Chapter 14
Wastewater Treatment Through Nanotechnology: Role and Prospects

Vivek K. Chaturvedi, Ankita Kushwaha, Shweta Maurya, Nazish Tabassum, Himani Chaurasia, and M. P. Singh

Abstract Water is a most crucial and limited resource on the Earth, which has contaminated due to the addition of heavy metals, pathogens, pesticides, and many organic and inorganic substances. Currently, the research has been focused on the sustainable remediation approach for waste reclamation. Therefore, an affordable technology of wastewater treatment could tackle the problem of water. Nanotechnology is an efficient, affordable, effective, and durable method for water treatment. Nanomaterials have several properties such as specific surface area, high reactivity, high degree of functionalization, size-dependent properties, etc., which make them appropriate materials in wastewater treatment. The present chapter comprehensively describes the characteristics of different nanomaterials and their role in the restoration of aquatic ecosystem.

Keywords Nanotechnology · Environmental pollution · Wastewater · Nanofiber membrane · Nanoadsorbents · Fullerenes

1 Introduction

Nanotechnology is an emerging technology of the twenty-first century used to solve the problem of water shortages and water pollution (Mueller and Nowack 2008). Nanotechnology provides new opportunities in technological developments for better wastewater treatment over the traditional physical, chemical, and biological process. Nano is derived from a Greek word which means “dwarf.” Nanomaterials are employed for the expulsion of toxic materials and wastages from water; therefore it plays a major role in the abstraction of water contamination (Amin et al. 2014).

V. K. Chaturvedi · A. Kushwaha · S. Maurya · N. Tabassum · M. P. Singh (✉)
Centre of Biotechnology, Institute of Interdisciplinary Studies (IIDS), University of Allahabad, Allahabad, India

H. Chaurasia
Department of Chemistry, University of Allahabad, Allahabad, India

A. K. Upadhyay et al. (eds.), *Restoration of Wetland Ecosystem: A Trajectory Towards a Sustainable Environment*,
https://doi.org/10.1007/978-981-13-7665-8_14

Water pollution is one of the main crises causing negative impact on plants and human health. Therefore, amplification of technologies for the betterment of the environment is the major need of the hour. Nanotechnology atop the traditional approaches propounds up to the minute opportunities in the technological upgradation for better wastewater technology scheme by employing antimicrobial nanomaterials (Pendergast and Hoek 2011). In this chapter, we enlighten the issue of fresh water and the cost-effective techniques of nanomaterials along with its interactions with several related biological systems (Theron et al. 2008) to treat the wastewater.

The Earth is the only planet of solar system where water (97%) exists (Grey et al. 2013; Pradeep 2009). However, due to its unprecedented utilization, mismanaged remediation of wastewater and high pollution level causes the water unfit for drinking and other agriculture activities. In a report of WHO, it was assumed that by 2025, half of the world's population will be living in water-deficient areas (WHO 2015). The water contains a number of toxic metals such as Hg, Cr, Pb, Co, Ni, As, and Ag, which damage the human health as well as the environment (Mishra et al. 2018; Theron et al. 2008; Yadav et al. 2017). Various traditional techniques are available for the treatment of wastewater, i.e., through a chemical and physical agent such as chlorine and its derivatives, ultraviolet light, boiling, low-frequency ultrasonic irradiation, distillation, reverse osmosis, water sediment filters, activated carbon, etc. This traditional technique of pollutants' removal from wastewater as well as drinking water suffers many disadvantages such as high cost, uses and disposal, and high energy requirement. So, there is an urgent need for the treatment of wastewater in a cost-effective and sustainable manner (Table 14.2).

Nanotechnology is a branch of nanoscience in which nanometer scale (1–100 nm)-sized particles are studied. Nanoparticles (NP) play an important role in willingness to numerous pollutants which is challenged to the environment due to their non-biodegradable and toxicity nature (Fig. 14.1) (Theron et al. 2008). Recently, a variety of approaches have been developed for the synthesis of high-quality nanoparticles (Kumari et al. 2015), nano-ovals, nanobelts (Fu and Wang 2011), and nanorings or other nanostructures. Nanostructured materials such as magnetic nanoparticle, carbon nanotubes, silver-impregnated cyclodextrin nanocomposites, nanostructured iron zeolite, carbon-iron nanoparticles, photocatalytictitania nanoparticles, nanofiltration membranes, and functionalized silica are able to treat the heavy metals, sediments chemical effluents, charged particles, and other pathogen like bacteria, viruses, as well as fungi (Table 14.1) (Amin et al. 2014; Chaturvedi et al. 2018).

Nanoparticles (NPs) are one dimensional structure with less than 100 nm (Amin et al. 2014) in size. Different type of nanoparticles are used for wastewater treatment but among them, metal oxide nanoparticles like titanium dioxide (TiO_2), zinc oxide (ZnO), and cerium oxide (CeO_2) show high reactivity and photolytic properties against wastewater. They act as a good adsorbent for water purification because they have a large surface area and their affinity can be enhanced by using various functionalized groups (Lu et al. 2016). ZnO nanoparticles have been used

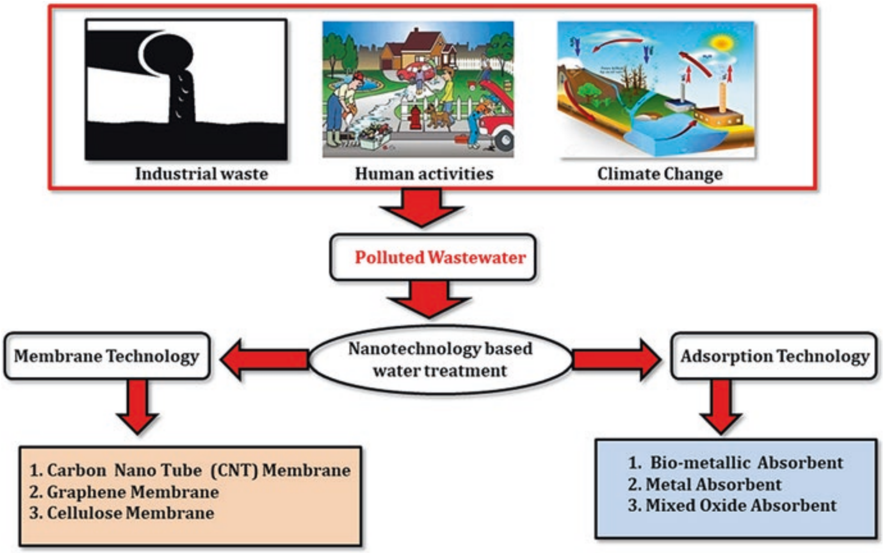

Fig. 14.1 Nanotechnology based wastewater treatment

to get rid of arsenic from water (Muñoz-Fernandez et al. 2016). Ag NPs has high antibacterial activity so that it fixed to filter materials for treatment of water waste. It is cost-effective and considered as the best NP for water purification. Several investigators reveal about fabricated nanostructured ceramic membrane containing zinc oxide and titanium involving in degradation of photo catalytically pollutants and check the growth of microorganisms (Reinhart et al. 2010). Since nanoparticle-based wastewater treatment has high in demand, its usage cost should be managed according to competition in the market (Crane and Scott 2012). A number of nanomaterials such as nanocatalysts, nanostructured catalytic membranes, biomimetic membrane, nanosorbents, bioactive nanoparticles, and molecularly imprinted polymers (MIPs) are also used for removing toxic metal ions, disease-causing microbes, organic and inorganic solutes from water waste (Anjum et al. 2016).

2 Role of Inorganic Nonmaterials in Wastewater Treatment

Inorganic nanomaterials are made of up inorganic compound which is used in the wastewater treatment (Fig. 14.2). Here, we described different type of inorganic nanomaterials and their role in a wastewater treatment.

Table 14.1 Summary of the removal of heavy metals from wastewater

S.N.	Zero valent iron (ZVI)	Removal of heavy metal ions from water	Summary	References
1.	Z-nZVI	Pb(II)	More than 96% of the Pb(II) was removed from 100 mL of a solution containing 100 mg Pb(II)/L within 140 min of mixing with 0.1 g Z–nZVI	Kim et al. (2013)
2.	nZVI	Cd(II)	Simultaneous removal of cadmium and nitrate in aqueous media by nanoscale zero valent iron (nZVI) and Au doped nZVI particles	Su et al. (2014)
3.	K-nZVI	Pb(II)	More than 96% of Pb(II) was removed from aqueous solution using K-nZVI at an initial condition of 500 mg/L Pb(II) within 30 min under the conditions of 10 g/L of K-nZVI, pH 5.10, and a temperature of 30 °C	Zhang et al. (2011)
4.	Ferragels	Cr(VI) and Pb(II)	Quick removal of Cr(VI) and Pb(II) from aqueous solution using supported nZVI ("Ferragels"). The result indicates supported nZVI, while oxidizing the Fe to goethite (R-FeOOH) reduced the Cr to Cr^{3+} and the Pb to Pb°	Ponder et al. (2000)
5.	nZVI	Cd(II)	They reported NZVI for the removal of Cd(II) (conc. range 25–450 mg/L). The results recommend the competent removal of Cd(II) from contaminated water	Boparai et al. (2011)
6.	P-NZVI	Hg(II) and Cr(VI)	They investigated NZVI supported on pumice (P-NZVI) successfully removed Hg (II) and Cr (VI) from wastewater. The maximum uptake of Hg(II) and Cr(VI) onto P-NZVI was 332.4 and 306.6 mg/g, respectively	Liu et al. (2014)

2.1 Iron Oxide Nanomaterials

Colloidal and particulate forms of iron metals are constitutes in hydroxides, oxides, silicates, sulfides, or grab to adsorbed on clay, silica, or organic matter (Boparai et al. 2011). Iron oxides exist in various forms in nature out of which magnetite (Fe_3O_4), maghemite (Fe_2O_3), and hematite (Fe_2O_3) abide the uttermost prevalent forms (Ferroudj et al. 2013; Wang et al. 2013). In recent years scientist focuses on the preparation of iron oxide nanomaterials for wastewater treatment due to their high surface area to volume ratio and superparamagnetism (Mahdavian and Mirrahimi 2010; Oliveira et al. 2003; Ponder et al. 2000; Pendergast and Hoek 2011). Furthermore, iron oxide nanoparticles show lesser toxicity, chemical inertness, and biocompatibility and exhibit outstanding potential in consolidation with biotechnology (Morones et al. 2005; Nakamura and Isobe 2003). For removal of toxic heavy metals from groundwater, the surface functionalized iron oxide nanomaterials have been used as a nanosorbent. Improvement in iron oxide nanomaterial

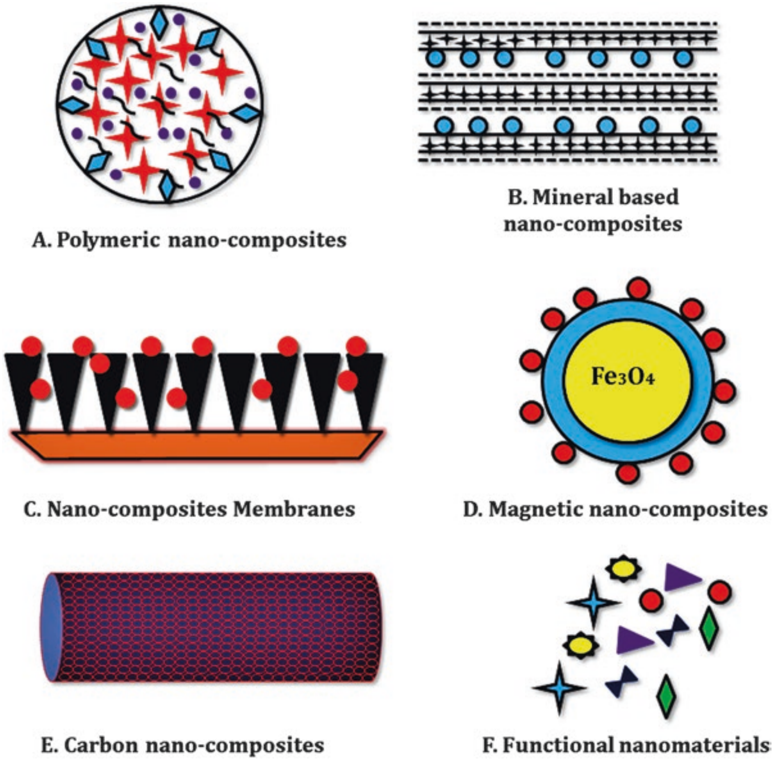

Fig. 14.2 Schematic illustration of nanomaterials used in the removal of wastewater treatment

development, along with the achievement of monodisperse, shape formation is validated on the basis of surface active sites (Li et al. 2016). The removal of water waste by iron oxide nanomaterials is worked at the micro- or macro-scale level, which allows nanoparticles to exhibit their reactivity while being complemented by the adsorbent properties of the accompanying materials. Chitosan is a well-known example of iron oxide nanomaterial. Chitosan is a natural substance and hydrophilic in nature and contains active sites along its polymeric chain due to $-NH_2$ groups. Hence, chitosan regarded as a novel biosorbents for water and wastewater treatment (Ahmaruzzaman 2008; Ngah et al. 2011).

Iron oxide nanoparticles have magnetic property and can react with a various functional groups so that researchers approached toward modification of iron oxide nanomaterials by incorporation of various functional groups. To accelerate iron oxide nanoparticle stabilizer, electrostatic surfactant and steric polymers had been used with non-specific moieties and group-specific or highly specific ligands. Durability and sustainability of iron oxide colloid suspensions could be achieved by surface modification through the implementation of suitable functional groups, such as phosphoric acids, carboxylic acid, and amine (Liu et al. 2010). We know that the in vitro modifications of nanomaterial are medium specific, and a series of the medium can be needed to introduce functional groups in iron oxide nanoparticle. For this, a robust protocol is needed to achieve alteration of nanomaterials. The iron oxide nanomaterials are well dispersed even in industrial application. It should be noted that the application of iron oxide nanomaterials is related to their intrinsic properties, which depend on the preparation method and modification mediums (Neyaz et al. 2014)

Selection of the best method and material for wastewater treatment is a highly complex and tough task, considering a number of factors, such as the quality standards to be met and the efficiency as well as the cost. Therefore, the following four criteria must be considered for preparation of nanomaterials on wastewater treatment technologies: (1) treatment flexibility and final efficiency, (2) reuse of treatment agents, (3) environmental security, and (4) low cost (Xu et al. 2012; Zhang et al. 2013). Magnetism is a distinctive property that helps in water purification by influencing the physical properties of contaminants in water. Therefore, for water treatment and environmental clean-up adsorption procedure, the magnetic separation has been extensively used. At industrial level wastewater treatment, iron oxide nanomaterials show promising results because of their low-cost, simple separation, strong adsorption capacity, and increased stability. The ability of iron oxide nanomaterials to remove contaminants has been demonstrated at both laboratory and field scale tests (Boparai et al. 2011). Current applications of iron oxide nanomaterials in contaminated water treatment can be divided into two groups: (a) technologies which use iron oxide NMs as a kind of nanosorbent or immobilization carrier for removal efficiency enhancement (referred to here as adsorptive/immobilization technologies) and (b) those which use iron oxide nanomaterials as photocatalysts to break down or to convert contaminants into a less toxic form (i.e., photocatalytic technologies) (Oliveira et al. 2003; Ponder et al. 2000). Water contamination with heavy metals not only is a threat to the aquatic organisms but also causes severe health disorder in humans by accumulation through precipitation and adsorption and transferring through the food chain. The toxicities of heavy metals may be caused by the inhibition and reduction of various enzymes, a complication with certain ligands of amino acids and substitution of essential metal ions from enzymes (Zhang et al. 2011; Oliveira et al. 2003).

2.2 TiO_2 Nanoparticles

Titanium (Ti) is the seventh most abundant metal in the Earth's crust with significant worldwide reserves >600 million tons, with the annual production, approximately 4.3 million tons titanium dioxide (TiO_2) (Wang et al. 2012). Ti has multifarious industrial applications such as in metal alloying, in aerospace applications, and in biomedical devices (Ghaly et al. 2011). Food-grade TiO_2 ranges in size from tens to hundreds of nanometres; the typical mean diameter is proximately 200 nm. Approximately, 95% of mined Ti is refined to pure TiO_2 by extraction of Ti-bearing ores along with carbon, chlorine, oxygen, or sulfuric acid. In the current period, a number of TiO_2 nanoparticle aggregates are deployed (i.e., bulk TiO_2 products), and industrial trends have been suggested that much higher amount of TiO_2 will be deployed in the near future because of its inert nature, somewhat opaque, and resist fading nature (Kiser et al. 2009). Active and passive depletion of consumer products comprise of nanomaterials (e.g., food additives, pharmaceuticals, and clothing) cause to excretion of engineered nanomaterials into domestic sewage (Khin et al. 2012; Malato et al. 2009). A recent study presented the evidence of the release of synthetic TiO_2 nanoparticles from paints on building facades and measured a significant amount of TiO_2 nanoparticles in urban runoff. Basically, three kinds of nanoparticles (nano-TiO_2 nanosilver, and carbon nanotube) have been studied, in which, nano-TiO_2 in WWTP effluents (0.7–16 μg/L) were close to or higher than the permissible level (1 μg/L) (Kiser et al. 2009; Lu et al. 2016).

Nanocrystalline titanium dioxide shows several activities. It is a photocatalyst which works in water splitting to produce hydrogen fuel as energy catalyst and behaves as an environmental catalyst for water and air purification or an electron transport medium in dye-sensitized solar cells (Chong et al. 2010; Khin et al. 2012; Pelaez et al. 2012). Water purification by nanocrystalline titanium dioxide worked as an advanced oxidation process because of its high efficiency and eco-friendliness with the ecosystem. Photocatalytic decomposition of wastewater by nanocrystalline titanium dioxide is mainly carried by a series of hydroxylation reactions initiated by hydroxyl radicals which attack the contaminant present in the wastewater, and water get purified (Lu et al. 2009; VanGrieken et al. 2009). Scientists made efforts to increase the photocatalytic activity of nanocrystalline titanium dioxide which includes the synthesis of mesoporous titanium dioxide (Nakata et al. 2012; Wang and Lewis 2005); the utilization of different morphologies of titanium dioxide such as nanowires, nanotubes, and nanospheres (Sun et al. 2011); and surface treatments of nanocrystalline titanium dioxide (Monllor-Satoca et al. 2011).

2.3 Silver Nanoparticles

The applications of silver nanoparticles are abundant during the recent periods. It is also applied to an open wound and burn treatment along with wastewater treatment (Pradeep 2009). The elementary studies exhibit that ~20 ppm silver colloidal solution (~30 nm diameter) in pure water circumscribed the 100% cure rate for malaria (Politano et al. 2013). In the wastewater treatment, spherical aggregates of nanoparticles (Pradeep 2009) able to form resin beads were usually employed. Ag and gold nanoparticles had been widely used for detection of trace level of organic contaminants in view of their unique optical properties (Sajanlal and Pradeep 2008). Raman spectra reveal the optical properties of silver nanostructures (Amin et al. 2014). Several Ag/Pt, Au/Pt, or Ag/Au bimetallic nanoparticle-based electrodes were studied for contaminant sensing, monitoring, as well as photocatalysis (Kumari et al. 2015; Zhang et al. 2016). The biocidal activity of silver nanoparticles was deployed in regard to water purification. The water inhabitable microorganisms like *E. coli* become inactivated when reaching in the influence of Ag nanoparticles (Xiu et al. 2011). It has been shown that Ag nanoparticles provoke destruction to the cellular membrane when it comes in direct contact of the microorganism (Morones et al. 2005). Ag nanoparticle is also used as a disinfectant for surgical masks and textile fibers. Nanoparticles, derived from noble metals, were also exploited for photocatalytic degradation of several water pollutants such as pesticides, dyes, and halogenated organic matters. These metals are able to act as electron sinks, inhibiting the photo-generated e −/h + recombination, at the time of promotion of surface charge separation (Pradeep 2009). A number of noble metal-based nanocomposites, e.g., Ag/ZnO and Pt/ZnO nanocomposites (Muñoz-Fernandez et al. 2016), Au-CuS-TiO_2 nanobelts (Chen et al. 2016), and Ag/AgBr/graphene oxide nanocomposites (Esmaeili and Entezari 2016), have been developed and exhibited upgraded photocatalytic performance against certain organic contaminants.

2.4 Carbon-Based Nanomaterials

Carbon-based nanomaterials depend on various factors like size, length, chirality, and the number of layers in the fullerene cage. The current fabrication techniques for synthesis of carbon nanomaterial lacks complete exactness and uniformity between growth conditions. To overcome these problems, scientists modified the synthesis technique of carbon nanomaterial. The modification takes place in various factors such as temperature, pressure, catalyst, purity, and physical orientation for specific applications (Tofighy and Mohammadi 2011). There are various carbon-based nanomaterials available which are used in wastewater treatment, e.g., activated carbon, graphene, carbon nanosorbent, and fullerene.

Activated carbon reduced the organic wastes and odor from water and wastewater treatment (Liu et al. 2012). Carbonaceous nanosorbents are also very effective in wastewater treatment because toxicity has prevented in water. In 2005 Savage and Diallo have proposed the incorporation of nanosorbents into traditional packed bed reactors, but the details of the immobilization strategies have not been presented (Savage and Diallo 2005). Several types of research show that nanosorbents have used for the removal of specific contaminants such as trihalomethanes, polycyclic aromatic hydrocarbons, or naphthalene (Chen 2004). Moreover, most of the literature focuses on the physical properties of nanomaterials and demonstrated that they are dependent upon aggregation state and solvent chemistry. Various types of impurities such as vapor, biomolecules, and metals adsorb to the surface of nanomaterials and change the aggregation behavior and thermal and physicochemical properties of the nanomaterials. Hence, it is necessary to resolve these problems for widespread use of carbonaceous nanomaterials for wastewater treatment. To target the low concentration contaminant and specific micropollutant, functionalized nanosorbents may provide an optimized approach for removal of this contaminant and improve subsurface mobility (Lecoanet et al. 2004).

2.4.1 Classification of Carbon-Based Nanomaterials

The classification of carbon-based nanomaterials (Yu et al. 2011) is mostly based on their geometrical structures. Carbon nanostructures possess particles having tube-shaped, horn-shaped, spherical, or ellipsoidal. On the basis of the shape, nanoparticles having tube-like shape are called as carbon nanotubes; spheres or ellipsoids belong to the set of fullerenes; and horn-shaped particles are called nanohorns (Das et al. 2014). Carbon nanomaterials have been widely used technically as micro- and nano-electronics, production matter of conductive plastics, gas storage, composites, displays, textiles, antifouling paints, batteries with improved sturdiness, gas biosensors, etc. (Ramnani et al. 2016).

Fullerenes

Fullerenes are an allotropic modification of carbon discovered by Kroto et al. (1985) who were later awarded the Nobel Prize for chemistry in 1996. A number of atomic C_n clusters ($n > 20$), constitutes from carbon atoms on a spherical surface, are considered as fullerene family (Pyrzyńska and Bystrzejewski 2010; Wang et al. 2012). One of the best-inquiries of fullerenes is its C60 isoform also called as buckminsterfullerenes (Das et al. 2014; Lam et al. 2006). A spherical molecule of a fullerene is comprised of 60 carbon atoms that have great symmetry and are occupied with the vertices of 12 pentagons and 20 hexagons. The diameter of fullerene C60 is 0.7 nm (Fu and Wang 2011). C60 is a powerful photocatalyst, used in wastewater treatment, in UV and solar disinfection reactors, and in advanced oxidation process reactors. It augmented the oxidative processes which destroy a variety of contaminant including carcinogens and endocrine disruptors, simultaneously with disinfection (Tsydenova et al. 2015).

Carbon Nanotubes and Surface-Modified Nanotube (CNT)

CNTs are one of the well-known carbon allotropes with unprecedented virtue relevant for technical implications upon carbon-based nanomaterials. CNT was discovered by the Japanese researcher Iijima (1991). CNTs are specified cylindrical structures having a diameter of several nanometres, comprised of rolled graphene sheets (Lam et al. 2006). It varies in diameter, length, chirality, as well as a number of layers. Based on their structure, they can be classified into two main groups: single-walled nanotubes (SWCNTs) and multi-walled nanotubes (MWCNTs) (Tasis et al. 2006). Further a distinct class of CNTs had been introduced by some researchers as they have a different framework of double-walled carbon nanotubes (DWCNTs) (Thostenson et al. 2001). Single-walled nanotubes (SWNT) are of 1–3 nm in diameter along with the length of a few micrometers, whereas multi-walled CNTs hold a diameter of 5–40 nm and proximately 10 μm length (Bahgat et al. 2011). CNTs structure prevails upon notable features amidst a privileged composite of rigorousness, stability, and elasticity in comparison with other fibrous materials (Kumar et al. 2014; Yu et al. 2011). For instance, in comparison to other materials, CNTs exhibit considerably higher aspect ratios (length to diameter ratios) and larger aspect ratios for SWCNTs as compared with MWCNTs due to their smaller diameter (Pyrzyńska and Bystrzejewski 2010). On the other hand, CNTs show high thermal and electrical conductivity in comparison with other conductive materials (Thostenson et al. 2001).

CNTs have shown higher efficiencies for adsorption of bacteria and other microorganisms than other adsorbents such as granulated activated carbon (GAC) and powdered activated carbon (PAC) which are used in the wastewater treatment processes (Kang et al. 2008) Several studies reveal that pH level plays an important role in removing heavy metals contaminant in wastewater through CNTs (Ye et al. 2007). One of the studies demonstrated the efficiency of removal of lead from water can be augmented by optimizing the pH level. In the case of chromium contaminant, it was seen that by maintaining the pH higher than 4, it can efficiently remove chromium from wastewater. This study deduced that CNTs can behave as an effective adsorbent for removal of heavy metals from wastewater by increasing the pH, resulting in decreased protonation of the surface which increases the adsorption capacity of CNTs (Addo Ntim and Mitra 2011). CNT membranes are considered as a model water distillation tool. It consists of open-end single empty structure which is settled upright with resistant filter media. CNT-based membrane shows several advantages over CNTs such as these membranes are hard-like ceramic membrane and soft-like polymeric membranes. The second major advantage of CNT membrane is it permits fast infiltration of water. Scientist demonstrated that graphene membrane produced more precise results than CNTs membranes (Das et al. 2014). Nowadays, the detection of the pathogen in wastewater is a major challenge due to the low quantity of some pollutants that are present in water and the high difficulty of the wastewater mediums. Hence, advanced sensors technologies are used to detect the pathogen in the wastewater. So, high discrimination and sensitivity, with fast kinetics, are needed for sensing contaminant detection in wastewater (Savage and Diallo 2005; Theron et al. 2008; Upadhyayula et al. 2009)

Graphene Nanoparticles

A two-dimensional allotropic form of carbon is known as graphene, constitutes of a single layer of carbon atoms (Zhao et al. 2011). Graphene is a carbon allotrope like graphite, carbon nanotubes, and fullerenes (Chen et al. 2012; Gao et al. 2012; Georgakilas et al. 2012). From the ancient time period, the theoretical studies on graphene began. The Canadian theoretical physicist P. R. Wallace first explored the theory of graphene in 1947, while the first graphene samples were described 57 years later (in 2004) by A. Geim (Dutch-British physicist) and K. Novoselov (Russian-British physicist), awarded with a Nobel prize in 2010 (Allen et al. 2009) (Table 14.2).

Table 14.2 Potential applications, advantages and disadvantages of nanotechnology in the wastewater treatment

S.N.	Nanomaterials/ nano-objects	Application	Advantages	Disadvantages
1.	Carbon nanotubes	Contaminant preconcentration/detection, adsorption of recalcitrant contaminants, ultralong carbon nanotubes with extremely high specific salt adsorption	Highly assessable sorption sides, bactericidal, reusable	High production costs, possibly health risk
2.	Nanoadsorbents	Point-of-use, removal of organics, heavy metals, bacteria	High specific surface, higher adsorption rates, small footprint	High production costs
3.	Membranes and membrane processes	All fields of water and wastewater treatment processes	Reliable, largely automated process	More energy demand
4.	Nanometals and nanometal oxides	Heavy metals (arsenic) and radionuclides removal, media filters, slurry reactors, powders, pellets	Short intraparticle diffusion distance compressible, abrasion-resistant, magnetic photocatalytic	Less reusable
5.	Polymeric nanoadsorbents (dendrimers)	Expulsion of organics and substantial metals biodegradable, biocompatible, nontoxic bioadsorbent	Bifunctional (inner shell adsorbs organics, outer branches adsorb heavy metals), reusable	Complex multistage production process
6.	Magnetic nanoparticles	Forward osmosis, groundwater remediation	Simple recovery by magnetic field	Stabilization is required
7.	Nanosilver and nano-TiO2	Point-of-use water disinfection, anti-biofouling surfaces, decontamination of organic compounds, remote areas, TiO2 modification for activation by visible light, TiO2 nanotubes	Bactericidal, low human toxicity nano-TiO2: high chemical stability, very long life time	Nanosilver, limited durability nano-TiO_2 requires ultraviolet activation
8.	Zeolites	Disinfection processes, nanozeolites by laser-induced fragmentation	Controlled release of nanosilver, bactericidal	Reduced active surface through immobilization of nanosilver particles

(continued)

Table 14.2 (continued)

S.N.	Nanomaterials/ nano-objects	Application	Advantages	Disadvantages
9.	Nanocomposite membranes	Highly dependent on the type of composite, e.g., reverse osmosis, removal of micropollutants Bionanocomposite membranes	Increased hydrophilicity, water permeability, fouling resistance, and thermal/ mechanical robustness	Resistant bulk material required when using oxidizing nanomaterial, possibly release of nanoparticles
10.	Nanofiber membranes	The filter cartridge, ultrafiltration, prefiltration, water treatment, stand-alone filtration device Composite nanofiber membranes, bionanofiber membranes	High porosity, tailor-made, higher permeate efficiency, bactericidal	Pore blocking, possibly release of nanofibers

3 Organic Polymer Nanomaterials in Remediation of Wastewater

3.1 Organic Polymer Nanomaterials

Hazardous and recalcitrant pollutants can be removed from the wastewater through the process of adsorption, which is the most effective and simplest approach (Wan et al. 2010). Activated carbon is used for the adsorption purpose, but it is highly costly and didn't adsorb the functional group. Therefore, organic polymers have been used to the uptake of heavy metals. Organic nanosorbents having properties such as large surface area and polyfunctional groups are highly rigid, and it is easily regenerate under the mild condition (Jain et al. 2018). The large surface area of nanosorbents provides a good contact between the solid sorbent and metal ions. On the other hand poly functional groups provide a large number of active sites for the adsorption reaction (Huang et al. 2011). Polyphenylenediamine, organic polymers, have polyfunctional groups such as amino and imino groups which can effectively adsorb the heavy metal ions. However, due to their relative small specific area, their adsorption rate is slow (Huang et al. 2011). In 2006, Huang et al. reported that poly (p-phenylenediamine) (PpPD) and poly(m-phenylenediamine) (PmPD) were directly synthesized by a facile oxidative precipitation polymerization and their strong ability adsorbs lead ions from aqueous solution (Huang et al. 2006). The strong adsorption of the lead ion on the microparticles makes them suitable adsorbents candidate for wastewater treatment. Some thiol-functionalized mesoporous silica microspheres showed the behavior in mercury ion adsorption (Bibby and Mercier 2002), while humic acid (HA)-coated Fe_3O_4 nanoparticles (Fe_3O_4/HA) were developed for the removal of toxic Hg, Pb, Cd, and Cu from water (Liu et al. 2014). In 2010, Liu et al. documented that new hybrid polymers were prepared from the ring-opening polymerization of pyromellitic acid dianhydride (PMDA) and phenylaminomethyltrimethoxysilane (PAMTMS) and are capable for the removal of Pb (II) ions from Pb(II)/Cu(II)-mixed aqueous solution and can be applied to separate and recover the heavy metal ions from contaminated wastewater (Liu et al. 2010). In 2010, Cai et al. reported an efficient method for synthesis of poly (acrylic acid) stabilized amorphous calcium carbonate nanoparticles (ACC) and their application for removal of toxic heavy metal ions from aqueous solutions. The maximum removal capacities for Cd, Pb, Cr, Fe, and Ni ions were found to be 514.62, 1028.21, 258.85, 320.5, and 537.2 mg g^{-1}, respectively. The unique characteristic of the ACC nanoparticles in wastewater treatment involves not only high removal capacities but also decontamination of trace ions (Cai et al. 2010). Zhang et al. (2013) demonstrated that thiol-modified Fe_3O_4-SiO_2 as a robust, highly effective, and recycling magnetic sorbent for Hg removal. In 2013, Wang and their coworker developed the rhodamine hydrazide-modifying Fe_3O_4 microspheres (Fe_3O_4-R6G) for detection and removal of mercury (Hg) from wastewater. The maximum adsorption capacity of the Fe_3O_4-R6G for Hg was 37.4 mol g^{-1} (Huang and Chen 2009; Zhang et al. 2013). In 2016, Chen and their coworker prepared the magnetic Fe_3O_4 nanoparticles (MNP) coated with 3-aminopropyltriethoxy-silane (APTES), and magnetic absorbent was formed (Fe_3O_4.SiO2-NH-HCGs) by grafting of different heterocyclic groups (HCG) on amino groups through the substitution reaction. This magnetic absorbent was used for the removal of heavy metal cations such as Cu, Hg, Pb, and Cd. Results showed that 96% heavy metals were removed from the wastewater within 20 min at normal temperature and have good stability and reusability (Chen et al. 2016). Mahdavian et al. developed magnetic iron oxide nanoparticles by modification with APTES and acryloyl chloride (AC). Further, the surface of these nanoparticles was modified by graft polymerization with acrylic acid. Then the grafted magnetite nanoparticles were used for separation of heavy metal cations such as Cd, Pb, Ni, and Cu from the wastewater. Huang et al. (2011) reported that poly (5-sulfo-1-aminoanthraquinone) nanoparticles were synthesized by a chemical oxidative polymerization of 5-sulfo-1aminoanthraquinone. In particular, a large amount of—SO_3^- —NH_2/—NH—/—N=/=O groups are added which shows high specific area with fast and strong adsorb ability toward heavy metal ions from the wastewater (Mahdavian and Mirrahimi 2010).

3.2 *Organic Polymer-Supported Nanocomposites*

Wang et al. (2011) prepared a multifunctional inorganic−organic hybrid nanomaterial (MMS−Py) by immobilization of a pyrene-based receptor (Py) within the channels of magnetic mesoporous silica nanocomposites (MMS) which is used for the removal of Hg ions from the wastewater. Polymer-layered silicate nanocomposites made nanocomposite material catching the attention of both academic and industries because they exhibit dramatic improvement at very low filler contents (Pavlidou and Papaspyrides 2008). Eisazadeh (2007) demonstrated the polyaniline (PAn) and its nanocomposites for the removal of Cr ions from wastewater. Huang et al. (2014)

reported that conjugated polymers based nanocomposites for polyaniline (PAn), polypyrrole (PPy), and polythiophene (PT) have been widely used in wastewater purification. Poly (N-ethylaniline)/chitosan composite exhibited the highest removal ability to Cr (229.8 mg/g) from wastewater. However, other conjugated polymers such as polyacetylenes, poly(phenylenevinylene) (PPV), poly(p-phenylene) (PPP), etc. may also be applied as composites in wastewater treatment, but due to the absence of heteroatom for the functional group, their practical applications are not reported till date (Huang et al. 2014).

4 Patented Products of Nanomaterials for Purification of Water

There are various patented product of nanomaterials that are present such as wastewater treatment method and wastewater treatment apparatus invented by Yamasaki et al. (2007) (Table 14.3).

5 Conclusions

In a current scenario, there is a significant need for advanced water technologies to ensure a high quality of water, elimination of chemical, and biological pollutants and intensify industrial production processes of wastewater. The universal solvent water is one the most crucial for all living organisms exist on Earth. Contaminated water is the major challenge of the current era, and there are several reasons which are responsible for water contamination. The contaminants contain undesired substances such as microorganisms and unnecessary elements, as well as chemicals, that leads to water pollution and water becomes unsafe for all purposes. Untreated water creates a great threat to living beings and the environment. In this regard, nanotechnology is one of the ideal technologies to advance wastewater treatment processes. Various nanomaterials have been developed and investigated successfully for wastewater treatment. Nanotechnology has a significant prospective in magnifying water quality by wastewater management as it profound potential supremacy such as cost-effective, reiterate, and highly proficient in expelling and recuperating the pollutants. The efficiency of nanomaterials as anti-pollutant is due to its size in nano-range which makes it worth working as it has a large surface to volume ratio, high reactivity, rapid dissolution, and high adsorption. For the development of antimicrobial nanomaterials, knowledge of biotechnology is employed for removal of microbes from water. Moreover, further work is required on developing cost-effective methods of synthesizing nanomaterials and testing the efficiency of nanomaterials at large scale for successful field application on purification of wastewater treatments.

Table 14.3 Some examples of patented products of nonmaterial for the purification of water

S.N.	Claimed title/patent name	Patent No.	Nanomaterials claimed activity	Inventers
1.	Wastewater treatment method and wastewater treatment apparatus	US 20070068869	Micro-nano, nanomaterials used to decompose organic compound and microorganism	Yamasaki et al. (2007)
2.	Process for biochemical treatment of wastewater using nanomaterials	US 20030010712	Nanomaterial used such as carbon black to induce micropores to degrade organic pollutants and enhance the effect of biological cleaning of wastewater	Gao et al. (2003)
3.	Drinking water filtration device	US20070175196	Nano-alumina fibers shows antimicrobial for sterilization of retained microbes for purifying drinking water	Tepper and Kaledin (2008)
4.	Water treatment by dendrimer enhanced filtration	US20080185341	Cation-binding dendrimers, anion-binding dendrimers, and organic compound-binding dendrimers used in filtration of wastewater	Diallo (2008)
5.	Adsorption filter	US20060123991	An adsorption activated carbon particles used as simple and cost-effective filters	Braeunling et al. (2006)
6.	Reduced graphene oxide-based-composites for the purification of water	US20130240439	A nanocomposite is disclosed comprising reduced graphene oxide (RGO) an adsorbent comprising the nanocomposite and an adsorbent comprising the nanocomposite bound to silica by using chitosan	Pradeep et al. (2013)
7.	Portable drinking water purification device	US20100102002	Activated carbon or nano-filter in portable water chamber and having a very small pore size	O'Brien et al. (2013)
8.	Purification of fluids with nanomaterials	US 20080041791	Nanostructured material carbon nanotubes	Cooper et al. (2008)

(continued)

Table 14.3 (continued)

S.N.	Claimed title/patent name	Patent No.	Nanomaterials claimed activity	Inventers
9.	Water purification device	US20170203244	A water purification device includes a heavy metal removal layer configured to remove heavy metal ions and perfluorinated compounds from contaminated water	Chen et al. (2017)
10.	Method for biological disposal of organic wastewater and biological disposal apparatus	US 20090277832	A biological treatment method and device for organic wastewater, whereby the amount of minute organisms which reduce the amount of excess sludge	Fujishima and Kurita Water Industries Ltd (2009)
11.	Water purification and disinfection device and method	US 20060151393	Purify and filter water, particularly brackish water, so that it is made potable. The system includes the use of physical and chemical treatment means, including carbon, reverse osmosis, and antimicrobial media	Badger (2006)
12.	Double chamber water purification device	US 8425771	A portable device for filtering and purifying water comprised of an outer chamber and an inner chamber that is activated carbon bed, removing any remaining contaminants before the potable water exits through a mouthpiece	O'Brien et al. (2013)

References

Addo Ntim S, Mitra S (2011) Removal of trace arsenic to meet drinking water standards using iron oxide coated multiwall carbon nanotubes. J Chem Eng Data 56:2077–2083

Ahmaruzzaman M (2008) Adsorption of phenolic compounds on low-cost adsorbents: a review. Adv Colloid Inter Sci 143:48–67

Allen MJ, Tung VC, Kaner RB (2009) Honeycomb carbon: a review of graphene. Chem Rev 110:132–145

Amin M, Alazba A, Manzoor U (2014) A review of removal of pollutants from water/wastewater using different types of nanomaterials. Adv Mater Sci Eng 2014:1–24

Anjum M, Miandad R, Waqas M, Gehany F, Barakat M (2016) Remediation of wastewater using various nano-materials. Arab J Chem. https://doi.org/10.1016/j.arabjc.2016.10.004

Badger T (2006) Aquatic Treatment Systems Inc,. Water purification and disinfection device and method. U.S. Patent Application 11/320,199
Bahgat M, Farghali A, El Rouby W, Khedr M (2011) Synthesis and modification of multi-walled carbon nano-tubes (MWCNTs) for water treatment applications. J Anal Appl Pyrol 92:307–313
Bibby A, Mercier L (2002) Mercury (II) ion adsorption behavior in thiol-functionalized mesoporous silica microspheres. Chem Mat 14:1591–1597
Boparai HK, Joseph M, O'Carroll DM (2011) Kinetics and thermodynamics of cadmium ion removal by adsorption onto nanozerovalent iron particles. J Hazard Mater 186:458–465
Braeunling V, Stahl U, Felber U, Bader R, Schacht H, Freudenberg Carl KG (2006) Adsorption filter. U.S. Patent Application 11/290,290
Cai GB, Zhao GX, Wang XK, Yu SH (2010) Synthesis of polyacrylic acid stabilized amorphous calcium carbonate nanoparticles and their application for removal of toxic heavy metal ions in water. J Phys Chem C 114:12948–12954
Chaturvedi VK, Singh A, Singh VK, Singh MP (2018) Cancer nanotechnology: a new revolution for cancer diagnosis and therapy. Curr Drug Metabol. https://doi.org/10.2174/1389200219666180918111528
Chen G (2004) Electrochemical technologies in wastewater treatment. Sep Purif Technol 38:11–41
Chen D, Feng H, Li J (2012) Graphene oxide: preparation, functionalization, and electrochemical applications. Chem Rev 112:6027–6053
Chen D, Awut T, Liu B, Ma Y, Wang T, Nurulla I (2016) Functionalized magnetic Fe_3O_4 nanoparticles for removal of heavy metal ions from aqueous solutions. e-Polymers 16:313–322
Chen F, Gong AS, Zhu M, Chen G, Lacey SD, Jiang F, Li Y, Wang Y, Dai J, Yao Y, Song J (2017) Mesoporous, three-dimensional wood membrane decorated with nanoparticles for highly efficient water treatment. ACS Nano 11:4275–4282
Chong MN, Jin B, Chow CW, Saint C (2010) Recent developments in photocatalytic water treatment technology: a review. Water Res 44:2997–3027
Cooper CH, Cummings AG, Starostin MY, Honsinger CP, Seldon Technologies LLC, (2008) Nanomesh article and method of using the same for purifying fluids. U.S. Patent 7,419,601
Crane RA, Scott TB (2012) Nanoscale zero-valent iron: future prospects for an emerging water treatment technology. J Hazard Mater 211:112–125
Das R, Ali ME, Hamid SBA, Ramakrishna S, Chowdhury ZZ (2014) Carbon nanotube membranes for water purification: a bright future in water desalination. Desalination 336:97–109
Diallo MS (2008) Water treatment by dendrimer enhanced filtration. U.S. Patent 7,470,369
Eisazadeh H (2007) Removal of chromium from waste water using polyaniline. J Appl Polym Sci 104:1964–1967
Esmaeili A, Entezari MH (2016) Sonosynthesis of an Ag/AgBr/Graphene-oxide nanocomposite as a solar photocatalyst for efficient degradation of methyl orange. J Coll Inter Sci 466:227–237
Ferroudj N, Nzimoto J, Davidson A, Talbot D, Briot E, Dupuis V, Abramson S (2013) Maghemite nanoparticles and maghemite/silica nanocomposite microspheres as magnetic Fenton catalysts for the removal of water pollutants. Appl Catal B Environ 136:9–18
Fu F, Wang Q (2011) Removal of heavy metal ions from wastewaters: a review. J Environ Manag 92:407–418
Fujishima S, Kurita Water Industries Ltd (2009) Method and equipment for biological treatment of organic wastewater. U.S. Patent Application 12/285, 955
Gao M, Xue J, Zhao P, Ye J, Liang Y, Hou X, Gao L, Liu L, Chai B (2003) Process for biochemical treatment of waste water using nano materials. U.S. Patent Application 10/125,327
Gao Y, Li Y, Zhang L, Huang H, Hu J, Shah S, Su X (2012) Adsorption and removal of tetracycline antibiotics from aqueous solution by graphene oxide. J Coll Inter Sci 368:540–546
Georgakilas V, Otyepka M, Bourlinos AB, Chandra V, Kim N, Kemp KC, Kim KS (2012) Functionalization of graphene: covalent and non-covalent approaches, derivatives and applications. Chem Rev 112:6156–6214
Ghaly MY, Jamil TS, El-Seesy IE, Souaya ER, Nasr RA (2011) Treatment of highly polluted paper mill wastewater by solar photocatalytic oxidation with synthesized nano TiO2. Chem Eng J 168:446–454

Grey D, Garrick D, Blackmore D, Kelman J, Muller M, Sadoff C (2013) Water security in one blue planet: twenty-first century policy challenges for science. Phil Trans R Soc A 371(2002):20120406

Huang SH, Chen DH (2009) Rapid removal of heavy metal cations and anions from aqueous solutions by an amino-functionalized magnetic nano-adsorbent. J Hazard Mater 163:174–179

Huang MR, Peng QY, Li XG (2006) Rapid and effective adsorption of lead ions on fine poly (phenylenediamine) microparticles. Chem A Eur J 12:4341–4350

Huang MR, Huang SJ, Li XG (2011) Facile synthesis of polysulfoaminoanthraquinone nanosorbents for rapid removal and ultrasensitive fluorescent detection of heavy metal ions. J Phys Chem C 115:5301–5315

Huang Y, Li J, Chen X, Wang X (2014) Applications of conjugated polymer based composites in wastewater purification. RSC Adv 4:62160–62178

Iijima S (1991) Helical microtubules of graphitic carbon. Nature 354:56–58

Jain M, Yadav M, Kohout T, Lahtinen M, Garg VK, Sillanpää M (2018) Development of iron oxide/activated carbon nanoparticle composite for the removal of Cr (VI), Cu (II) and Cd (II) ions from aqueous solution. Water Resour Ind 20:54–74

Kang S, Mauter MS, Elimelech M (2008) Physicochemical determinants of multi walled carbon nanotube bacterial cytotoxicity. Environ Sci Technol 42:7528–7534

Khin MM, Nair AS, Babu VJ, Murugan R, Ramakrishna S (2012) A review on nanomaterials for environmental remediation. Energy Environ Sci 5:8075–8109

Kim SA, Kamala-Kannan S, Lee KJ, Park YJ, Shea PJ, Lee WH, Oh BT (2013) Removal of Pb (II) from aqueous solution by a zeolite–nanoscale zero-valent iron composite. Chem Eng J 217:54–60

Kiser MA, Westerhoff P, Benn T, Wang Y, Perez-Rivera J, Hristovski K (2009) Titanium nanomaterial removal and release from wastewater treatment plants. Environ Sci Technol 43:6757–6763

Kroto HW, Heath JR, O'Brien SC, Curl RF, Smalley RE (1985) C60: Buckminsterfullerene. Nature 318:162–163

Kumar R, Khan MA, Haq N (2014) Application of carbon nanotubes in heavy metals remediation. Crit Rev Environ Sci Technol 44:1000–1035

Kumari MM, Jacob J, Philip D (2015) Green synthesis and applications of Au–Ag bimetallic nanoparticles. Spectrochim Acta Part A Mol Biomol Spectrosc 137:185–192

Lam CW, James JT, McCluskey R, Arepalli S, Hunter RL (2006) A review of carbon nanotube toxicity and assessment of potential occupational and environmental health risks. Crit Rev Toxicol 36:189–217

Lecoanet HF, Bottero JY, Wiesner MR (2004) Laboratory assessment of the mobility of nanomaterials in porous media. Environ Sci Technol 38:5164–5169

Li H, Shan C, Zhang Y, Cai J, Zhang W, Pan B (2016) Arsenate adsorption by hydrous ferric oxide nanoparticles embedded in cross-linked anion exchanger: effect of the host pore structure. ACS Appl Mater Inter 8:3012–3020

Liu J, Ma Y, Xu T, Shao G (2010) Preparation of zwitterionic hybrid polymer and its application for the removal of heavy metal ions from water. J Hazard Mater 178:1021–1029

Liu F, Chung S, Oh G, Seo TS (2012) Three-dimensional graphene oxide nanostructure for fast and efficient water-soluble dye removal. ACS Appl Mater Inter 4:922–927

Liu T, Wang ZL, Yan X, Zhang B (2014) Removal of mercury (II) and chromium (VI) from wastewater using a new and effective composite: pumice-supported nanoscale zero-valent iron. Chem Eng J 245:34–40

Lu N, Zhou SG, Zhuang L, Zhang JT, Ni JR (2009) Electricity generation from starch processing wastewater using microbial fuel cell technology. Biochem Eng J 43:246–251

Lu H, Wang J, Stoller M, Wang T, Bao Y, Hao H (2016) An overview of nanomaterials for water and wastewater treatment. Adv Mater Sci Eng 2016:1–10

Mahdavian AR, Mirrahimi MAS (2010) Efficient separation of heavy metal cations by anchoring polyacrylic acid on superparamagnetic magnetite nanoparticles through surface modification. Chem Eng J 159:264–271

Malato S, Fernández-Ibáñez P, Maldonado MI, Blanco J, Gernjak W (2009) Decontamination and disinfection of water by solar photocatalysis: recent overview and trends. Cat Today 147:1–59
Mishra S et al (2018) Heavy metal contamination: an alarming threat to environment and human health. In: Sobti RS, Arora NK, Kothari R (eds) Environmental biotechnology: for sustainable future. Springer Nature Singapore, Singapore, pp 103–125. ISBN 978-981-10-7284-0
Monllor-Satoca D, Lana-Villarreal T, Gómez R (2011) Effect of surface fluorination on the electrochemical and photoelectrocatalytic properties of nanoporous titanium dioxide electrodes. Langmuir 27:15312–15321
Morones JR, Elechiguerra JL, Camacho A, Holt K, Kouri JB, Ramírez JT, Yacaman MJ (2005) The bactericidal effect of silver nanoparticles. Nanotechnology 16:2346
Mueller NC, Nowack B (2008) Exposure modeling of engineered nanoparticles in the environment. Environ Sci Technol 42:4447–4453
Muñoz-Fernandez L, Sierra-Fernández A, Milošević O, Rabanal ME (2016) Solvothermal synthesis of Ag/ZnO and Pt/ZnO nanocomposites and comparison of their photocatalytic behaviors on dyes degradation. Adv Powder Technol 27:983–993
Nakamura E, Isobe H (2003) Functionalized fullerenes in water. The first 10 years of their chemistry, biology, and nanoscience. Account Chem Res 36:807–815
Nakata K, Ochiai T, Murakami T, Fujishima A (2012) Photoenergy conversion with TiO2 photocatalysis: new materials and recent applications. Electrochim Acta 84:103–111
Neyaz N, Siddiqui WA, Nair KK (2014) Application of surface functionalized iron oxide nanomaterials as a nanosorbents in extraction of toxic heavy metals from ground water: a review. Int J Environ Sci 4:472
Ngah WW, Teong LC, Hanafiah MAKM (2011) Adsorption of dyes and heavy metal ions by chitosan composites: a review. Carbohydr Polym 83:1446–1456
O'Brien PW, Engel M, Miracle Straw Corp Inc (2013) Double chamber water purification device. U.S. Patent 8,425,771
Oliveira LC, Rios RV, Fabris JD, Sapag K, Garg VK, Lago RM (2003) Clay–iron oxide magnetic composites for the adsorption of contaminants in water. Appl Clay Sci 22:169–177
Pavlidou S, Papaspyrides C (2008) A review on polymer–layered silicate nanocomposites. Prog Poly Sci 33:1119–1198
Pelaez M, Nolan NT, Pillai SC, Seery MK, Falaras P, Kontos AG, Dunlop PS, Hamilton JW, Byrne JA, O'shea K, Entezari MH (2012) A review on the visible light active titanium dioxide photocatalysts for environmental applications. Appl Catal B Environ 125:331–349
Pendergast MM, Hoek EM (2011) A review of water treatment membrane nanotechnologies. Energy Environ Sci 4:1946–1971
Politano AD, Campbell KT, Rosenberger LH, Sawyer RG (2013) Use of silver in the prevention and treatment of infections: silver review. Surg Inf 14:8–20
Ponder SM, Darab JG, Mallouk TE (2000) Remediation of Cr (VI) and Pb (II) aqueous solutions using supported, nanoscale zero-valent iron. Environ Sci Technol 34:2564–2569
Pradeep T (2009) Noble metal nanoparticles for water purification: a critical review. Thin Solid Films 517:6441–6478
Pradeep T, Maliyekkal SM, Sreenivasan ST, Indian Institutes of Technology (2013) Reduced graphene oxide-based-composites for the purification of water. U.S. Patent Application 13/820,403
Pyrzyńska K, Bystrzejewski M (2010) Comparative study of heavy metal ions sorption onto activated carbon, carbon nanotubes, and carbon-encapsulated magnetic nanoparticles. Coll Surf A Physicochem Eng Asp 362:102–109
Ramnani P, Saucedo NM, Mulchandani A (2016) Carbon nanomaterial-based electrochemical biosensors for label-free sensing of environmental pollutants. Chemosphere 143:85–98
Reinhart DR, Berge ND, Santra S, Bolyard SC (2010) Emerging contaminants: nanomaterial fate in landfills. Waste Manag 30:2020–2021
Sajanlal PR, Pradeep T (2008) Electric-field-assisted growth of highly uniform and oriented gold nanotriangles on conducting glass substrates. Adv Mater 20:980–983

Savage N, Diallo MS (2005) Nanomaterials and water purification: opportunities and challenges. J Nano Res 7:331–342
Su Y, Adeleye AS, Huang Y, Sun X, Dai C, Zhou X, Keller AA (2014) Simultaneous removal of cadmium and nitrate in aqueous media by nanoscalezerovalent iron (nZVI) and Au doped nZVI particles. Water Res 63:102–111
Sun Y, Wang G, Yan K (2011) TiO_2 nanotubes for hydrogen generation by photocatalytic water splitting in a two-compartment photoelectrochemical cell. Int J Hydro Energy 36:15502–15508
Tasis D, Tagmatarchis N, Bianco A, Prato M (2006) Chemistry of carbon nanotubes. Chem Rev 106:1105–1136
Tepper F, Kaledin LA (2008) Drinking water filtration device. U.S. Patent 7, 390,343
Theron J, Walker JA, Cloete TE (2008) Nanotechnology and water treatment: applications and emerging opportunities. Crit Rev Microbiol 34:43–69
Thostenson ET, Ren Z, Chou TW (2001) Advances in the science and technology of carbon nanotubes and their composites: a review. Compos Sci Technol 61:1899–1912
Tofighy MA, Mohammadi T (2011) Adsorption of divalent heavy metal ions from water using carbon nanotube sheets. J Hazard Mater 185:140–147
Tsydenova O, Batoev V, Batoeva A (2015) Solar-enhanced advanced oxidation processes for water treatment: simultaneous removal of pathogens and chemical pollutants. Int J Environ Res Public Health 12:9542–9561
Upadhyayula VK, Deng S, Mitchell MC, Smith GB (2009) Application of carbon nanotube technology for removal of contaminants in drinking water: a review. Sci Total Environ 408:1–13
VanGrieken R, Marugán J, Sordo C, Martínez P, Pablos C (2009) Photocatalytic inactivation of bacteria in water using suspended and immobilized silver-TiO_2. Appl Catal B Environ 93:112–118
Wan MW, Kan CC, Rogel BD, Dalida MLP (2010) Adsorption of copper (II) and lead (II) ions from aqueous solution on chitosan-coated sand. Carbohydr Polym 80:891–899
Wang H, Lewis JP (2005) Effects of dopant states on photoactivity in carbon-doped TiO_2. J Phys Condens Mater 17:209
Wang Y, Li B, Zhang L, Li P, Wang L, Zhang J (2011) Multifunctional magnetic mesoporous silica nanocomposites with improved sensing performance and effective removal ability toward Hg (II). Langmuir 28:1657–1662
Wang Y, Westerhoff P, Hristovski KD (2012) Fate and biological effects of silver, titanium dioxide, and C60 (fullerene) nanomaterials during simulated wastewater treatment processes. J Hazard Mater 201:16–22
Wang Z, Wu D, Wu G, Yang N, Wu A (2013) Modifying Fe_3O_4 microspheres with rhodamine hydrazide for selective detection and removal of Hg^{2+} ion in water. J Hazard Mater 244:621–627
WHO (2015) Drinking-water: fact sheet N 391. http://www.who.int/mediacentre/factsheets/fs391/en
Xiu ZM, Ma J, Alvarez PJ (2011) Differential effect of common ligands and molecular oxygen on antimicrobial activity of silver nanoparticles versus silver ions. Environ Sci Technol 45:9003–9008
Xu P, Zeng GM, Huang DL, Feng CL, Hu S, Zhao MH, Xie GX (2012) Use of iron oxide nanomaterials in wastewater treatment: a review. Sci Total Environ 424:1–10
Yadav A, Chowdhary P, Kaithwas G, Bharagava RN (2017) Toxic metals in environment, threats on ecosystem and bioremediation approaches. In: Das S, Singh HR (eds) Handbook of metal-microbe interactions and bioremediation. CRC Press/Taylor & Francis Group, Boca Raton, pp 128–141. isbn:9781498762427
Yamasaki K, Chujo K, Ishibashi H, Sharp Corp (2007) Metal containing waste water treatment method and metal containing waste water treatment equipment. U.S. Patent 7, pp 294–268
Ye C, Gong QM, Lu FP, Liang J (2007) Adsorption of uraemic toxins on carbon nanotubes. Sep Purif Technol 58:2–6
Yu JG, Huang DS, Huang KL, Hong Y (2011) Cross-linking of multi-walled carbon nanotubes with polyethylene glycol. Polym Plas Technol Eng 50:328–331

Zhang X, Lin S, Chen Z, Megharaj M, Naidu R (2011) Kaolinite-supported nanoscale zero-valent iron for removal of Pb^{2+} from aqueous solution: reactivity, characterization and mechanism. Water Res 45:3481–3488

Zhang S, Zhang Y, Liu J, Xu Q, Xiao H, Wang X, Zhou J (2013) Thiol modified Fe_3O_4 and SiO_2 as a robust, high effective, and recycling magnetic sorbent for mercury removal. Chem Eng J 226:30–38

Zhang C, Zhang Y, Du X, Chen Y, Dong W, Han B, Chen Q (2016) Facile fabrication of Pt-Ag bimetallic nanoparticles decorated reduced graphene oxide for highly sensitive non-enzymatic hydrogen peroxide sensing. Talanta 159:280–286

Zhao G, Li J, Ren X, Chen C, Wang X (2011) Few-layered graphene oxide nanosheets as superior sorbents for heavy metal ion pollution management. Environ Sci Technol 45:10454–10462