Prospects of Nanobioremediation as a Sustainable and Eco-Friendly Technology in Separation of Heavy Metals From Industrial Wastewater

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Abstract Rapid industrial development and discharge of effluents into rivers has polluted water with heavy metals and other toxic matter. Most of the conventional techniques for waste water treatment are known to cause harmful impact on environment by releasing hazardous components. Some industries use bioremediation to remove heavy metals which is eco-friendly but ineffective where the environment itself is toxic to microorganisms due to presence of chemicals and non-biodegradable metals. Advanced nanotechnology such as nano-adsorption and nanomembrane, is an emerging field to treat effluents with high efficiency though it's not cost effective and eco-friendly. The solution to these problems can be integrating bioremediation with nanotechnology. In this chapter, the structure and characteristics of nanomaterials are discussed. Additionally, the chapter also highlights the integration of microbiology and nanotechnology in two ways: Firstly, in green synthesis of nanoparticles which is less expensive and sustainable and secondly, coating nanoparticles in microbes for effective remediation.

Keywords Nanotechnology · Bioremediation · Nanobioremediation · Industrial waste water treatment · Heavy metals · Green synthesis

1 Introduction

The sustainability of human civilization depends on the judicious usage of natural resources such as water. With the advent of rapid industrialization during last century and usage of water as the universal solvent for many industrial processes, it is becoming apparent to deal with the waste water being generated by many industries. As the discharge of large amounts of untreated water in to the environment from industry is not desirable and governed by many regulations, there are various process/methods that are being used for treating the waste water (Rajeshwari et al.

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2000; Ali 2012; Zheng et al. 2015; Edwards 2019; Shah 2021a, b; Singh et al. 2019; Ajiboye et al. 2021; Nazaripour et al. 2021). Most of industrial waste water contains toxic chemicals and metals that could pose problems for the environment and can cause serious health issues to the surrounding population. If left untreated and released into the surroundings, this water could contaminate and pollute the ground water and could cause chronic health issues ranging from skin diseases to cancer. Hence the removal of metals and other toxicants from the waste water is an urgent priority. There are many technological processes that utilize chemical or biological agents for industrial water remediation. Conventional physicochemical methods are being used for treating the water to remove toxic metals and chemicals (Shahedi et al.2020; Shah 2020; Gunatilake 2015; Zawierucha et al. 2016; Edwards 2019; Crini and Lichtfouse 2019; Mao et al. 2021). However, these methods suffer from being cost intensive and cannot be adapted universally for all kinds of industrial waste water treatment (Crini and Lichtfouse 2019). During last few decades, with the better understanding of microorganisms spanning all life forms, their utility as a bioremediation agent has been actively explored as the process of bioremediations seems to be natural and cost effective. There are many microorganisms or their products that are being used or exploited for removing organic and non-organic components such as metals from the industrial waste water (Rajeshwari et al. 2000; Crini and Lichtfouse 2019; Sharma et al. 2021). Although bioremediation is successful in many instances, its use for large scale or complete remediation or control over microbes is still debatable. Nanotechnology is relatively modern field having implications across various spectrum of sciences, engineering and medicine (Rajeshwari et al. 2000; Sawhney et al. 2008; Rashidi et al. 2011; Hussain et al. 2017; Ramos et al. 2017; Crini and Lichtfouse 2019). This field has seen an explosion in development over the last couple of decades and its applications virtually touch all the fields. Recently, nanomaterials are being conceived as remediations agents for treatment of polluted water not only from industry but from other sources of human consumption (Sawhney et al. 2008; Rashidi et al. 2011; Li et al. 2015; Hussain et al. 2017; Ramos et al. 2017; Nasrollahzadeh et al. 2021).

In this chapter, we will review the nature of nanomaterials and their usage in the treatment of waste water and future perspectives of use of nanomaterials in waste water treatment.

2 Structure and Characteristic Properties of Nanomaterials

Nanotechnology, during last few decades burst in to attention due to its potential applications to all the fields of technology and engineering. Nanomaterials are expected to perform or to be used in endless potential applications due to their size ranging in nanoscale. Nano scale is defined as the range where at least one dimension of the material falls under 100 nm (nM) (Emil Roduner 2006). Because of their size, the physical and chemical properties of nanomaterials are different from the bulk materials of the same element with which they are made (Wu et al. 2020; Juh

Tzeng Lue 2007; Murty et al. 2013). One important aspect of being at nanoscale is the surface to volume ratio is more and this is being exploited for better utility or for many applications as the availability of more atoms on the surface in comparison to the bulk material. Nanomaterials comes in various shapes and forms. Based on the number of dimensions nanomaterials can be classified as zero-, one-, two- and three-dimensional nanomaterials. In case of zero all dimensions are at nano scale (nano spheres), in one dimension, two dimensions are at nanoscale and the other is outside nano scale and in two-dimensional (nanotubes, nanofibres, nanorods, nano wires), one dimension is at nano scale and the other two outside the nanoscale (nano films, nano layers). Three dimensional nanomaterials are not at nanoscale but are made up of repeating units of nanomaterials (dendrimers). Based on the composition of elements, nanomaterials can be classified as carbon based (nanofibers, nano tubes,) and metal based such as gold and silver nanoparticles and TiO_2 oxide nanoparticles. The physical and chemical properties of nanomaterials are different from the corresponding bulk material. Catalytic activity of some nanomaterials is better as the surface to volume ratio is more(ref). They possess better electrical conductivity in case of ceramics and magnetic composite nanomaterials while metal nanomaterials may have increased resistance. Nanomatrials generally have increased magnetic activity and also behave as super paramagnetic material. Some metal nanomaterials show marked toughness, ductility and plasticity (Wu et al. 2020; nanotechnology and 2007 2007). Some nanomaterials are characterized by shift in optical absorption, fluorescence and increased quantum efficiency. When it comes to biological applications or in medicine, nanomaterials are proved to be better in overcoming biological barriers such as cell membranes and also shown to be more biocompatible (Hu et al. 2006, 2017; Kyriakides et al. 2021). Because of changes in physical and chemical properties at nano scale, nanomaterials are being exploited for their usage in purification of water either from natural sources or from the sources of contamination such as an industry.

3 The Science Behind Nanobioremediation

Industrial harmful contaminants have distinct physical and chemical properties and each contaminant interacts in a different manner with environmental parameters. Due to this the conventional techniques to treat waste water is not so effective. Bioremediation is used in many industries for their low cost and varied applications Recently in several investigations, nanomaterials have been used in association with bioremediation technologies which prevents formation of dangerous by-products as well as accelerates the process of degradation or removal of contaminants (Vázquez-Núñez et al. 2020). Using nanomaterials for bioremediation has many benefits. Because of its nanosize, the material will have high surface area which increases reactivity with surrounding components. They require less activation energy for reactions. Nanomaterials have the advantage of exhibiting surface plasmon resonance which can be applied in detecting toxic substances. Due to small size, nanomaterials have the potential to reach deep into contamination zones. Also, oxide coating with nanomaterials can increase reactivity to a large extent. Some metal nanoparticles can function as biocatalysts. For example, few studies revealed Palladium nanoparticles which are coated on the cell walls of *Shewanella oneidensis* gets charged with radicals in the presence of substrates which act as electron donors such as acetate, hydrogen etc. When these cells coated with nanoparticles and charged with substrates come in contact with compounds containing chlorine, the radicals present in palladium removes chlorine. Immobilization of microorganisms is possible by using metal nanoparticles which are magnetic in nature. These cells have been efficiently applied in degradation or recovery of components. In one of the observations, the microorganisms treated or coated with magnetic nanoparticle effectively separated organic sulfur from fossil fuels on large scale in reactors (Rizwan et al. 2014). Interaction of nanoparticles with living organisms can lead to any outcomes like sorption, biotransformation, dissolution etc. which leads to degradation of toxic compounds (Vázquez-Núñez et al. 2020). Nanoparticles can either inhibit or activate the metabolism of living organisms participating in bioremediation. Therefore, it is very essential to confirm the effects of nanoparticles with living organisms before its application in remediation processes. Some of the parameters that needs to be studied are nanoparticles size and shape, surface area, chemical properties of both toxic components and nanoparticles, nature and type of organism, growth media, pH, temperature etc. (Tan et al. 2018). Due to involvement of so many factors, it is very difficult to study their individual effects. There are not many research studies done which establish the relationship between these parameters. Sorption studies are one of the significant methods in nanobioremediation. Contaminant removal either can be through adsorption which is surface phenomena or through absorption where the toxic compound penetrates the nanoparticle and gets separated as a solution. Additionally, either the sorption can be by chemical means or by physical methods. Several research has been performed on adsorption isotherms, thermodynamics, and kinetic studies to understand the type of adsorption processes and interaction between nanoparticles and contaminants. Nanoparticles can degrade contaminants by photocatalytic processes. In some cases, enzymes produced by living organisms degrade pollutants (Vázquez-Núñez et al. 2020).

4 Formation of Nanoparticles Using Natural Sources

Synthesis of nanoparticles naturally using microorganisms and plants is cost effective, safe and eco-friendly. Not all organisms can produce metal nanoparticles. Formation of nanoparticles from organisms is natural and can be in any two ways: First method is by bio-reduction where metal nanoparticles are produced by reduction using biological tools. In this method, metal ions are reduced and enzymes are oxidized. Nanoparticles can be then recovered from the contaminated samples. The second method is bio-sorption where metal ions from polluted locations are bound to the cell walls of organisms or the organisms synthesize peptides which assemble into suitable nanoparticles (Zhang et al. 2020).

4.1 Sources for Synthesis of Nanoparticles

Bacteria

Several species of bacteria are widely studied to have the capacity to produce nanoparticles by reducing metal ions. It is relatively easy to engineer bacteria as per the requirements for the synthesis of nanoparticles (Singh et al. 2018). Some bacteria known for production of silver nanoparticles are *Escherichia coli*, *Lactobacillus casei*, *Bacillus sp.*, *Pseudomonas sp.*, *Enterobacter cloacae*, *Corynebacterium* sp. and *Shewanella oneidensis.* Gold nanoparticles production from bacteria are comparatively complex and few bacterial species recognised includes *Shewanella alga, Escherichia coli, Bacillus sp.*, *Desulfovibrio desulfuricans*, and *Rhodopseudomonas capsulate.*

Synthesis of palladium has been studied for *Escherichia coli* and Psedomonas cells. Reports claim that copper nanoparticles from *Morganella morganii* need to be stabilized immediately after their formation since copper metal is usually unstable and readily gets oxidized to form cupric oxide. Copper nanomaterials accumulates extracellularly as a result of intracellular uptake of copper ions which is then enzymatically reduced (Zhang et al. 2020). Nanomaterials formed from different strains of bacteria vary in size, shape, morphology and time duration for their synthesis.

Fungi

Fungi are found to be better sources relative to bacteria for production of metal and metal oxide nanoparticles in view of the fact that many intracellular enzymes, proteins and reducing agents are present on their cell surfaces which aid in the mechanism. The process is cost effective and efficient resulting in large amount of nanoparticles of well-defined morphologies (Singh et al. 2018). *Fusarium oxysporum, Aspergillus fumigatus and Trichoderma reesei* have been identified to produce silver nanoparticles extracellularly. Since *Trichoderma reesei* morphology is extensively studied, there is advantage of manipulating them for the nanoparticle synthesis. *Aspergillus fumigatus* produce silver nanoparticles within minutes of exposure. White rot fungi form silver nanoparticles intracellularly. Although not much work is done on production of gold nanoparticles form fungi, but there are studies reported on the formation of gold nanoparticles from *Verticillium* species by reducing Tetrachloroaurate ($AuCl_4$) ions externally on the mycelium (Zhang et al. 2020).

Few research work reveals synthesis of single platinum nanoparticles (PtNPs) intracellularly by *Neurospora crassa. Fusarium oxysporum* also synthesizes PtNPs both extra and intracellularly. Some fungi such as *Fusarium oxysporum* and *Verticillium* sp. produce metal oxides like magnetite nanoparticles (MaNPs) intracellularly (Zhang et al. 2020).

Fungal mycelia have relatively larger surface area. In addition, for large scale production and purification process use of fungal species has been proven efficient and less expensive through investigations. Furthermore, enormous number of proteins and enzymes are formed in fungi, which are required for high production of nanoparticles. However, most of the fungi are pathogenic and might be a concern (Zhang et al. 2020).

Yeasts

Like fungi, yeasts also have large surface area to their advantage. They synthesize metal nanoparticles through various methods such as precipitation, sorption, sequestration etc. Most of the nanoparticles are produced intracellularly by yeasts. For example, *Candida glabrata* produces CdS quantum dots intracellularly in the presence of cadmium salts. Also, *Torulopsis* sp. in the presence of lead ions forms PbS quantum dots and *Pichia jadinii* is known to produce gold nanoparticles intracellularly (Zhang et al. 2020).

Plants

Plants have the tendency to store heavy metals. In addition, plants have varied biomolecules such as carbohydrates, proteins, fats, enzymes etc. and phytochemicals like sugars, ketones, aldehydes, carboxylic acids, flavonoids and terpenoids, which play a key role in reduction of metal ions to nanoparticles and makes them one of the best sources with regards to ease of process, faster synthesis, stability and cost. Many plants have been studied over the past few years for production of nanoparticles which includes *Aloe barbadensis* (Aloe vera), *Azadirachta indica* (Neem), *Avena sativa* (Oats)*, Osimum sanctum (*Tulsi*), Coriandrum sativum* (coriander) and *Cymbopogon flexuosus* (lemon grass) for synthesis of silver and gold nanoparticles to name a few. Other metal nanoparticles like zinc, cobalt, nickel and copper are found to be synthesized from *Brassica juncea* (mustard), *Helianthus annuus* (sunflower), *Coriandrum sativum* (coriander), *Hibiscus rosa-sinensis* (China rose), *Camellia sinensis* (green tea), *Acalypha indica* (copper leaf) and *Aloe barbadensis* (Aloe vera). Most of the metal and metal oxides nanoparticles are produced by reduction of metal salt ions accumulated in plants. For example, flavonoids reduce metal ions into metal nanoparticles by transformation of enol to the keto forms. Studies show that conversion of enol- to keto is the key mechanism in the formation of silver nanoparticles from *Ocimum basilicum* (sweet basil) extracts. Sugars like glucose also participate in metal nanoparticles synthesis with different size and shapes. Also, proteins comprising of amino acids reduce the metal ions to form nanoparticles. Some investigations reveal that few amino acids are capable of binding with silver ions and hence produce silver nanoparticles. Furthermore all the naturally occurring amino acids were examined and tested to study their reduction process of gold ions (Singh et al. 2018).

Plants used for metal nanoparticle synthesis differ in their process times and form nanoparticles of various shapes and sizes. *Jatroa curcas* extracts synthesize homogenous silver nanoparticles of small sizes from silver nitrate ($AgNO_3$) salt in about 4 h. On contrary, *Acalypha indica* leaves form homogeneous silver nanoparticles of slightly bigger sizes (Singh et al. 2018). *Medicago sativa* seeds were found very effective in the synthesis of silver nanoparticles as the process was faster and took less than an hour and more than 90% of silver ions reduced. The temperature requirement is also low to enable action of enzymes. The nanoparticles were triangular or spherical with a rather heterogeneous size range (Zhang et al. 2020). In another study, silver and gold nanoparticles were formed from a single component such as phyllanthin isolated from the plant *Phyllanthus amarus*, rather than using whole plant or plant parts. Concentrations of phyllanthin highly influenced the shapes of nanoparticles. For instance, phyllanthin added in large amounts resulted in spherical nanoparticles (Singh et al. 2018).

Some extracts from plants like *Anacardium occidentale* (cashew nut), *Azadirachta indica* (neem), *Swieteni amahagony* (mahogany) and vegetable extracts (Zhang et al. 2020) have been reported to synthesize bimetallic silver and gold nanoparticles.

Algae

Cyanobacteria or blue green algae, such as *C. vulgaris,* and *S. Platensis L. majuscule*, and *C. prolifera*, are yet another cost-effective sources for green synthesis of nanoparticles. Recently, synthesis of gold metal nanoparticles by reduction of Au^{3+} ions to gold oxide (AuO) using cyanobacteria *S. platensis* proteins, have been reported (Aman Gour et al. 2019).

Viruses

The capsid proteins on the surface of virus make them highly reactive towards metals leading to formation of nanoparticles. For example, Tobacco mosaic virus (TMV) has close to 2000 capsid proteins on their surface which reacts with silver or gold ions in addition to plant extracts of *Nicotiana benthamiana* (Round-leaved native tobacco) or *Hordeum vulgare* (Barley) (Zhang et al. 2020). The synthesized nanoparticles were relatively smaller in size.

4.2 Solvents

Water is the most commonly used solvent for nanoparticle synthesis as it is relatively cheaper and readily available (Shanker et al. 2016). For example, gold and silver nanoparticles are produced from gallic acid prepared in an aqueous medium. Furthermore, oxidation of gold nanoparticles by the oxygen available in the water, increases its efficiency and reactivity and enhances its role in bioremediation (Singh et al. 2018).

4.3 Factors Modulating Formation of Metal Nanoparticles

The size and shape of nanoparticles depends on various parameters such as reaction time, reactant concentrations, pH, and temperature. These factors need to be optimized for the synthesis of nanoparticles of desired morphology.

pH

pH of the reaction medium is very important factor and alters the size and shape of nanoparticles. For example, rod-shaped gold nanoparticles of size in the range 25-85 nm were formed from biomass of *Avena sativa* (Oat) at acidic pH of 2. These gold nanoparticles were relatively smaller (5–20 nm) and nucleation was comparatively good when pH was maintained at 3 or 4. Slight alkaline conditions (pH > 5) are required for synthesis of silver nanoparticles from *Cinnamon zeylanicum* extracts which are homogenous and spherical in nature (Zhang et al. 2020).

Reactant Concentration

The presence and concentration of phytochemicals and other bio-components in the extract determine the size and shape of the nanoparticles. For example, the growth of gold and silver nanomaterials formed from extracts of *Cinnamomum camphora* (camphor) were reported to be influenced by the quantity of biomass in the reaction mixture. Also, addition of chloroauric acid to *Aloe vera* leaf extract led to spherical nanoparticles rather than triangular plates. It was also reported that the size of the nanoparticles can be manipulated by varying the concentrations of the substrates. In another similar study, varied shapes of silver nanoparticles including the desired spherical profiles, were synthesized by altering the concentration of *Plectranthu samboinicus* extract in the process mixture (Zhang et al. 2020).

Reaction Time

Yet another factor influencing morphological characteristics of the nanoparticles is the reaction time. A research investigation observed formation of spherical silver nanoparticles of average size 12 nm from *Anana scomosus* (Pineapple) extract and $AgNO_3$, within 2 min of time showing a rapid color change. *Chenopodium album* leaf extract produced silver and gold nanoparticles within 15–20 min of the reaction and the process persisted for more than 2 h. In another study, it was revealed that different sizes of nanoparticles formed from *Azadirachta indica* leaf extract and silver nitrate (ranging 10–35 nm) resulted in an increase in reaction time from half an hour to more than 4 h (Zhang et al. 2020).

Reaction Temperature

The temperature modulates the structure, size, and productivity of nanoparticles synthesized from different plants. One of the experimental studies reported that temperature had reciprocal effects on the size of nanoparticles synthesized from the *Citrus sinensis* (sweet orange) extracts from its rind. The nanoparticle size decreased with an increase in temperature. Also, in few other studies it was noted that the temperature altered shape of gold nanoparticles produced using *Avena sativa* (oat). The gold nanoparticles formed at lower temperature were spherical compared to nanoparticles at higher temperatures which exhibited non-spherical patterns. Process temperature conditions also affects productivity like it was noticed in few observations that the yield of platinum nanoparticles synthesized extracellularly, was around 5.66 mg l^{-1} which varied with temperature (Zhang et al. 2020).

4.4 Identification and Removal of Heavy Metal Ions from Waste Water

Industrial development has led to accumulation of contaminants and pollutants in soil, air and water. Industrial effluents especially are discharged into water bodies. Most of the effluents include harmful heavy metals like copper, lead and cadmium which are detrimental even at low concentrations. There are several methods for identifying these pollutants but these conventional techniques are not cost effective, consume lot of time and also require skilled and experienced personnel. Use of metal nanoparticles has many advantages due to its size and optical properties like the process is simple, relatively cheaper and has high sensitivity to detect toxic heavy metals even at low concentrations. In one of the investigations reported, silver nanoparticles were synthesized from different plant sources which were sensitive in identification of heavy metals based on their plant source. For example, silver nanoparticles prepared from mango leaves displayed calorimetric sensing selectively for lead and mercury ions. Another significant pollutant from industries like textile, plastic, leather, paper and food are coloured dyes. Dyes are important component used in manufacturing process in textile industries. About 10–15% of dyes are discharged as wastes into water bodies. These are very dangerous as they increase turbidity in water thereby preventing penetration of sunlight which can be fatal for marine life. For removal of dyes from water, usually metal oxide nanoparticles like zinc oxide (ZnO), titanium dioxide (TiO_2), and copper oxide (CuO) with photocatalytic properties are used for their high surface area. High surface area increases absorption of reactive dyes at low concentrations as nanoparticles have large number of reactive sites available due to high surface energies. Furthermore, very less quantity of these nanoparticles is required for large mass of effluents (Singh et al. 2018).

5 Coating of Nanomaterials Inside Microbes for Effective Bioremediation

Nanomaterials can be potentially used for treating industrial wastewater and ground water. Nanomaterials can treat the wastewater by means of adsorption, photocatalysis, disinfection and membrane application. Adsorption is a common mechanism used with nanoparticles to treat the wastewater. Properties such as high surface area, selective adsorption sites, short diffusion distance between particles, alterable surface chemistry, reusability and so on gives the advantage of nanoparticles in wastewater treatment. Most commonly, heavy metals, arsenic, chromium, mercury phosphates, organic compounds, PAHs, DDT are adsorbed by nanoparticles. Organic compounds, volatile organic carbon, azo dye, congo red dye and so forth are removed from wastewater by means of photocatalytic oxidation. Nanoparticles with high photocatalytic activity such as TiO_2, ZnO, iron oxide nanoparticles are used in this technique. Nanoscale zero-valent iron (nZVI), nanoscale calcium peroxide nanoparticles are used to treat wastewater with halogenated organic compounds, metals, nitrate, arsenate, oil, PAH, PCB by means of redox reactions. Some of the nanoparticles have strong antimicrobial properties like silver and TiO_2 nanoparticies that can be used to disinfect the waste water. These nanoparticles have low toxicity, high chemical stability and reusability. Several research studies have confirmed use of nanoparticles of metal and metal oxides such as silver, TiO_2, Zeolites and CNTs that exhibit strong hydrophilicity, high mechanical and chemical stability, high permeability and selectivity, can be embedded to the membranes to increase their effectiveness in purification of the wastewater (Yadav et al. 2017).

Few investigations observed that Palladium, Pd(0) nanoparticles can be used for removal of chlorine. The cell wall and inside the cytoplasm of *Shewanella oneidensis* were coated with Pd(0) nanoparticles which gets charged on reaction with suitable substrates The protons present in these charged Pd(0) coated cells when exposed to chlorine rich mixtures, react with phencyclidine, leading to the separation of the chlorine molecule.

Sarioglu et al. (2017) studied the dye removal capacity of bacterial cells encapsulated within electrospun nanofibrous webs. Commercially available strain of *Pseudomonas aeruginosa* was immobilized using polymers like polyvinyl alcohol (PVA) and polyethylene oxide (PEO). The extent of encapsulation and the viability of bacteria were examined using advanced and modern tools and techniques. It was reported that bacteria encapsulated in PEO web showed higher methylene blue dye removal efficiency which could be due to better accessibility of bacteria trapped in the nanofibrous webs. Studies reported that the encapsulated bacterial cells remained alive for about a couple of months when the webs were stored at 4 °C and thus could be preferred to lyophilized cells which selective culture media and space for storage. In addition, some research reveal that the electrospun nanofibrous webs containing viable cells find scope in bioremediation of water systems.

The electrospun cyclodextrin fibers (CD-F) manufactured by electrospinning technique has been used in few studies as carrier matrix and feed for encapsulation of bacteria which can be effectively applied for bioremediation purposes. N.O San Keskin et al. (2018) reported in his findings that electrospinning process is simple and easy for immobilization of bacteria into CD-F matrix and is widely applied in wastewater treatment. CD-F are not toxic and hence display cell viability for more than a weeks of time when stored at 4 °C. The observations were promising for nanobioremediation as the bacteria encapsulated with CD-F showed high heavy metals and dye removal efficiencies showing results as 70 ± 0.2%, 58 ± 1.4% and 82 ± 0.8% for Nickel, chromium and reactive dye, RB5, respectively. Added advantage is bacteria can consume CD as an extra carbon source when primary carbon source depletes thereby increasing their growth rate.

6 Conclusion

Over the last few years research studies on green synthesis of metal and metal oxide nanoparticles has increased due to its various advantages. Among the numerous sources, plant extracts have been observed to have significant roles as stabilizing and reducing agents which under optimized reaction conditions can lead to formation of nanoparticles with desired sizes, shapes, and other morphological characteristics. Nanoparticles play a vital role in degradation of heavy metals in waste water. Nanoparticles on one hand degrades waste that might be toxic to microorganisms and on the contrary, improves performance of microorganisms in remediation of harmful substances. Though studies have investigated the inter-relation between nanoparticles and microorganisms in degradation of harmful substances in batch experiments, but the findings are not sufficient to comprehend the synergetic effect of nanoparticles and microorganisms during a nanobioremediation process and its applications. Also, there is no safety data available that indicates the long-term effects on use of nanoparticles with microorganisms. Hence, there is lot of scope in this field to explore and research and apply nanobioremediation technologies in varied applications following the regulatory framework and safety guidelines.

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