO_2 (Chen and Goodman 2006).

Another approach is to use nanostructured membranes that have pores small enough to separate methane or CO_2 from exhaust. It has been reported that nanostructured membranes composed of single-walled carbon nanotubes (SWCNTs) can efficiently be utilized as nanoscale vessels for selective encapsulation of tetrafluromethane at 300 K and operating external pressure of 1 bar. The rate of adsorption is directly related to the pore size of the nanotubes (Kowalczyk and Holyst 2008). Due to their unique structural features with abundant pores, large surface-to-volume ratio, and strong adsorption and desorption capabilities for gases, carbon nanotubes (CNTs) are being exhaustively studied for their role in purification of air. The hypothesis behind the use of CNTs as efficient gas absorbent relies on the fact that absorption of gas molecules on the surface of CNTs change the shape of CNTs and trigger redistribution of electrons, leading to a macroscopic change in resistance (Zhang et al. 2010). Scientists of the University of Queensland are researching CNTs for trapping greenhouse gas emissions caused by coal mining and power generation. CNT can trap gases up to a hundred times faster than other methods, allowing integration into large-scale industrial plants and power stations. Unlike conventional membranes that can only separate or process gaseous substances, this CNT-based technology can do the both for large volumes of gas effectively. The substances filtered out still present a problem for disposal because waste removed from the air only return to the ground and there is no net benefit. Uchida et al. found a way to collect the soot filtered out of diesel fuel emissions and recycle it into manufacturing material for CNT (Uchida et al. 2006). The diesel soot is used to synthesize the SWCNT filter through laser vaporization, thus the filtered waste becomes the filter.

Silica-titania nanocomposites are being investigated for the removal of mercury vapors such as those coming from combustion sources (Pitoniak et al. 2005). Here, high surface area of nanosilica and unique photoctalytic property of titania molecules has been amalgamated to make novel nanocomposite for improved mercury absorption. Moreover, it is shown that superior mercury removal efficiency was ensured with significant reduction of contact angle up to 10° by this silica-titania nanocomposite.

Researchers have also developed new materials that inexpensively capture CO_2 efficiently and selectively. They have used materials based on metalorganic frameworks (MOFs) to make tiny "cages" capable of capturing CO_2. These MOFs are 2–3 times more efficient in absorbing CO_2 compared to conventional sorbents. This CO_2 can be released from the MOF by pull of a vacuum and can then be pumped deep into the Earth where it becomes stable in the form of carbonate minerals. This particular work has been pioneered by the Yaghi Group, relies on organic ligand molecules that can associate with multiple metal ion bonding which form an extended porous network (Yaghi et al. 1995). It can be made from inexpensive source material in a very mild condition. MOF 210, having highest surface area and an amine functionalized mmen-CuBTri MOF having highest heat absorption and selectivity are being mostly used for this purpose.

Waste water and industrial effluent treatment

Increasing industrial and agricultural pollution has led to a greater need for processes that remove specific pollutants such as nitrogen and phosphorus compounds, heavy metals, and chlorinated compounds. NPs have very high flexibility for both in situ and ex situ purification of waste water and

Table 1 Application of different nanomaterials in environment remediation

Nanoparticle	Application	Reference
Carbon nanotube	Sensor for H_2S, SO_2	Zhang et al. (2012c)
	Absorption of tetrafluoromethane	Kowalczyk and Holyst (2008)
	Absorption of Zn(II) from water	Lu and Chiu (2006)
	Absorption of Fluoride from water	Li et al. (2003a, 2003b)
	Adsorption of dichlorobenzene from water	Peng et al. (2003)
	Adsorption of Pb^{2+}, Cu^{2+}, and Cb^{2+} ions	Li et al. (2003a, 2003b)
	Fuel cells	Liu et al. (2002)
	Adsorption of Carbon tetrachloride	Kondratyuk and Yates (2005)
Graphene	Efficient solar cell	Wang et al. (2013)
Iron	Removal of Barium ions	Celebi et al. (2007)
	Nickel sequestration in water	Li and Zhang (2007)
	Arsenic removal	Kanel et al. (2006)
	In situ dehalogenation of dense, non-aqueous phase liquids containing trichloroethene	Quinn et al. (2005)
	Removal of Pb, Cr	Ponder et al. (2000)
	Removal of nitrate from water	Choe et al. (2000)
	Dechlorination of trichloroethene, polychlorinated biphenyls	Wang and Zhang (1997)
Iron sulphide	Degradation of lindane from drinking water	Paknikar et al. (2005)
Bimetallic Iron/Palladium	Dechlorination of chlorinated ground water	Elliott and Zhang (2001)
Titanium dioxide	Improved photovoltaic performance of solar cells	Sun et al. (2012a, 2012b)
	Photovoltaic cell	Chen et al. (2012)
	Removal of benzene and toluene	Chuang et al. (2008)
	Self cleaning surface	Euvananont et al. (2008)
	Degradation of dye	Srinivasan and White (2007)
	Degradation of Butachlor in aqueous solution	Mahmoodi et al. (2007)
	Sonochemical degradation of parathion	Wang et al. (2006)
	Photocatalysis of dye	Peng et al. (2005)
	Photocatalysis of water, polluted from dyeing and printing process	Chen et al. (2003)
	Photodecomposition of phenol	Andersson et al. (2002)
Zirconium and Niobium-doped titanium oxide	Photoinduced decomposition of acetone	Mattson et al. (2009)
Core-shell titanium dioxide /strontium ferrite	Magnetic catalysis of fluid	Fu et al. (2006)
Titanium dioxide/PVDF membrane	Oxidization of nitrobenzene	Sun et al. (2012a, 2012b)
Silica	Treating grasserie disease of silkworm	Das et al. (2013)
	Biosafe insecticide	Debnath et al. (2010)
	Thermal insulation	Schmidt and Schwertfeger (1998)
Silica-titania nanocomposite	Mercury vapor removal	Pitoniak et al. (2005)
Zinc oxide	Solar cell	Al-Juaid and Merazga (2013)
	Antifungal agent	Patra et al. (2012)
Gold thin film	Conversion of CO to CO_2	Chen and Goodman (2006)
Core-shell gold-silica	Plasmon-enhanced light absorption in solar cell	Brown et al. (2011)
Platinum nanoparticle	Fuel cell	Gebauer et al. (2014)
Bimetallic Palladium-gold	Dechlorination of TCE	Nutt et al. (2005)
Microporous metalorganic framework	Trapping of aromatic compounds	Yaghi et al. (1995)
Bimetallic nickel-iron	Dechlorination of TCE	Schrick et al. (2002)

Table 1 (continued)

Nanoparticle	Application	Reference
Bimetallic nickel-iron	Degradation of carbon tetrachloride, chloroform	Feng and Lim (2005)
Poly(amidoamine) (PAMAM) dendrimer	Removal of copper from soil	Xu and Zhao (2005)
	Separation of heavy metals	Rether and Schuster (2003)
	Removal of Cu(II) ions from aqueous solution	Diallo et al. (1999)
Amorphous alumina/carbon nanotube	Absorption of Fluoride from water	Li et al. (2001)
Jacobsite ($MnFe_2O_4$)	Removal of Cr(VI)	Hu et al. (2005)
Amphiphilic polyurethane	Decontamination of polynuclear aromatic hydrocarbons from ground water	Tungittiplakorn et al. (2004)
Poly(ethylene) glycol modified urethane acrylate	Decontamination of aquifer from phenanthrine	Tungittiplakorn et al. (2005)
Indium phosphide nanowire	Efficiency increase of solar cell	Wallentin et al. (2013)

industrial effluents. For example, NPs can easily be deployed in ex situ slurry reactors for the treatment of contaminated soils, sediments, and solid wastes. Alternatively, they can be anchored onto a solid matrix such as carbon, zeolite, or membrane for enhanced treatment of waste water.

The use of zero-valent iron (Fe^0) NPs for the remediation of contaminated groundwater and soil is a good example of nanotechnology-mediated environmental remediation. When exposed to air, oxidized iron easily turns to rust; however, when it is oxidized around contaminants such as trichloroethylene (TCE), carbon tetrachloride, and dioxins, these organic compounds are broken into simple, far less toxic carbon compounds. Ponder et al. found that 10–30-nm-sized Fe^0 NPs can be used for separation and immobilization of Cr (VI) and Pb (II) from aqueous solution by reduction of Cr and Pb (Ponder et al. 2000). Fe^0 nanopowder can be used for removal of nitrate from water (Choe et al. 2000). FeS NP can degrade lindane (γ-hexachlorocyclohexane) which is one of the major organic pollutants found in drinking water (Paknikar et al. 2005). This Fe^0 NP can also be used to combat arsenic pollution from drinking water (Kanel et al. 2006). Li and Zhang utilized core-shell iron NP as a sorbent and reductant to remove Ni(II) ion from aqueous solution (Li and Zhang 2007), whereas Celebi et al. showed that this NP can also efficiently remove Ba^{2+} ion from water (Celebi et al. 2007). One of the innovative uses of iron NP is in the degradation of halogenated organic compounds, like chlorinated aromatics, chlorinated aliphatics, and polychlorinated biphenyls (Wang and Zhang 1997).

Bimetallic iron NPs have been shown to be even more active and stable than Fe^0 NPs. These bimetallic NPs could be anchored on solid supports such as activated carbon or silica for the ex situ treatment of contaminated water or industrial wastes. In some newer studies, it was found that

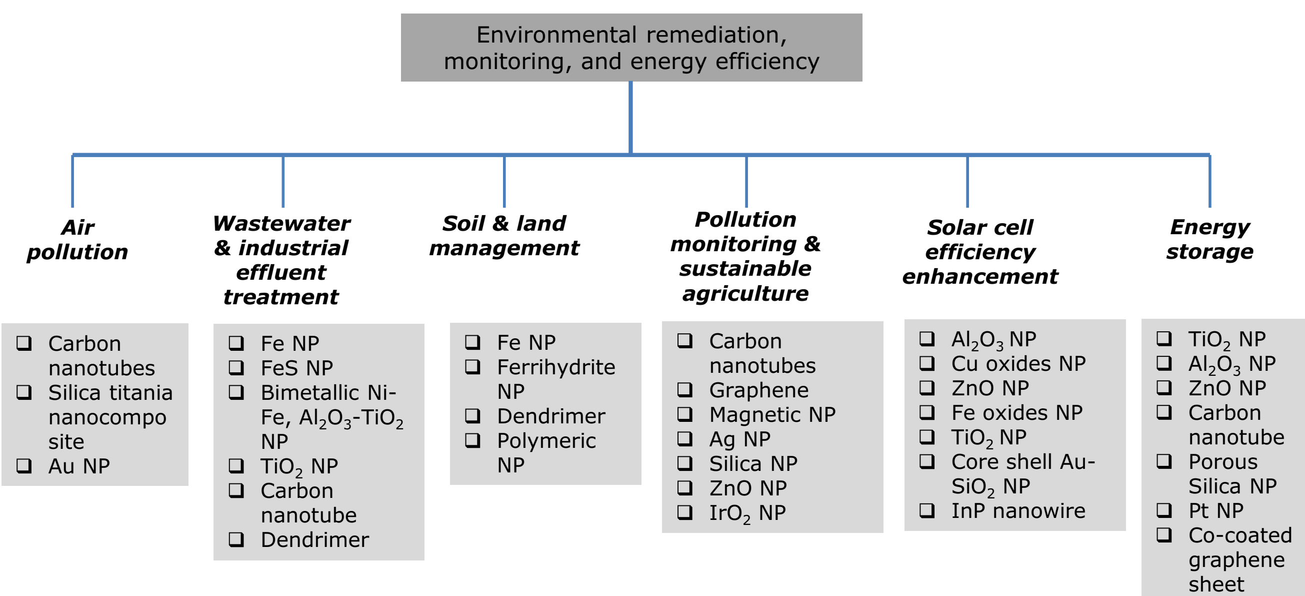


Fig. 1 Application of nanomaterials in environmental remediation, monitoring, and energy efficiency

palladized iron can completely dechlorinate many chlorinated aliphatic compounds to hydrocarbons (Wang and Zhang 1997). Nickel/Iron NP can be used for reduction of chlorinated compounds (Schrick et al. 2002; Feng and Lim 2005). Palladium NP, supported on gold NP, can also reduce chlorinated compounds from water (Nutt et al. 2005). Porous titanium silicate and alumina nanocomposite (Al_2O_3/TiO_2) can be utilized for the removal of heavy metals, particularly Pb^{2+} and Cd^{2+}.

Since tetravalent Ti carries two negative charges, which should be neutralized by two monovalent cations, it has great ion exchange or adsorption property. So TiO_2 NP is now being widely studied for its property to purify water. It is being used in removal of toxic phenol contamination by wet oxidation technique from waste water through photocatalytic activity of both rutile and anatase forms of TiO_2 NP (Andersson et al. 2002). Next level advancement in this field came from development of a composite reactor consisting of a UV lamp and TiO_2 NPs (Chen et al. 2003). UV lamp is used to provide energy to excite photocatalyst nano-TiO_2 molecules to produce electron hole pairs. This system in turn accumulates H_2O_2 molecules which ultimately help in degradation of rhodamine contamination in polluted water coming from dyeing and printing process. Mesopororous TiO_2 molecules are also being developed for rhodamine removal by Peng et al. (Peng et al. 2005). Catechols are one of the most abundant organic pollutants of our environment. Chen et al. reported a very unique complete mineralization of catechol pollutants using photocatalytic oxidation and ozonization by carbon-black-modified nano-TiO_2 thin films supported on alumina sheet (Chen et al. 2003).

Application of external magnetic field is an alternative for separation and recycling of photocatalyst molecules for cost-effective usage. For this core, $SrFe_{12}O_{19}$ NPs within TiO_2 nanocrystals were developed as the magnetic photocatalytic particles (Fu et al. 2006). Ultrasonic energy is also coming out as emerging technology to activate sonocatalytic nano-TiO_2 molecules after vigorous treatment with high temperature for increasing the organic pollutant degradation activity (Wang et al. 2006). Mahmoodi et al. studied the effect of immobilized TiO_2 NP on the removal of Butachlor (*N*-butoxymethyl-2-chloro-2, 6-diethylacetanilide) which is one of the organic pollutants in agricultural soil and waste water (Mahmoodi et al. 2007). Similar immobilization-based technology was also used in removal of two other major agricultural pollutants (Diazinon and Imidacloprid as *N*-heterocyclic aromatics) (Mahmoodi et al. 2007). The advantage of this technology relies on easy separation and recycling of nano-TiO_2 molecules from aquatic environment. Accelerated photodegradation of methylene blue over three-dimensionally ordered macroporous titania (pore sizes 0.5 and 1 μm) was demonstrated by Srinivasan and White (2007). It showed that the macroporous anatase nano-TiO_2 catalysts were more efficient in relation to dye pollutant removal in comparison with commercial and other powdered TiO_2. Nano-TiO_2 along with polyvinylidene fluoride (PVDF) membrane is also being used for successful oxidation and removal of nitrobenzene molecules under ozonation. Effect of pH, concentration of nitrobenzene, and nano-TiO_2/PVDF membrane combination was found to have direct relation with nitrobenzene removal. This pH-dependent mechanism was showing maximum oxidation at pH 10 (Sun et al. 2012a). Benzene and toluene removal is another important breakthrough for pollution control using carbonized bamboo (*Phyllostachys pubescens*) coated with TiO_2 NPs. Sorption mechanism of benzene and toluene by this technology is based on hydrophobic-hydrophobic interaction, observed by depletion of untreated bamboo (UB) carbohydrates during carbonization (Chuang et al. 2008).

Nanotechnology can also be employed for the fabrication of nanofilters, nanoadsorbents, and nanomembranes with specific properties to be used for decontaminating water. In principle, "nanotraps" can be designed for a certain contaminant. Researchers in Rice University have developed iron oxide ceramic membranes (ferroxane membrane) that are capable of remediating organic waste in water (Cortalezzi et al. 2005). Dendrimers, which are highly branched polymers and obviously in nanoscale dimension, can be designed to act as "cages" and trap metal ions and zero-valent metals, making them soluble in appropriate media, and able to bind to certain surfaces. Diallo et al. first explored the potential of poly amidoamine (PAMAM) dendrimers for removal of copper from water (Diallo et al. 1999). A water-soluble benzoylthiourea-modified ethylenediamine core PAMAM dendrimer developed by Rether and Schuster can be used for selective removal and enrichment of toxic heavy metal ions (Rether and Schuster 2003). Diaminobutane poly (propylene imine) dendrimers functionalized with long aliphatic chains can remove organic impurities like polycyclic aromatic hydrocarbons from water.

CNTs have excellent adsorption capability for removal of heavy metals such as Pb, Cu, Co, Cd, Zn, Mn, etc. Li et al. found that oxidized CNTs have enhanced cadmium (II) adsorption capacity in comparison with normal CNTs, due to the functional groups introduced by oxidation process (Li et al. 2003a). Commercial SWCNTs and multi-walled carbon nanotubes (MWCNTs) were purified by Lu et al. with the help of sodium hypochlorite solutions, and these were used as adsorbent for the removal of zinc from water (Lu and Chiu 2006). Similarly amorphous alumina supported on CNT was used to adsorb fluoride from drinking water (Li et al. 2001). A new type of CNT, synthesized from catalytic degradation of xylene, can also be used for removal of fluoride from water (Li et al. 2003b). CNTs also show adsorption capability for the removal of pollutants like 1,2-dichlorobenzene, trihalomethanes, *n*-nonane, etc. from water (Peng et al. 2003; Kondratyuk and Yates 2005). Hu et al. developed surface-functionalized $MnFe_2O_4$ NP as a novel adsorbent for rapid removal of Cr (VI) from waste water (Hu et al. 2005).

Nanotechnology is not only being used for treatment of waste water but also for purifying drinking water. Researchers from the University of California Los Angeles (UCLA) have developed a nanomembrane which can be used in form of new reverse osmosis membrane for sea water desalinization and waste water remediation [http://oip.ucla.edu/quantumflux-reverse-osmosis]. The membrane is made of a uniquely cross-linked matrix of polymers and engineered nanoparticles, drawing ions in water but repels contaminants. This is possible due to the nanosize of the holes forming the membrane which are "tunnels" accessible to water molecules, but the NPs embedded in the membrane repels organics and bacteria. Compared with conventional RO membrane, these ones are thus less prone to clogging, which increase the membrane lifetime with an obvious economic benefit.

Management of waste, soil, and land treatment

Reduction of waste in manufacturing process, reduction in the use of harmful chemicals, reduction in the emission of greenhouse gases, and use of degradable plastic are only few of the many approaches that can be taken to reduce the pollution of the environment. Moreover, there are highly efficient, nanotechnology-enabled, modular and multifunctional processes for waste water treatment and management that relies least on high throughput instrumentation and labor-intensive approaches (Qu et al. 2013a, b). Nanocatalysts, having increased "active surface," have greater reaction efficiency. Nanocatalysis is being investigated for desulfurizing fuels, with the aim of developing clean fuel containing very low sulfur products. A commercial example is Oxonica's Envirox fuel which uses nanosized cerium oxide as a catalyst to enhance efficiency [http://www.nanotech-now.com/news.cgi?story_id=07726]. It was found that vehicles need less amount of this fuel in comparison with control ones.

Iron NPs are widely being used in environmental pollution remedial management for their unique physicochemical properties developed from extremely small size and high surface area to volume ratio. A huge number of pollutants can be removed from waste with the use of these NP, as for example Cd, chloroform, DDT, chlorobenzene, trichloroethane, arsenic, perchlorate, nitrate, dichlorobenzene, lindane, trichloroethane, etc. (Zhang 2003). Particles of iron also can be used in ex situ slurry reactors to treat soil, sediment, and solid waste. In cases of water and/or waste water treatment, anchoring NPs onto a solid matrix, such as activated carbon, can prove extremely effective (Zhang 2003). The most challenging part in this technology is the application of these nanotools in the ground. It provides coverage of greater surface area under remedial benefits. Not only for soil, but these tiny NPs (Fe^0 or bimetallic NPs like iron NP coated with catalytic metals such as Pd and Pt etc.) can also be used for sediment and solid waste treatment. Moreover, they are also capable of aqueous phase remediation including removal of dense non-aqueous phase liquids (Elliott and Zhang 2001; Quinn et al. 2005).

Ferritin, a kind of iron storage protein present in animal, plant, and microbial kingdom, pays a pivotal role in iron storage and sequestration like a protein cage. After assembly of iron molecules in cage-like protein structure, they undergo mineralization and translate into a NP of ferrihydrite, a ferric oxyhydroxide of 5 to 7.5 nm (Kim et al. 2002). It has been reported that ferritin can be used for remediation of toxic compounds like chlorocarbons (Moretz 2004). Report also showed the probable application of this technology is to remediate groundwater that has been contaminated from the slow leakage of nuclear waste. PAMAM is also attracting much interest in waste water and soil management like Cu removal (Diallo et al. 1999). The presence of high concentration of nitrogen bonds within internal branches of these dendrimers makes it appropriate for metal ion chelation functionalities (Xu and Zhao 2005). Apart from these, polymeric NPs like polyurethane acrylate anionomer (UAA) and poly(ethylene glycol)-modified urethane acrylate (PMUA)-based NPs have great potential in the field of toxic pollutant remediation of hydrophobic organic compounds and polycyclic aromatic hydrocarbons because of their surfactant micelle-like properties (Tungittiplakorn et al. 2004, 2005). Micron-sized zeolites are experimented to be efficient to remediate waste water containing cationic species, such as ammonium and heavy metals, as well as chemicals, such as ^{137}Cs and ^{90}Sr. Studies are also there in lab scale to identify the potential role of nanosized crystalline zeolite compounds in toxic pollutant removal.

Nanotechnology can also be used to produce biodegradable plastics made of polymers that have a molecular structure optimal for degradation, and many other environment friendly products like nontoxic nanocrystalline composite materials to replace lithium-graphite electrode in rechargeable battery, self-cleaning glasses, etc. (Massawe 2013). Self-cleaning glass is covered with TiO_2 nanocrystals and when this glass is exposed to daylight, it reacts in two ways. First, it breaks down any organic dirt deposits on the glass and second, when exposed to water, it allows the loosened dirt to be washed away very easily. Sea water very often becomes polluted with crude oil spilled from the oil tankers. Nanoscience researchers are constantly trying to find out nanotechnology-mediated ways to oil spill cleanup. Scientists at MIT developed a mat of nanowires that can absorb up to 20 times its weight in oil [http://www.nanowerk.com/spotlight/spotid=20215.php]. The oil will evaporate if this membrane is heated above boiling point of the oil. The vapor can then be condensed back into liquid, and the nanowire membrane can also be reused.

Detection and monitoring of environmental pollutants

Nanoscale devices are being used for enhanced sensing, treating, and remediating environmental contaminants. The unique characteristics of nanomaterials used in nanoscale devices may be used to monitor unforeseen environmental problems. Continuous and highly specific air pollution measurement is one of the basic strategic movements for controlling environment pollution. NP-based sensors can be a suitable tool for rapid detection of air pollutants. Much progress in this regard has been made with the invention of intelligent dust, composed of a set of very light computerized nanosensors, which can easily remain in the atmosphere for hours (Mohammadian et al. 2013). Apart from being smaller and sensitive than others, these nanosensors have the advantages of being cost effective due to very limited power utilization and efficient execution.

Majority in this aspect is contributed by carbon-based nanosensors for label-free sensing of environmental pollutants (Ramnani et al. 2015). CNT-based nanosensors are being designed to sense even very few amount of pernicious and killer gases present in the environment industrial effluents. According to the report of Kong et al., SWCNTs can be synthesized and deposited on Si substrates that can detect very minute amount of NO_2 (2–200 ppm) and NH_3 (0.1–1 %) present in air (Kong et al. 1998). Reduction of conductivity of SWCNT after absorption of NH_3 is used to detect the presence of this gas in air. These CNT-based gas sensors are reported to be ensuring faster response, greater sensitivity, and lower working temperature than conventional sensors (Zhang et al. 2012a, b). Graphene, another carbon-based structure, is also getting intense importance in devising nanosensor for their fascinating optical and electrochemical properties (Wu et al. 2013). Scientists at Pacific Northwest National Laboratory (PNNL), USA in partnership with PANalytical B.V., USA, developed functionalized nanoporous thin films (FNTF). The technology is a low-cost, highly selective means for detecting heavy metals in aqueous environments. It allows testing for virtually every heavy metal (including Hg, Pb, and Cd) with potential to negatively affect human health and the environment, and increases sensitivity by more than a thousand times the previous capability. Unique optical properties of silver NP are utilized to develop highly sensitive Hg^{2+} sensor (Wu et al. 2012; Ahmed et al. 2014). Similarly, plasmonic properties of gold NPs have facilitated their use as colorimetric detection agent of nitrate and nitrite contaminations (Daniel et al. 2009; Ye et al. 2015). Novel bimetallic Pt NP (PtM (M = Ru, Au, and Ir)) based biosensor was found to have more efficiency than Pt catalyst alone for target-specific H_2O_2 detection (Zhang et al. 2012c). Magnetic NP-mediated sensors (polydopamine-coated Fe_3O_4 NPs) are recently being developed for direct detection of small pollutant molecules (Ma et al. 2013). Recently, Nanobioelectronics and Biosensors group from Catalan Institute of Nanotechnology in Bellaterra, Spain has developed unique low-cost, user friendly, and efficient bacterial cellulose nanopaper (BC)-based sensors (Morales-Narváez et al. 2015). A highly sensitive *Leishmania* DNA detection platform, made up of iridium oxide NP and polythionine thin film, was developed by the same group (Mayorga-Martinez et al. 2015). Aptamer-based electrochemical sensor is also another emerging technique to detect toxic contaminants (Hayat and Marty 2014).

The cost of establishing and implementing ordinary monitoring systems is extremely high; the use of analytical instruments are time-consuming, expensive, and can seldom be applied for real-time monitoring in the field, even though these can give a precise analysis (Lee and Lee 2001). Hence, a new generation of detectors, solid state gas sensors, offer an excellent alternative for environmental monitoring due to low-cost, light weight, extremely small size, and also due to the reason that they can be deployed anywhere so as to receive data that can eventually be transmitted through a wireless network system as a rapid monitoring tool to the general public. This portable device, comprising solid state gas sensors integrated to a personal digital assistant (PDA) linked through Bluetooth communication tools and global positioning system (GPS), will allow rapid dissemination of information on pollution levels at multiple sites simultaneously. The air quality report generated can be then published using Internet GIS to provide a real-time information service for the PCD, for increased public awareness and enhanced public participation. The local deterministic and geostatistical interpolation methods have been used for spatial prediction, and to find out the most suitable method for studying air pollution, based on observations at each monitoring site.

Sustainable agriculture

Indiscriminate use of agrochemicals in the form of pesticides, herbicides, fertilizers, etc. is one of the major sources of polluting soil and ground water, which ultimately pollutes the whole ecosystem. Nanotechnology promises to reduce pesticide use, improve plant and animal breeding, and create new nano-bioindustrial products. It promises higher yields and lower input costs. It also offers the potential to employ less skilled and therefore cheaper, farm machinery operators.

Precision farming has been a long-desired goal to maximize agriculture output (i.e., crop yields) while minimizing input (i.e., fertilizers, pesticides, herbicides, etc.) through monitoring environmental variables and applying targeted action. Nanotechnology will have a large impact on future precision farming methodologies enabled by tiny sensors and monitoring systems. Precision farming makes use of computers, GPS, and remote sensing devices to measure highly localized environmental conditions thus determining whether crops are growing at maximum efficiency or precisely identifying the nature and location of problems. By using centralized data to determine soil conditions and plant development, seeding, fertilizer, chemical, and water use can further lower the production costs and potentially increase the production. It can also help reduce agricultural waste and keep environmental pollution to the minimum. Nanotechnology-enabled devices will increase use of autonomous sensors linked to a GPS system for real-time monitoring. These nanosensors can be suitably placed in the field to monitor soil conditions and crop growth. Multilayer silver NP-modified optical fiber tip has already been developed as sensing device that can detect 200 nM of the Rhodamine 6G dye in remote sensing mode (Fan et al. 2011). Similar study has also resulted in nanomaterial-based portable sensing device to detect polyphenolic antioxidants in remote locations without the need of high throughput instrumentation (Sharpe et al. 2014; Sharpe and Andreescu 2015). Recently, NP-based sensors for trapping toxic metal cations in environmental samples have been developed. The working principle of this nanosensor is based on the measurement of the tunneling current across cross-linked films of NPs, decorated with striped monolayers of organic ligands (Rurack 2012; Cho et al. 2012).

It is well known that prolonged exposure to chemical pesticides like organophosphates, pyrethroides, and fumigants may lead to neuronal and hormonal disorders, and also lead to environmental contamination (Haviland et al. 2009; Bouchard et al. 2010; Harari et al. 2010). One such commonly used fumigant methyl bromide is directly implicated in depletion of ozone layer. The Montreal Protocol has banned its use in developed countries and its use is restricted in developing countries (USDA 2000). Slow release agrochemicals will obviously reduce the dosage of these hazardous chemicals and will ultimately reduce the load of pollutant (Cao et al. 2005). Our research group has made a host of NPs to protect crops from insect and microbe attack. For example, Debnath et al. showed that surface-functionalized nanosilica can be an alternative to the commercially available insecticides (Debnath et al. 2010, 2011). It was found that these nanosilica-based insecticides are extremely effective against different grain storage pests like *Sitophilus oryzae* (Fig. 2), *Tribolium castaneum*, etc. and also field insect pests like *Spodoptera litura* (Fig. 3), *Lipaphis pseudobrassicae*, etc. These physically active nanocides disrupt the cuticular water barrier of insects and the insects begin to lose water and they ultimately die due to desiccation. Toxicological studies in murine model system revealed that these nanocides are nontoxic to human beings if applied in physiologically relevant dosage (Debnath et al. 2012).

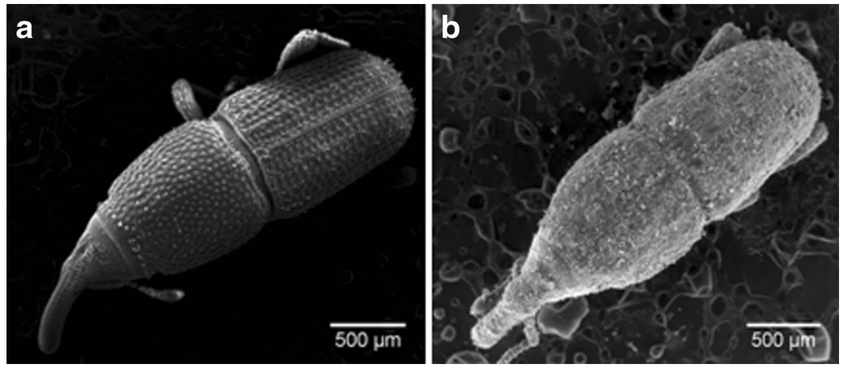
Patra et al. demonstrated that nano zinc oxide could cause ROS-mediated damage to fungal hyphae of *Aspergillus niger* and *Fusarium oxysporum*, two fungi of important agricultural pathogens. In all these cases, nanoformulations proved to be much more effective than their pathogenic counterpart (Patra et al. 2012). Das et al. showed that lipophilic nanosilica caused physical distortion to the polyhedral wall of *Bombyx mori* nuclear polyhedrosis virus (BmNPV), the dreaded virus causing 100 % mortality of silkworm larvae (Das et al. 2013). Treating BmNPV with lipophilic nanosilica reduced the virulence of this virus to a great extent (survivability of treated BmNPV-infected silkworm larvae was increased to 70 %). Detailed toxicological study both in vitro and in vivo model systems revealed that all these nanoformulations are almost nontoxic to mammalian system, if applied in physiologically relevant dosage. Moreover, toxicogenomics study in wild-type *Drosophila melanogaster* established that these nanocides did not perturb the genome (Das et al. 2012).

Efficiency enhancement of renewable energy systems

Secure, affordable, and clean energy supply is fundamental to global economic growth and human development and presents huge challenges for the whole world. Moreover, the popular sources of generating energy like combustion of fossil fuel produce green house gases. In this scenario, solar energy is the most suitable alternative for cleaner energy source to cater the energy demand of human civilization. Nanotechnology can be used to make solar power cheaper and more efficient. Development of "3D graphene" in which the graphene sheets are held apart by lithium carbonate to replace the platinum in a dye-sensitized solar cell has achieved 7.8 % conversion of sunlight to electricity (Wang et al. 2013). Another report from researchers at MIT, USA, have shown that solar cell composed of graphene coated with ZnO nanowires is moving toward the development of low-cost flexible solar cells at high enough efficiency [http://mitei.mit.edu/news/nanowires-and-graphene-keys-low-cost-flexible-solar-cells]. Aerotaxy is another breakthrough of nanotechnology in solar energy development where semiconducting nanowires are growing on gold NPs to use self-assembly techniques to align these nanowires, leading toward formation of highly efficient solar cell or other electrical devices (Wallentin et al. 2013). Incorporation of core-shell gold-silica (Au-SiO_2) NPs into dye-sensitized solar cells along with an active layer (thinner than the wavelength of light) resulted in entrapment of most of the light in the solar cell and also eliminated losses due to reflection of light. The entrapment was due to plasmon-enhanced light absorption and photocurrent (Brown et al. 2011).

Metal oxide semiconductors are today the most promising materials for photoelectrochemical production as they absorb photons from the solar light exiting the electron to a higher energy level, leaving a positive "hole." Both the electron and hole then move to the surface where the energy can be utilized

Fig. 2 SEM images of **a** control and **b** nanosilica-treated *Sitophilus oryzae* showing mortality



for different molecular reactions. So the whole process is dependent on optimization of photocatalyst, optimized band structures, defined particle size for surface charge distribution, and crystallinity. Recent advancement in this field came from development of hybrid nanostructure based on doped and non-doped TiO_2, ZnO, and Fe_2O_3. Hybrid complex made from the combination of silver nanowires, TiO_2 NPs, and a polymer that absorbs infrared light makes solar cell about 70 % transparent to visible light. These solar cells are much cheaper and even can be used in windows (Mattson et al. 2009; Richter et al. 2007; Service 2013; Aroutiounian et al. 2005).

Fossil fuel is another natural source of energy to mankind which is also limiting with ever-increasing global need. In this context, development of low-cost fuel cell is another challenge to the living world. Conventional fuel cell utilizes highly expensive platinum as catalyst to produce hydrogen ions from fuel sources like hydrogen and methanol, and also they use costly membranes to selectively pass through only hydrogen ions limiting other atoms or ions, such as oxygen. Researchers are using nanotechnology to create alternative for platinum-based catalyst and more efficient membranes that will allow them to build lighter and longer lasting inexpensive fuel cells. In this regard, platinum NPs can be a suitable alternative to reduce platinum usage as catalyst. It has been found that the spacing between platinum NPs affected the catalytic behavior, and the amount of platinum needed in a fuel cell can be reduced by controlling the packing density of the platinum NPs (Liu et al. 2002; Gebauer et al. 2014). Graphene sheet coated with cobalt is also being used as an alternative catalyst to fuel cell that totally eliminates the usage of platinum.

Proton exchange membrane fuel cells with silicon-based inorganic–organic membrane offers high potential for applications in energy conversion and energy storage with respect to conventional Nafion-based fuel cell membrane due to higher proton conductivity, and membrane electrode assembly construction capabilities (Pengwang et al. 2010). Here, the proton exchange membrane uses a silicon layer with pores of about 5 nm in diameter capped by a layer of porous silica. The silica layer is designed to ensure that water stays in the nanopores making the fuel cell more efficient. Since we are consuming disproportionate amount of energy, conservation of energy is of utmost importance. Several NP-based applications have been developed for this specific sector to improve the strength and efficiency of construction components, energy efficiency, and safety of the buildings. TiO_2, Al_2O_3, and ZnO NPs are now being used widely as durable and pollutant-

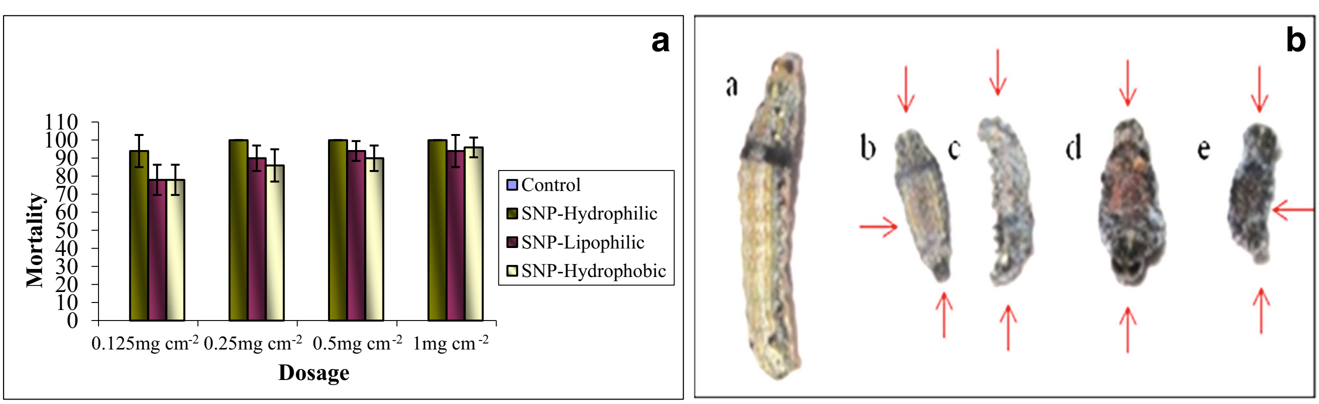


Fig. 3 **a** Mortality of surface functionalized nanosilica-treated *Spodoptera litura* larvae after 24 h of treatment. **b** Control larva was flaccid (*a*), whereas dead bodies of nanosilica-treated larvae (*b–e*) dehydrated and shrunk

resistant coating on construction ceramics and photovoltaic cells as well (Euvananont et al. 2008; Sun et al. 2012a, b; Chen et al. 2012; Al-Juaid and Merazga 2013; Hoex et al. 2008; Calnan 2014).

NPs can be synthesized with crystallite size of 50 nm, indicating greater surface area and thus better heat transfer. This concept has been utilized to develop new class of heat transfer fluid "nanofluid." It has been found that these fluids are capable of developing highly conductive thermal insulator. Oxide nanofluid consisting of a mixture of CuO and Al_2O_3 NPs showed substantially higher thermal conductivities than the same liquids without NPs (Lee et al. 1999). Similar study also reported that conductivity of ethylene glycol was found to be augmented by up to 40 % for a nanofluid consisting of 0.3 % (*v*/*v*) nanosized copper particles (10 nm) (Eastman et al. 2007). Silica-based aerogels consisting of nanopores filled with air have high thermal conductivity which makes them suitable to make lighter weight, more effective insulators for home, electronic components, clothing, and even spacecraft (Schmidt and Schwertfeger 1998).

Conclusions

Due to novel physicochemical properties, NPs have huge potential to combat environment pollution. A large array of nanomaterials are being investigated for their potential to make the earth clean. But most of these nanomaterial-based environment remedies are still in R&D stage. Only a few commercial products are available in the market for their large-scale application. It is expected that in the coming years, there will be numerous nanotools for environmental remediation. But at the same time, it should be closely monitored that these materials do not contaminate the environment further.

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