Chapter 29
Nanotechnology for Remediation of Water Environment

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Abstract The application discussed in this paper is of nanotechnology in remediation and treatment of the water environment. Water treatment and remediation are considered one of the most promising environmental applications of nanotechnology, as various nanoparticles can purify water through a variety of mechanisms. Various types of nanoparticles are actively being researched and developed due to their particular activity against refractory pollutants and application versatility. Nanoparticles or nanomaterials are those which at least have one dimension in the 1–100 nm range. They have created a whole new generation of water purification technology. The application of advanced method of nanotechnology in comparison with contemporary processes such as sedimentation, chlorination, filtration, and disinfection creates the new potential for technological advancements in treatment of water and wastewater. The advantageous properties of nanoparticles in applications have been spotlighted in this paper. When in comparison with the traditional techniques, positive features of these materials as well as technical hurdles are also discussed in this paper. As best of my knowledge, not much developmental work has been completed out in this area. This paper is completely based on the literature review, and most measures mentioned in this paper are based on the theoretical or conceptual ideas, though their practical implications may behave as expected.

Keywords Nanotechnology · Nanoparticles · Environment · Nanomaterials · Sedimentation · Chlorination · Filtration · Disinfection

29.1 Introduction

Water is an inorganic, transparent, tasteless, odourless, and almost colourless chemical substance which is one of the main constituent of earth's hydrosphere and all known living organisms' fluids in which this acts as a solvent. It is necessary for all known forms of life, despite the fact that it contains no calories or organic ingredients.

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Water covers about one-third of the earth's total surface. Most of the available water is saline and unfit for the human consumption. Out of total world's total available water on earth, fresh water makes up only 2.5% of the total. One of the most serious problems that people confront around the world is a lack of access to clean and safe water. The provision of safe and clean water has been become a basic human requirement.

Water contains various contaminants and the chemicals which are used whilst treatment of water includes chlorine (Cl2), ammonia (NH3), hydrochloric acid (HCl), ozone (O3), permanganate, ferric salts, coagulants, ion exchange resins, etc. All these compounds can damage freshwater resources to a larger extent. Contemporary water treatment technologies such as the coagulation, sedimentation, filtration, desalination, disinfection, and decontamination have been used since the early twentieth century. Chemically and operationally intensive, the foregoing processes necessitate big systems, infrastructure, and engineering skills, all of which are costly, making these processes inconvenient, unproductive, time- consuming ineffective, and expensive to use.

Membrane processes are significantly increasing in the water purification, as traditional water treatment procedures are unable to remove organic pollutants at the required levels. Nanofiltration (NF), microfiltration (MF), and ultrafiltration (UF) for the water and wastewater treatment and reverse osmosis (RO), nanofiltration (NF) for the desalination and water reclamation are examples of membrane techniques commonly employed in water purification. All traditional water purification systems have a number of disadvantages, whereasnanotechnology provides a framework for delivering speedy results. Nanotechnology has a number of intriguing applications to filter out organic and inorganic pollutants. Nanotechnology can efficiently remove various heavy metals such as cadmium, arsenic, lead, and mercury. It can also remove biological pollutants which can cause water-borne illnesses such as typhoid and cholera fever.

The study of manipulating matter on an atomic scale is known as nanotechnology. It refers to the micro-engineering and creation of functional systems. Nanomaterials and nanostructures have the nanoscale diameters ranging from 1 to 100 nm, and they frequently shows novel and drastically altered physical, chemical, and biological properties.

As nanoscale materials have a huge surface area compared to their volume, their reactivity in biological or chemical surface mediated reactions can be significantly increased when compared to the same substance at much larger sizes. They can be enhanced for specific applications to provide unique characteristics not present in micro or macroscale particles of the same substance. However, they can show changes in reaction rates that surface area alone cannot account for. These characteristics allow for higher interaction with contaminants leading in quick contaminant concentration reduction. Nanoscale materials can also penetrate very small spaces in sub-surface and remain suspended in groundwater provided proper coatings are applied, owing to their small size. Under the category of remediation and treatment, nanotechnology has huge potential in order to contribute to the long-term water quality, viability, and availability of water resources.

29.1.1 Classification of Nanoscale Materials

Nanoscale materials can be classified into majorly three classes such as natural, accidental, and artificial nanoscale materials.

Materials at nanoscale that can be obtained naturally or created artificially includes:

- Carbon nanotubes and fullerenes which exist as hollow spheres (bucky balls), ellipsoids, or tubes (nanotubes) made completely of carbon. They have great thermal and electrical conductivity. They are potent antioxidants, stable, little reactivity. Biomedical, super-capacitor, sensor, and photovoltaic applications all use them.
- Zinc oxide (ZnO), cerium oxide (CeO_2), iron oxide (Fe_3O_4) and titanium dioxide (TiO_2) are nanosized metal oxides that may block UV light. They are made up of hundreds or thousands of atoms in closely packed semiconductor crystals. Metal oxides are used in photo catalysts, pigments, medications to regulate release, medical diagnostics, and sunscreen.

Engineered nanoscale materials include:

- Zero-valent metals, for example, nanoscale zero-valent iron (nZVI), which has a high-surface reactivity and is used in the remediation of water, soil, and sediments.
- Dendrimers are defined as highly branched polymers with a wide variety of functional groups that can be designed and synthesized. Cones, spheres, and disc-like structures are common shapes of dendrimers. They are employed in medication delivery, chemical sensing, electrode modification, and DNA transfer agents.
- Two or more than two different nanoscale materials, or only one nanoscale substance mixed with bulk type materials, make up the composite nanoscale materials. Biological and synthetic molecules can be incorporated with the composite nanoscale materials to provide new electrical, catalytic, magnetic, mechanical, thermal, and imaging capabilities.

29.2 Methodology

As mentioned earlier, basis of this report is theoretical study and conceptual analysis. So, I have used various sources such as case studies on the applications of nanotechnology in remediation of water environment.

As nanotechnology encompasses a wide range of tools, techniques, and applications involving particles with diameters varying from a few to hundreds of nanometers and these size of particles has several unusual physicochemical and surface features that lend itself to new applications. Indeed, proponents of nanotechnology argue that this field of study might help solve some of the world's most pressing difficulties, such as providing a steady supply of safe drinking water for a growing population, as well as issues observed in medicine, energy, and agriculture.

Here, on the basis of properties, a comparative study between various types of nanoparticles has been done. I have considered some basic features that may affect the various properties of nanoparticles under variety of conditions, and then, the subsequent changes in the result of nanoparticles are mentioned. Using various case studies, I have also looked into the performance of nanoparticles in a variety of water environments. There is a critical comparison of the nanoparticles as not much developments are performed in this area yet. Hence, there is a dire requirement to consider the applications of nanotechnology in this area.

Although here lab testing was not done, the results obtained in this study are very much dependent on the theoretical verification and that forms the foundation for the future studies on the topic, as there are various other aspects which still have not been discussed as they are not in the scope of the study, such as the economical aspect and departmental willingness to adopt newer technologies and apply them on the existing circumstances.

29.3 Literature Review

29.3.1 Different Types and Applications of Nanoparticles

See Fig. 29.1.

29.3.2 Properties of Nanoparticles

All the bulk or heavy materials have diverse properties, such as mechanical, electrical, and optical qualities, which are further dependent on their structural properties like metals, insulators, and semiconductors. Nanoparticles have features that distinguish them from tiny molecules and their chemistry along with the manufacture can be considered to be complicated.

The ability of molecules to interact with nanoparticles on their surfaces and interchange with other molecules or particles indicates the chemistry of nanoparticles and how it relates to their fate in surface waters and sediments, as this is a critical factor in determining their ultimate fate. When one of the three spatial dimensions is comparable to or smaller than the wave length of de Broglie (λ) of the charge carrier of electrons and holes or the wavelength of light, periodic boundary conditions destroy crystalline materials or change the atomic density on the surface of amorphous materials. Many of the physical properties of the nanoparticles differ significantly from those of bulk materials as the result of this trait, resulting in a wide range of novel uses.

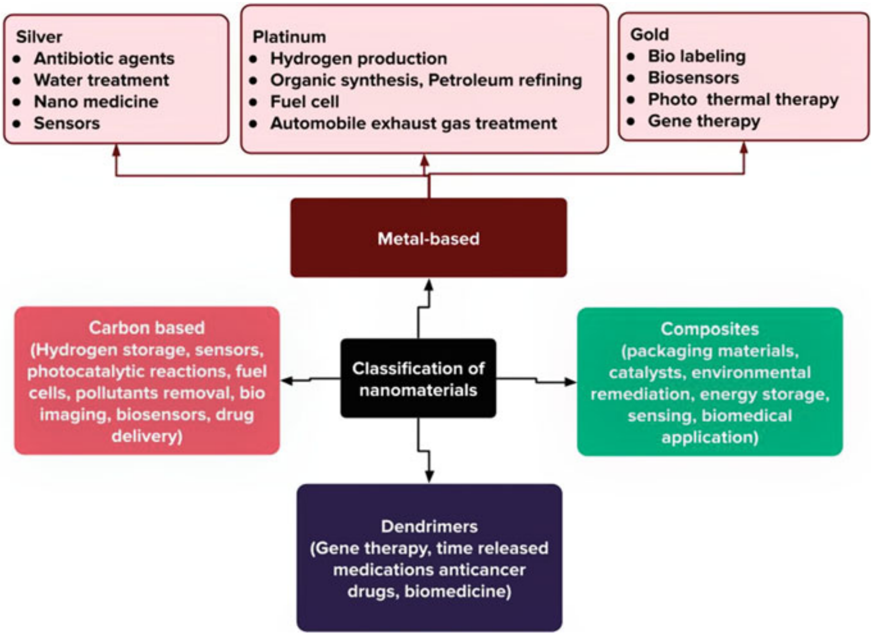

Fig. 29.1 Classification as well as the broad range of utilization of various types of nanoparticles

29.3.2.1 Adsorption

Adsorption is defined as the property of all solid state substances to attract molecules of liquids or gases to their surfaces when they are in close proximity. Adsorbents are solids which are used in order to adsorb the gases or dissolved chemicals, and the molecules which are adsorbed are referred to as the adsorbate collectively. Nanoadsorbents have a far higher rate for the adsorption of organic chemicals than granular or powdered activated carbon because of their large specific surface area.

They hold significant promise for developing new, more effective, and faster decontamination techniques for inorganic and organic pollutants such as the heavy metals and micro-pollutants. The increased process efficacy allows for the development of even more compact water and wastewater treatment devices having smaller footprints specifically for the decentralized applications and of point-of-use systems, in addition to saving adsorbent materials (Table 29.1).

Out of the following types of nanomaterials mentioned above, nanoadsorbents are the subject of current research:

- nanoadsorbents made of carbon such CNTs
- nanoadsorbents made of metals such as ZnO, TiO_2
- polymeric nanoadsorbents
- zeolites

Table 29.1 Overview of types of nanoparticles with properties and respective applications

Nanomaterial	Positive properties	Negative properties	Applications
1. Nanoadsorbents	High-specific surface, higher adsorption rates, small footprint, short intra-particle diffusion distance	High-production costs	Point-of-use, removal of organics, heavy metals, bacteria
2. Nanometals and nanometal oxides	short intra-particle diffusion distance, compressible, abrasion-resistant, magnetic, photocatalytic (WO_3, TiO_2)	Less reusable	Removal of heavy metals (arsenic) and radionuclides, media filters, slurry reactors, powders, pellets
3. Membranes and membrane processes	Reliable, largely automated process	Relative high-energy demand	All fields of water and wastewater treatment processes

(i) Carbon nanotubes (CNTs)

Carbon nanotubes (CNTs) are carbon allotropes with a cylindrical nanostructure. CNTs are classified as the single walled nanotubes or multi-walled nanotubes depending upon their manufacturing procedure. CNTs have a large specific surface area, as well as highly assessable adsorption sites and a chemistry that may be adjusted. CNTs also have antibacterial characteristics because they cause oxidative stress in bacteria and damage cell membranes. Despite of the fact that chemical oxidation takes place, no harmful by-products are formed, which is a significant benefit over traditional disinfection methods like chlorination and ozonation.

Adsorption-based techniques are simple and easy to use for point-of-use water purification devices, but their capacity to remove salts is limited. Traditional desalination methods are energy-intensive and technically demanding. Despite their major benefits over activated carbon, CNTs are unlikely to be used on a broad scale for big municipal wastewater and water treatment plants in the coming future due to high-production costs.

(ii) Nanoadsorbents made of metals

Nanoscale metal oxides are one of the potential adsorbents for heavy metals and for the radionuclides which are effective alternatives to activated carbon. They have a huge amount of specific surface area, a short intra-particle diffusion distance which can be compressed without losing much of their available surface area. Because some of these tiny metal oxides are superparamagnetic, they can be separated and recovered using a low-gradient magnetic field. Adsorptive media filters and slurry reactors can both benefit from them.

Nanometals and nanometal oxides are typically compacted into porous pellets or used as powders in industrial applications (Table 29.2).

Table 29.2 Metal-based nanoadsorbents with properties and respective applications

Nanometals and nanometal oxides	Positive properties	Negative properties	Applications	Novel approaches
Nanosilver and nano-TiO_2	Nanosilver: bactericidal, low-human toxicity Nano-TiO_2: high-chemical stability, very long life time	Nanosilver: limited durability Nano-TiO_2: requires ultraviolet activation	Point-of-use, water disinfection, anti-biofouling surfaces, decontamination of organic compounds	TiO_2 modification for activation by visible light, TiO_2 nanotubes
Magnetic nanoparticles	Simple recovery by magnetic field	Stabilization is required	Groundwater remediation	Forward osmosis
Nano zero-valent iron	Highly reactive	Stabilization is required (surface modification)	Groundwater remediation (chlorinated hydrocarbon, perchlorates)	Entrapment in polymeric matrices for stabilization

(iii) Polymeric nanoadsorbents

Dendrimers which are repetitively branched molecules are the polymeric nanoadsorbents that can be used to remove organics and heavy metals. The interior of hydrophobic shells can adsorb organic substances, whilst the specialized outer branches can adsorb heavy metals.

Dendrimers are used in an ultrafiltration device to extract copper from the water. Using this combined dendrimer-ultrafiltration technology, nearly all the copper ions were collected. A pH adjustment is all it takes in order to renew the adsorbent. They are able to remove up to the count of 99% of some dyes.

However, because to the complicated multistage synthesis of dendrimers, no commercial providers have emerged so far.

(iv) Zeolites

Since the early 1980s, zeolites in conjunction with the silver atoms or particles have been well known. Nanoparticles such as silver atoms can be incorporated in the structure of porous zeolite. They are then exchanged with the other cations present in solution and freed from zeolite matrix. When a metallic surface comes into contact with liquids, a considerable small number of silver ions is released.

For the elimination of heavy metals such as arsenic, both CNTs and nanometals are particularly effective nanoadsorbents. Nanometals and zeolites are benefitted from their cost-effectiveness and their compatibility with the current water treatment systems in this application field because they are capable of being used in pellets and in beads for the fixed absorbers. In terms of ecotoxicity, the nanometals, carbon

Table 29.3 Overview of various types of nanoadsorbents with their properties and their respective applications

Nanoadsorbents	Positive properties	Negative properties	Applications	Novel approaches
Carbon nanotubes	Highly assessable sorption sides, bactericidal, reusable	High-production costs, possibly health risk	Point-of-use, heavily degradable contaminants (pharmaceuticals, antibiotics)	Ultra-long carbon nanotubes with extremely high-specific salt adsorption
Nanoadsorbents made of metals	Highly reactive	Stabilization is required (surface modification)	Groundwater remediation (chlorinated hydrocarbon, perchlorates)	Entrapment in polymeric matrices for stabilization
Polymeric nanoadsorbents	Bi-functional (inner shell adsorbs organics, outer branches adsorb heavy metals), reusable	Complex multistage production process	Removal of organics and heavy metals	Biodegradable, biocompatible, nontoxic bio-adsorbent (combination of chitosan and dendrites)
Zeolites	Controlled release of nanosilver, bactericidal	Reduced active surface through immobilization of nanosilver particles	Disinfection processes	Nanozeolites by laser induced fragmentation

nanotubes, and zeolites discussed here are made up of well-characterized fundamental materials that are found in nature and are categorized as harmless. As a result, the potential toxicity of nanoadsorbents is largely determined by their size and form, as well as chemical stabilizers and surface modifications. Because the ecotoxicity of each new alteration of a recognized nanomaterial must be re-evaluated, a general assessment of nanoadsorbents in terms of their toxicity potential is impossible (Table 29.3).

29.3.3 Nanomaterials and the Water Environment

In recent years, researchers have looked into the performance of nanoparticles in a wide variety of aqueous environments, including the ocean, river, lake, and wetlands. Environmental research groups have made it a priority to find environmentally friendly remediating agents in order to achieve the goal of restoring damaged soil and water bodies in order to begin an environmentally friendly economy.

Several recent analyzes have raised concerns about electro membrane (separation) technologies for removing charged components from solutions, such as producing fresh water from brackish water. Currently, nanoparticles are commonly used for treatment of sewage, and nano-photocatalytic technology is regularly used for oxidizing various organic compounds present in water by producing the hydroxide ions and superoxide ions with excellent activity and strong oxidation. Different nanostructured materials are currently employed in capacitive deionization (CDI), a new water treatment method.

In aqueous environments, the nanoparticles exhibit a variety of characteristics, with some nanomaterials demonstrating greater potential for water contamination remediation (Fig. 29.2).

Nanofiltration (NF) membrane technology, which uses pressure-driven membranes to separate the chemicals found in sewage, is also available. Furthermore, the hydroxyl groups on the nanoparticle surface bind to specific cations, causing certain nanomaterials to have an obvious adsorption impact on organics or metal ions. Carbon nanoparticles, for example, offer higher stability in acidic or alkaline environments and have a considerable large specific surface area (SSA), porous structure, and specialized binding sites, when compared to the traditional

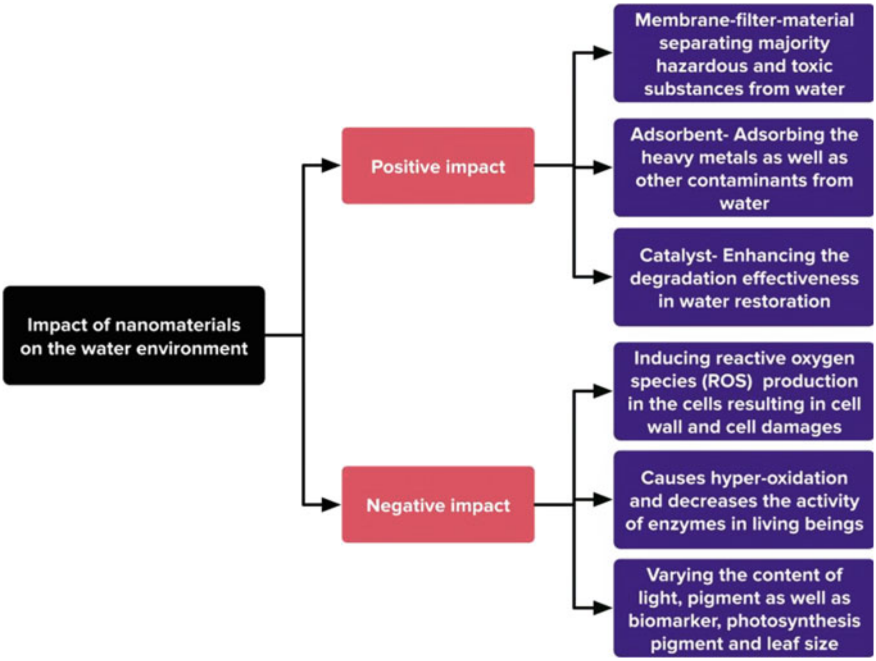

Fig. 29.2 Environmental impacts of variety of nanoparticles on water environment

sewage treatment chemicals. As a result, using nanoparticles for wastewater, treatment overcomes the shortcomings of traditional technology whilst simultaneously demonstrating good remedial efficacy.

29.3.4 Applications of Various Nanomaterials in the Water Environment

Various nanomaterials such as TiO_2 nanoparticles, silver nanoparticles, nano zerovalent iron (nZVI), zinc oxide (ZnO) nanoparticles, nanoscale graphene, nanofiber materials, carbon nanotubes, and nanofiltration membrane materials can help to clean up the contaminated water. Table 29.4 shows the most often used manufacturing procedures, operational principles and pollution cleans up for the aforementioned nanomaterials.

Mechanical milling is a nanomaterial fabrication technology which was developed in the 1970s as a method for creating sophisticated alloys and phase mixtures from the powder particles. The aforementioned technique can overcome the quantity limitations of nanocrystalline synthesis, allowing for large-scale production of nanocrystalline powders. One notable advantage is that it can operate at lower temperatures, allowing the grains to develop more slowly. The plasma process can be divided into two types: plasma spray synthesis and microwave plasma synthesis.

The ability to generate unagglomerated particles, a narrow particle size distribution, and better production rates is all advantages of this approach. Chemical reactions between the gaseous precursor and the substrate surface are stimulated in the chemical vapour deposition (CVD) method to deposit a thin solid coating onto the substrate. Because of its simplicity of scale-up, high-production yields, and low set-up cost, the aforementioned approach is a widely utilized material-processing technology. Laser ablation is a manufacturing technology that entails the use of a laser beam with an optical focussing system and a feeding apparatus.

Because of its lower yield and higher operational expense, the laser ablation process is not widely used, especially on a large scale. The centrifugal force can be used to create ultrafine fibres and nanoscale fibres utilizing centrifugal spinning technology. As a substitute approach for generating nanofibers, a solution blow spinning process combines components of both melt blowing and electrospinning technologies.

29.3.5 Limitations of Nanoparticles in Remediation for Water Applications

The influence of nanoparticles for water and wastewater technology on the water environment is critical to their commercialization. To examine the health concerns

Table 29.4 Use of different nanomaterials in treatment of polluted water

S. No.	Nanomaterials	Mechanism	Remediation	References
1	Titanium dioxide (TiO_2) nanoparticles	Ultraviolet light has the potential to excite TiO_2 nanoparticles and produces free radicals with high-catalytic activity, resulting in increased photo-oxidation and reduction capacity	Different inorganic and organic substances like formaldehyde	[13]
2	Silver nanoparticles	Bacteria will dry up and die as a result of the interaction with their metabolic enzymes. The smaller the particle, better the germicidal effectiveness	Role of water photocatalyst and the antibacterial agent	[14]
3	Zero-valent iron (nZVI)	Pollutant adsorption could be aided by the thin iron oxide core's surface complexation and electrostatic interaction	Azodyes, heavy metals, chlorinated aromatic compounds, organo-chlorine and nitro-aromatic compounds	[15]
4	Graphene nanomaterials	Porous features of the nanomaterial adsorb pollutants from the water	Dyes and heavy metals	[16]
5	Nanofiber material	Membranes of different pore widths are used to filter particles of varied dimensions	Different contaminants present in eutrophicated landscape water	[17]

of nanoparticles, numerous research has been conducted including toxicity tests, life cycle analysis, technology assessment, and routes of distribution of nanoparticles in water bodies.

The findings of these studies have led to a better understanding of the behaviour of nanoparticles such as carbon nanotubes (CNTs), titanium dioxide (TiO_2), and silver nanoparticles in aqueous systems which have aided stakeholders from government, politics, and industry in developing new laws and regulations or amending existing ones. However, because no uniform standards and circumstances for experimental tests and measurements have been established, numerous research has produced contradicting results, slowing down the crucial decision-making processes.

29.4 Discussions and Conclusion

This paper has looked at how nanomaterials have recently been used in water remediation for environmental cleanup. We also talked about the detrimental effects of nanoparticles in water. Carbon nanotubes (CNTs), graphene-based nanomaterials, silver nanoparticles, zinc oxide (ZnO), titanium dioxide (TiO_2), and nano zero-valent iron were amongst the nanomaterials studied.

According to the observations, graphene nanoparticles have a high-adsorption capability for surfactants, antibiotics, and other hazardous pollutants. These nanoparticles can also successfully remove heavy metal ions in water at very low concentrations. Despite the fact that the manufacturing of graphene oxide-based nanomaterials and their usage in environmental pollution purification are fraught with problems, it is expected that graphene oxide-based composites will be used in the field of wastewater treatment in the coming years as a result of the various steps taken by scientists. Furthermore, carbon nanotubes also have the potential to operate as excellent purifiers as they are capable of separating biological, inorganic, and organic impurities from water. Furthermore, the functionalized carbon nanotubes have a remarkable ability to absorb heavy metals from water and eliminate organic dyes.

Their unregulated discharge, on the other hand, has the potential to threaten biota in a variety of environmental domains, including soil and water systems. Though the nanotechnology for water remediation is new and its application, more lab or even field investigations are still needed to better understand the possible risks of nanomaterials.

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