Integration of Nanotechnologies for Sustainable Remediation of Environmental Pollutants

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3.1 Introduction

Human exercises in the last few years have caused extreme concern related to the environment and its preservation. Water shortage, water contamination, air contamination, soil debasement, poor administration of waste, loss of biodiversity are some of the ecological concerns that have caused permanent health impacts on humans as well as on animals and plants. Also, the advancement in industrialization, just as science and innovation, has prompted the enhancement of waste and lethal materials in the environment. Thus, the degradation and diminution of natural resources must be circumvented to achieve a sustainable environment. The conventional physico-chemical strategies utilized for the reclamation of the common habitat were seen as improper because of cost, lower productivity and nonspecificity. Consequently, to overcome these constraints, biological methods were amalgamated with the nanotechnology-based physiochemical techniques for the removal of pollutants from the environment (Guerra et al. 2018). The present chapter reviews the existing physical, chemical and biological methods for the treatment of pollutants along with their merits, demerits and the application of nanotechnology in the bioremediation of contaminants. Furthermore, the chapter will likewise concentrate on the biological synthesis of the nanoparticles using microbes which will provide insight into nanobioremediation for removing contaminants from the environment. This nanobioremediation approach for the expulsion of toxicants from nature will be the most dependable and suitable technology as for the cost and effectiveness relative to the financial status of the developing countries.

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I. Haq, A. S. Kalamdhad (eds.), *Emerging Treatment Technologies for Waste Management*, https://doi.org/10.1007/978-981-16-2015-7_3

3.2 Present Day Treatment Methods for the Ouster of Pollutants

Since the contaminants are lethal in nature, they have been contemplated dangerous to the environment. The treatment of these toxins in an environmentally safe way is obligatory before they are being released into the environment. The physical, chemical and biological techniques are the current treatment methods used for the expulsion of contaminants from the environment. Physical techniques incorporate methods like adsorption, reverse osmosis, electrodialysis, etc. Countless toxins are being discharged into the environment, out of which some are exceptionally hard to be treated by regular physical techniques. To solve the limitations of physical techniques, some of the chemical methods like precipitation, ion exchange, electroflotation, coagulation, flocculation, reduction and so forth were utilized for the expulsion of contaminants from the environment. In spite of the fact that the chemical methods used are productive, quick and can remove a wide range of toxins present in nature, their utilization is constrained by the significant price and sludge disposal issues. Furthermore, plenty of chemicals and high level of energy are required by these chemical methods. Considering all the above constraints, biological methods including the utilization of microorganisms (bioremediation) were utilized for the expulsion of lethal contaminants present in the environment (Ojuederie et al. 2017; Sinha et al. 2016; Behl et al. 2019). The process of bioremediation is economically attractive as well as environmentally friendly. Also, there is an advantage of minimum sludge generation, regeneration of biosorbent and possibility of metal recovery. However, the processes are slow, additional nutrition and maintenance are required. Moreover, the pollutants sometimes become toxic to the microorganisms involved in the process. Thus, every above mentioned techniques have their own benefits and disadvantages which make them insufficient to manage the issue of contaminant expulsion from nature.

3.3 Nanotechnology

The remediation of the toxicants by the existing traditional physicochemical methods and biological methods was not very efficient and effective in cleaning up the environment. Therefore, a new technology named ‘nanotechnology’ can be applied for the bioremediation of contaminants from the environment. Nanotechnology is derived from the Greek word ‘dwarf’ (El Saliby et al. 2008) and can be defined as the science of micro-engineering. Micro-engineering is the technique that deals with particles smaller than 100 nm. Nanotechnology was first proposed by Richard Feynman (1960), which now has become one of the fastest developing areas of research and development all around (Yadav et al. 2017). Presently, the field of nanotechnology is regarded as the ‘Next Industrial Revolution’ as in the future it will lessen the industrial costs by diminishing the consumption of energy, environmental pollution and enhancing the production efficiencies in developed countries (Roco 2005). Moreover, nanotechnology may also prove helpful in handling particular

Table 3.1 Various nanomaterials used in remediation process

Process exploited	Target compounds	Nanomaterials	Properties of nanomaterials	References
Photocatalysis	Organic pollutants, NOX, VOCs, Azo dye, Congo red dye, 4-chlorophenol and Orange II, PAHs	TiO2, ZnO, species of iron oxides (Fe III, Fe2O3, Fe3O4)	Photocatalytic activity in solar spectrum, low human toxicity, high stability and selectivity, low cost	Khedr et al. (2009)
Redox reactions	Halogenated organic compounds, metals, nitrate, arsenate, oil, PAH, PCB	Nanoscale zero-valent iron (nZVI), nanoscale calcium peroxide	Electron transfers such as photosynthesis, respiration, metabolism and molecular signalling	Zhang et al. (2003)
Adsorption	Heavy metals, organic compounds, arsenic, phosphate, Cr (IV), mercury, PAHs, DDT, dioxin	Iron oxides, carbon-based nanomaterials such as dendrimers and polymers, carbon nanotubes (CNTs)	High specific surface area and assessable adsorption sites, selective and more adsorption sites, short intra-particle diffusion distance, tunable surface chemistry, easy reuse	Bhaumik et al. (2012)
Disinfection	Diamines, phenols, formaldehyde, hydrogen peroxide, silver ions, halogens, glutaraldehyde, acridines	Nanosilver/titanium dioxide (Ag/TiO2) and CNTs	Strong antimicrobial activity, low toxicity and cost, high chemical stability, ease of use	Amin et al. (2014)

social issues of developing nations like the necessity of clean water and treatment of epidemic diseases (Fleischer and Grunwald 2008; Schmidt 2007). Nanotechnology offers a large amount of environmental benefits in remediation, pollution prevention and contributes a lot to developing smaller, more accurate sensing and monitoring devices (Savage et al. 2008). The ability of nanotechnology to abridge contamination is in progress that can result in extensive and profound changes in pollution control (Watlington 2005). Table 3.1 lists some of the common nanomaterials utilized in the remediation process.

3.3.1 Properties of Nanoparticles

The essential part of nanotechnology is the very small particles called nanoparticles or ultrafine particles. Nanoparticles are particles somewhere in the range of

1–100 nm in size that can intensely change their physicochemical properties when contrasted with the bulk material. These particles are comprised of carbon, metal, metal oxides or organic matter and their function relies upon the type of synthesis, size and shape of the particles. They can be round, tubular, cylindrical and so on. Their surface can be uniform or irregular, while some are crystalline to amorphous with single or multi-crystal solids either free or agglomerated.

The nanoparticles are classified into organic, inorganic and carbon based. Organic nanoparticles incorporate dendrimers, liposomes, ferritin and so forth that are non-toxic, biodegradable and are likewise sensitive to thermal and electromagnetic radiation like heat and light, making them ideal for drug delivery (Tiwari et al. 2008). Inorganic nanoparticles are not comprised of carbon. They largely involve metal and metal oxide nanoparticles such as aluminium, copper, gold, iron, iron oxide, aluminium oxide, magnetite, etc. (Dreaden 2012). Carbon-based nanoparticles are totally comprised of carbon like graphene, fullerenes, carbon nanotubes (Saeed and Khan 2016).

The unusual chemical, physical, optical, thermal and electrical properties (Panigrahi et al. 2004) of nanoparticles can be used in various fields like drug delivery (Horcajada et al. 2008), medical imaging (Lee et al. 2008), optical receptors (Dahan et al. 2003), biolabelling (Liang et al. 2006), antimicrobial agents (Sanpui et al. 2008). There are other remarkable properties of nanoparticles like its small size which can cause increase in the surface area per unit mass that makes them profoundly helpful in bioremediation. Because of the small size, a lot of nanoparticles can come into contact with the surrounding medium, consequently influencing its reactivity. Nanoparticles show a remarkable property of surface plasmon resonance which helps in the detection of contaminants present in nature. Furthermore unique properties of nanoparticles likewise make them appropriate for the advancement of electrochemical sensors as well as biosensor (Peng and Miller 2011; Selid et al. 2009). Moreover, scientists have created nanosensors for the recognition of auxin and oxygen dissemination in plants (Koren et al. 2015). Because of the outstanding properties of nanoparticles, they have been proposed as a proficient, economical and environment friendly substitute to the present treatment advancements, in resource preservation as well as in ecological remediation (Friedrich et al. 1998; Dastjerdi and Montazer 2010). The ability of nanomaterials to abate pollution production is in progress and could potentially catalyse the most revolutionary changes in the environmental field in the coming decades (Fig. 3.1).

3.4 Synthesis of Nanoparticles

Nanoparticles can be synthesized by various strategies and approaches that incorporate physical, chemical and biological methods (Fig. 3.2) (Luechinger et al. 2010; Mohanpuria et al. 2008). Conventionally, the nanoparticles were produced by physicochemical strategies that enable them to be synthesized in enormous amounts with definite shape and size in a constrained timeframe; howbeit, these methods are

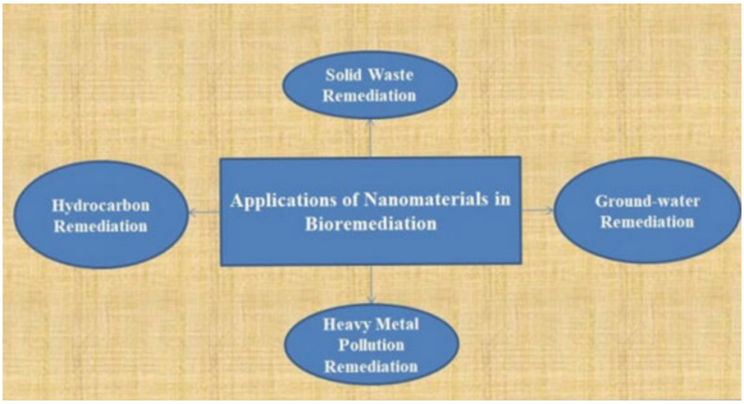

Fig. 3.1 Applications of nanomaterials in bioremediation

expensive, wasteful, complicated, utilize hazardous chemicals, require high energy and produce toxic by-products that are hazardous to the environment (Li et al. 2011a, b; Rodriguez-Sanchez et al. 2000).

Lately, the interest has been focussed on the production of economical and eco-friendly nanoparticles that do not give rise to dangerous and toxic by-products during the manufacturing procedure (Chauhan et al. 2012; Li et al. 2011a, b). Thus, recently, nanoparticles are being produced by biological methods that include microorganisms, plants and their by-products with the assistance of some biological tools. Biologically synthesized nanoparticles have striking and outstanding benefits over physical and chemical strategies like the production approaches are economical, quick and eco-friendly. In addition, the nanoparticles produced by biological path does not require any further stabilizing agents, as microorganisms and plants themselves act as stabilizing agents (Makarov et al. 2014). The biological synthesis of nanoparticles is a bottom-up approach where reducing and stabilizing agents help in synthesizing the nanoparticles (Fig. 3.2). Bio-fabrication of nanoparticles is in general achieved either through reduction or oxidation process. The biomolecules present in microbes or botanical species were found to be responsible for reduction-cum-stabilization of metal ions into their respective nanostructures (Singh et al. 2011). Biosynthesis of various nanoparticles using plants and microorganisms like bacteria, algae, fungi yeast and microbial polysaccharides is compiled below.

3.4.1 Synthesis of Nanoparticles Utilizing Plants

Biological synthesis of nanoparticles by plants is getting a lot of attention these days because of its simple, stable, rapid, cheap and eco-friendly method (Mittal et al. 2013). Additionally, plants are abundantly available, safe to handle and have a wide variability of metabolites that help in reduction. Plant extracts containing bioactive

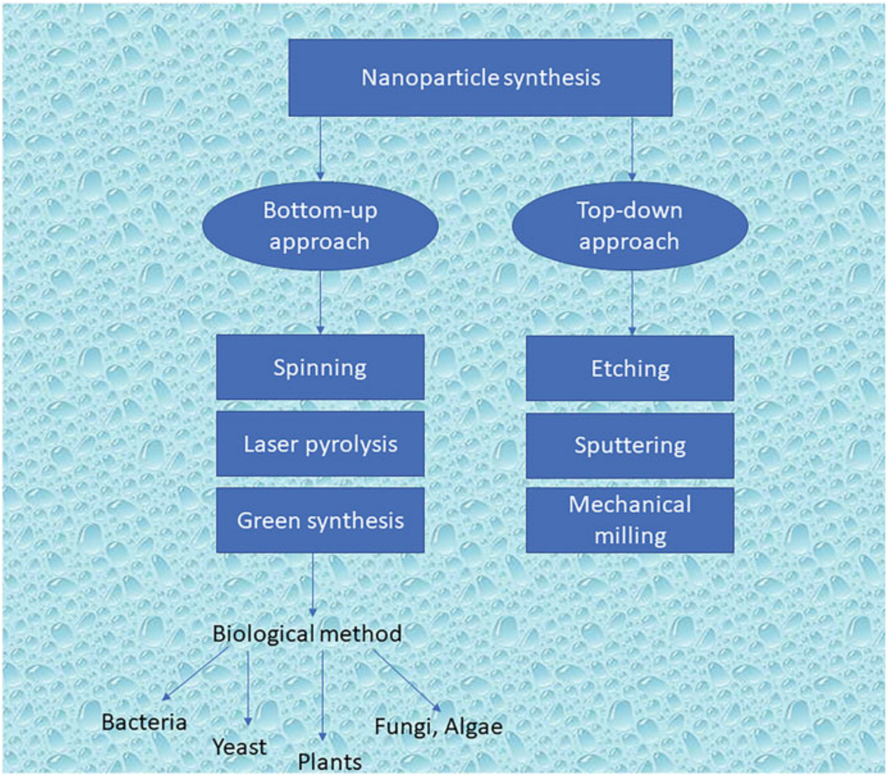

Fig. 3.2 Different methods and approaches for synthesizing nanoparticles. Source: (Siavash 2011)

alkaloids, proteins, sugars, phenolic acids, polyphenols play an important role in first reducing the metallic ions and then stabilizing them (Castro et al. 2011). Table 3.2 compiles the information on a large number of plants being utilized for the synthesis of various nanoparticles and it is clear from the information that the synthesis of nanoparticles, their size, application all vary from plant to plant.

3.4.2 Synthesis of Nanoparticles Utilizing Bacteria

Biosynthesis of nanoparticles utilizing bacteria has gained a lot of attention in the area of green nanotechnology over the globe because of their abundance in the environment and their capacity to adjust to extraordinary conditions. Additionally, these are fast-growing, inexpensive to cultivate and simple to control (Mehrotra et al. 2019a, b; Kumar et al. 2019). Moreover, the nanoparticles synthesized from bacteria have higher catalytic reactivity, more specific surface area and are of uniform size (Mehrotra et al. 2019a, b). Various species of bacteria till now have been effectively

Table 3.2 List of various plants used for the synthesis of nanoparticles

Plant species	Plant material	Type of nanoparticles	Mechanism/ causative agents	Size (in nm)	References
Azadirachta indica	Kernel	Silver, gold	Azadirachtin	50–100	Shukla et al. (2012)
Jatropha curcas L.	Latex	Lead	Curcacycline A and Curcacycline B	10–12.5	Joglekar et al. (2011)
Camellia sinensis	Leaves	Platinum	Pure tea polyphenol	30–60	Alshatwi et al. (2015)
Nephelium lappaceum L	Peels	Nickel oxide	Nickel–ellagate complex formation	50	Yuvakkumar et al. (2014)
Eucalyptus	Leaves	Iron oxide	Epicatechin and quercetin–glucuronide	20–80	Wang et al. (2014)
Syzygium aromaticum	Flower buds	Iron oxide	Eugenol	5–40	Subhankari et al. (2013)
Aloe barbadensis miller	Leaves	Zinc oxide	Phenolic compounds, terpenoids or proteins	25–40	Sangeetha et al. (2011)
Alfa sprouts	Living plant	Silver	In situ synthesis	2–20	GardeaTorresdey et al. (2003)
Asparagus racemosus	Tuber cortex	Palladium	Tuber cortex	1–6	Raut et al. (2013)

used for the synthesis of different nanoparticles like gold, silver, zinc, cadmium sulphide, palladium, etc. (Table 3.3).

3.4.3 Synthesis of Nanoparticles Utilizing Fungi and Yeast

The utilization of fungi in the synthesis of nanoparticles has gained fast interest because of their toleration and metal bioaccumulation capability (Sastry et al. 2003). A large amount of enzymes can be produced by utilizing fungi since they are magnificent secretors of extracellular proteins, which eventually can regulate the synthesis of nanoparticles (Castro-Longoria et al. 2012). Fungi is viewed as better than bacteria in the production of nanoparticles as these secrete huge volume of proteins which directly gets converted to nanoparticles, causing higher productivity (Mohanpuria et al. 2008). Furthermore, various fungal species grow very fast, making their maintenance in the research lab simple. In a similar way, easy maintenance of yeast production in the laboratory, its rapid growth and the use of simple nutrients are some of the remarkable advantages of yeast over bacteria for the mass production of nanoparticles (Skalickova et al. 2017). Fungi and yeast have supremacy over other biological systems because of their wide diversity, simple culture

Table 3.3 Some of the nanoparticles synthesized by bacteria

Nanoparticles	Bacteria	Size	Shape	Applications	References
Gold	*Bacillus subtilis* 168	5–25 nm	Octahedral	Metal uptake	Beveridge and Murray (1980)
	Marinobacter Pelagius sp.	20 nm	Spherical	Optical	Joerger et al. (2000)
	Lactobacillus sp.	20–50 nm	Hexagonal	Metal uptake	Nair et al. (2002)
	R. capsulata	10–20 nm	Spherical	–	Shiying et al. (2008)
	Stenotrophomonas maltophilia	40 nm	Spherical	Reduction in metallic toxicity	Sharma et al. (2012)
	E. coli K12	50 nm	Circular	Removal of nitroaromatic pollutants from water	Srivastava et al. (2013)
Silver	*P. stutzeri* AG259	<200 nm	Nanocrystal	Optical	Joerger et al. (2000)
	Pseudomonas aeruginosa	13 nm	Spherical	–	Kumar and Mamidyala (2011)
	Bacillus cereus	20–40 nm	Spherical	Antimicrobial	Silambarasan and Abraham (2012)
Cadmium sulphide	*Escherichia coli*	2–5 nm	Spherical, elliptical	Optical and electronic properties	Sweeney et al. (2004)
	Klebsiella aerogenes	20–200 nm	Spherical	–	Holmes et al. (1995)
Manganese sulphate and zinc sulphate	*Streptomyces sp.* HBUM171191	10–20 nm	Polymorphic	–	Waghmare et al. (2011)
Palladium	*Desulfovibrio desulfuricans* NCIMB 8307	5-10 nm	Icosahedral	Bioprocessing applications of precious metals	Naiz et al. (2002)
Magnetic	*Magnetosirillium magneticum*	50 nm	Spherical	Biomineralization	Mohanpuria et al. (2008)

methods, less time and low cost which successively lead to an eco-friendly approach for the synthesis of nanoparticles. Some of the fungal and yeast species successfully utilized for the production of the nanoparticles are documented in Table 3.4.

3.4.4 Synthesis of Nanoparticles Utilizing Algae

From the past few years, the utilization of algae for the biosynthesis of nanoparticles has increased tremendously because of their simple access and efficiency (Ogi et al. 2010; Singaravelu et al. 2007). At present, they are also called as 'biofactories' for the synthesis of nanoparticles since they are an excellent source of biomolecules (Manivasagan and Kim 2015). These biomolecules like proteins, pigments, starch, nucleic acids, fats and secondary metabolites such as alkaloids present in the algal cell wall act as reducing agents which eventually prompts the reduction and synthesis of metal and metal oxide nanoparticles at ambient conditions (Siddiqi and Husen 2016). Also, seaweeds are advantageous over different reductants because of their high metal accumulating capability, minimal effort, plainly visible structure and anti-biological fouling properties (Davis et al. 2003). In addition, seaweeds have both anti-inflammatory and inhibitory properties that can be utilized to treat diverse ailments and stifle a few types of malignant growth (Fawcett et al. 2017). The biogenic manufacturing of different nanoparticles utilizing diverse algal species is presented in Table 3.5.

3.4.5 Remediation Using Biogenic Polysaccharide

Polysaccharides are natural biopolymers of biological systems that have been extracted and put to extensive use. These biopolymers are renewable materials, environment friendly, non-toxic, biodegradable and have excellent functional properties. In recent years, polysaccharide nanomaterial composites have attracted attention of researchers in nanobioremediation due to improved processability, surface area, stability, tunable properties and cost-effectiveness. Table 3.6 provides an overview of biogenic polysaccharides that have been used in the preparation of bionanocomposites.

3.5 Nanobioremediation

Utilization of nanomaterials, synthesized from plants, algae, bacteria, fungi and yeast, to clean up the environmental pollutants such as organic or inorganic waste and heavy metals from the affected sites is termed as nanobioremediation (Yadav et al. 2017). The concept of green technology has gained immense interest in the area of nanomaterials for application in bioremediation and also due to its cost-effectiveness in large-scale use, enhanced efficiency and shortened time for the remediation process. Several other reasons contribute towards the use of

Table 3.4 Some of the nanoparticles synthesized by fungi and yeast

Nanoparticles	Fungi and yeast	Size	Shape	Applications	References
Gold	Thermophilic fungi	6–40 nm	Spherical	Biomedical	Molnar et al. (2018)
	Penicillium sp.	45 nm	Spherical	Antimicrobial	Sandhya and Suvarnalatha (2017)
	Mariannaea sp. HJ	37.4 nm	Spherical, hexagon, irregular	Photocatalytic	Pei et al. (2017)
	Pycnoporus sanguineus	29.30 nm	Spherical, pseudo-spherical, triangular	Catalytic	Shi et al. (2015)
	Magnusiomyces ingens LH-F1	10–80 nm	Triangle, hexagon, pentagon	Catalytic	Zhang et al. (2016)
	Aspergillus sp. WL-Au	4–29 nm	Spherical	Catalytic	Shen et al. (2017)
Silver	*Ganoderma enigmaticum*	15–25 nm	Spherical	Antibacterial	Gudikandula et al. (2017)
	Rhizopus stolonifer	9.47 nm	Spherical	Biomedical	Rahim et al. (2017)
	Alternaria sp	4–30 nm	Spherical	Antibacterial	Singh et al. (2017)
	Saccharomyces cerevisiae	1–10 nm	Spherical	Antimicrobial	Marquez et al. (2018)
	Saccharomyces cerevisiae, Rhodotorula glutinis and *Geotrichum candidum*	2.5–20 nm	Spherical	Biomedical	Zahran et al. (2013)
	Arthroderma fulvum	15.5 ± 2.5 nm	Spherical	Antifungal	Xue et al. (2016)
Copper carbonate	*Neurospora crassa*	10–20 nm	Spherical	–	Li and Gadd (2017)
Cadmium sulphide	*Candida glabrata* and *Schizosaccharomyces pombe*	2 nm	Spherical	–	Dameron et al. (1989)
Bioactive	*Lichen fungi* (*Usnea longissima*)	9.40–11.23 nm	Spherical	Medicinal	Shahi et al. (2003)

Table 3.5 List of some nanoparticles synthesized by algae

Nanoparticles	Algae	Size	Shape	Applications	References
Gold	*Sargassum muticum*	5.42 nm	Spherical	Pharmaceutical and biomedical	Namvar et al. (2015)
	Spirulina platensis	5 nm	Spherical	Antibacterial	Suganya et al. (2015)
	Ecklonia cava	30 nm	Spherical and triangular	Antimicrobial	Venkatesan et al. (2014)
	Chlorella vulgaris	2–10 nm	Spherical	Anti-pathogenic	Annamalai and Nallamuthu (2015)
	Turbinaria conoides	2–19 nm	Spherical and triangular	Antimicrobial	Vijayan et al. (2014)
	Sargassum myriocystum	60 nm	Spherical	Antibacterial	Ismail et al. (2018)
Silver	*Spatoglossum asperum*	20–46 nm	Spherical to oval	Antibacterial	Ravichandrana et al. (2018)
	Gelidium amansii	27–54	Spherical	Antibacterial	Pugazhendhi et al. (2018)
	Amphiroa anceps	10–80 nm	Spherical	Antibacterial	Roy and Anantharaman (2018)
	Sargassum ilicifolium	10–80 nm	Spherical, cubical and hexagonal shaped	Antimicrobial	Roy and Anantharaman (2018)
	Laminaria japonica	20 nm	Spherical- to oval-shaped	In seedling growth	Kim et al. (2017)
	Ulva compressa (L.) Kütz and Cladophora glomerata (L.) Kütz	200 to 300 nm	Irregular shaped	Antimicrobial	Minhas et al. (2018)
Aluminium oxide	*Sargassum ilicifolium*	20 nm	Spherical	–	Koopi and Buazar (2018)
Iron oxide	*Ulva flexuosa*	12.3 nm	Spherical	Antimicrobial	Mashjoor et al. (2018)
Copper oxide	*Bifurcaria bifurcata*	96–110	Spherical	Antimicrobial	Abboud et al. (2014)

Table 3.6 List of microbial polysaccharides utilized as bionanocomposites Source: Manikandan et al. (2017)

Polysaccharide	Source	Active functional group
Gellan	*Sphingomonas elodea*	OH
Dextran	*Lactobacillus sps, Streptococcus mutans*	OH
Cellulose	*Aerobacter, Acetobacter, Agrobacterium, Azotobacter, Pseudomonas*	OH
Alginate	*Azotobacter* and *Pseudomonas*	OH, COO^-
Chitosan	*Fungal cell walls, Cunninghamella elegans*	OH, COO
Hyaluronic acid	*Streptococcal sps* and *Bacillus subtilis*	OH
Zooglan	*Zoogloea ramigera*	OH
Pullulan	*Aureobasidium pullulans*	OH
Xanthan	*Xanthomonas campestris*	OH

nanotechnology in bioremediation. Firstly, the size in the range of nanoscale helps to increase the surface area per unit mass of a material, allowing enhanced reactivity rate. Secondly, nanomaterials exhibit quantum effect, thereby requires less activation energy to attain chemical reactions. Lastly, another feature shown by the nanomaterials is surface plasmon resonance (SPR) which can be used to detect toxic materials. There are a diverse range of multiple nanomaterials used for bioremediation, with high level of remedial versatility such as in removing wastes including hydrocarbons, heavy metals and radioactive materials like uranium, in remediation of soil, groundwater and wastewater.

The potential of nanomaterials to alleviate the pollution load is ongoing and could potentially bring about the most profound changes in the field of bioremediation sector in the upcoming years (Rizwan et al. 2014) (Table 3.7).

3.6 Conclusion

Nanotechnology has the potential to metamorphose all the existing technologies that include the techniques involving pollution control as well. This technology is gaining recognition globally for successfully removing the contaminants from the environment. The extraordinary properties of nanoparticles and their concurrence with the present day technologies offer a great opportunity to revolutionize environmental clean-up. It is clear from the reviewed literature that while much attention has been focused on the development and potential benefits of nanomaterials in water treatment processes, concerns have also been raised regarding their potential human and environmental toxicity. Biogenic synthesis of nanoparticles can solve the problem of toxicity to a great extent. Thus, the utilization of biologically synthesized nanoparticles for the process of bioremediation can go a long way in attaining a sustainable environment. Biosynthesis of nanoparticles using microbes helps to reduce the toxicity, is cheap, eco-friendly and saves time. Due to the remarkable

Table 3.7 Some of the nanoparticles used for removal of contaminants. Source: (Yadav et al. 2017; Yang et al. 2019; Vittal and Jamuna 2011)

Contaminant to be removed	Nanomaterials/nanoparticles
Lead	Ca-alginate iron oxide magnetic nanoparticles; polyacrylic acid-stabilized zero-valent iron nanoparticles (PAA-ZVIN)
Mercury	Carboxy-methylated chitosan ferromagnetic nanoparticles; thiol-functionalized silica ferromagnetic nanoparticles
Heavy metals	Thiol-functionalized super-paramagnetic nanoparticles
Arsenic	Zinc oxide nanoparticles
Cobalt and iron	Iron nanoparticles
Metal ions	Carbon nanoparticles
Lead, mercury, manganese, copper, cadmium, arsenic, chromium	Graphene based nanocomposites
Arsenic and copper metal	Iron nanoparticles
Methylene blue	Goethite nanoparticles
Tri-chloroethane (TCE)	Metallic gold nanoparticles coated with palladium
Chlorinated ethane	Metallic gold nanoparticles coated with palladium
Chlorinated methane	Metallic gold nanoparticles coated with palladium
Inorganic-mercury	Gold nanoparticles supported on alumina
Trihalomethanes (THM)	α-Fe_2O_3 sintered in zeolite form
Chlorpyrifos and malathion	Silver nanoparticles; gold nanoparticles
Escherichia coli and *Staphylococcus aureus*	Gold nanoparticles; silver nanoparticles
Pathogenic bacteria	Silver nanoparticles
Escherichia coli	Cerium oxide nanoparticles
Escherichia coli, Bacillus megaterium, Bacillus subtilis	Magnesium oxide nanoparticles; copper oxide nanoparticles
Escherichia coli	Aluminium nanoparticles; titanium dioxide nanoparticles
Escherichia coli, Pseudomonas fluorescens, Listeria monocytogenes, Salmonella enteritidis	Zinc oxide nanoparticles
Toluene, NO_2	Nanocrystalline zeolites
Heavy metal ions Benzene, toluene, ethylbenzene, xylene p-nitrophenol benzene, toluene, dimethylbenzene Heavy metal ions Trihalomethanes (THMs) Heavy metal ions THMs chlorophenols Herbicides Microcystin toxins	Carbonaceous nanomaterials CeO_2-carbon nanotubes (CNTs) Activated carbon fibres (ACFs) CNTs functionalized with polymers CNTs functionalized with Fe Single-walled carbon nanotubes Multi-walled carbon nanotubes

(continued)

Table 3.7 (continued)

Contaminant to be removed	Nanomaterials/nanoparticles
Inorganic ions Heavy metal ions Actinides and lanthanides	Self-assembled monolayer on mesoporous Supports (SAMMS) Anion-SAMMS Thiol-SAMMS HOPO-SAMMS
Heavy metal ions	Biopolymers
Polychlorinated biphenyls (PCBs) Inorganic ions Chlorinated organic compounds Heavy metal ions	Zero-valent iron nanoparticles (nZVI)
PCBs Chlorinated ethane Chlorinated methanes	Bimetallic nanoparticles Pd/Fe nanoparticles
TCE and PCBs Dichlorophenol Trichlorobenzene Chlorinated ethane Brominated organic compounds (BOCs)	Ni/Fe nanoparticles Pd/Au nanoparticles
Heavy metal ions Azo dyes Phenol Aromatic pollutants	Nanocrystalline TiO_2 Nitrogen (N)-doped TiO_2 Fe (III)-doped TiO_2 Supported TiO_2 nanoparticles

and significant capability of nanobioremediation, it is assumed that their application will enhance at a great leap in the near future and will perform a very important and indispensable part in achieving a green and renewable environment.

Acknowledgements The authors are grateful to Amity Institute of Biotechnology and Amity Institute of Marine Science and Technology, Amity University, Uttar Pradesh, for providing the research and laboratory facilities. We did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

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