Nanobioremediation Technologies for Sustainable Environment

A. Sherry Davis, P. Prakash and K. Thamaraiselvi

Abstract Hybrid technologies like nanobioremediation are significant in transforming and detoxifying pollutants which harm the ecosystem. In situ or ex situ it has the potential for large scale clean- up activities with reduced cost and minimal harmful byproducts. Here five nanoscale metallic biosynthesized particles formed the topic of study. Zn, Ag, Au, Fe and Cu particles can be biosynthesized using plant extracts, bacteria, fungi and algae. The potential of these metallic nanoparticles to degrade and remedy various contaminants in the environment has been researched widely. A combination of biosynthesis and remediation lead to sustainable development and ultimately a sustained environment.

Keywords Biosynthesis · Nanoparticles · Bioremediation · Environment

1 Introduction

Environmental sustainability is defined as responsible interaction with the environment to avoid depletion or degradation of natural resources and allow for long term environmental quality. However the world's definition of sustainability is sustainable development which results in environmental degradation. The advancement in science and technology contribute directly or indirectly to the increase in waste and toxic materials in the environment. Environmental sustainability programs include protection and restoration of the natural environment.

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One of the restoration strategies used nowadays is bioremediation which makes use of microorganisms. The advantages of bioremediation over conventional treatments is cost effectiveness, high competence, minimization of chemical and biological sludge, selectivity to specific metals, no supplementary nutrient requirements, regeneration of biosorbent, and the possibility of metal recovery (Kratochvil and Volesky 1998). However this treatment method is not feasible for sites contaminated with toxic substances as it is harmful to microorganisms.

Nanoparticles however have the unique capability to remediate such toxic environments and also provide a healthy substrate for microbial activity thus speeding up the process of environment clean-up. Nanoparticles can be prepared by physico-chemical methods (Masala and Seshadri 2004; Swihart 2003) but the use of hazardous chemicals, high cost and toxic byproducts has given biological nanoparticle synthesis an advantage (Konishi et al. 2006). Nanobioremediation is the use of nanoparticles to remove pollutants by enhancing microbial activity.

Nanoparticles (NPs) may be either metallic or nonmetallic and differently shaped. NPs are of the following types-single metal NPs, bimetallic NPs, carbon based NPs, modified NPs etc. Metal nanoparticles have applications in different fields like medical imaging (Lee et al. 2008a), drug delivery (Horcajada et al. 2008), electronics (Lipovsky et al. 2008), nanocomposites (Seager et al. 2007), biolabeling (Liang et al. 2006), biocide or antimicrobial agents (Sanpui et al. 2008), sensors (Jiang et al. 2008), non-linear optics (Ebothe et al. 2006), hyperthermia of tumors (Pissuwan et al. 2006), intercalation materials for electrical batteries (Klaus-Joerger et al. 2001), optical receptors (Dahan et al. 2003) etc. The wide range of applications of nanoparticles is due to their unique optical, thermal, electrical, chemical, and physical properties (Panigrahi et al. 2004).

Nanoscale materials has the following characteristics—Larger surface area per unit mass, show quantum effect and hence is more reactive, exhibit plasmon resonance and can diffuse or penetrate contaminated sites easily. Selective sample extraction can be achieved by modifying the surface functionality of the nanoparticles.

In this review we have focused on the biosynthesis of five nanoparticles (Zn, Ag, Au, Fe, Cu) using plant extracts, bacteria, fungi and algae. We have also compiled the different degrading and remediation activities of these nanoparticles for possible large scale restoration programs.

2 Biosynthesis of Zinc Nanoparticles (ZnNP's)

In the last two decades ZnNP's have been given significant attention owing to its applications in varied fields like piezoelectric films (Martin et al. 2000), piezoelectric sensor (Wang et al. 2004), ceramics (Grigorjeva et al. 2008), photo catalysis

Table 1 Biosynthesis of ZnNPs

Materials	Organism	References
Plant	*Aloe barbadensis miller*	Sangeetha et al. (2011)
	Calotropis giganta	Vidya et al. (2013)
	Corriandrum sativum, Acalypha indica	Gnanasangeetha and Thambavani (2013a, b)
	Parthenium hysterophorus	Rajiv et al. (2013)
	Azadirachta indica	Gnanasangeetha and Thambavani (2013c)
Bacteria	*Lactobacillus*	Prasad and Jha (2009)
	Lactobacillus plantarum	Ameer et al. (2010)
	Aeromonas hydrophila	Jayaseelan et al. (2012)
Fungi	*Candida albicans*	Mashrai et al. (2013)
Algae	*Cystophora moniliformis*	Vigneshwaran et al. (2006)

(Pal and Sharon 2002) solar cells (Gordillo 2002), bio-imaging, drug delivery (Xiong 2013) actuator, biosensors (Yang et al. 2012) and water purification specifically arsenic removal (Singh et al. 2013b).

Owing to the wide applications of ZnNP's it has been synthesized by methods such as wet chemical method (Lee et al. 2009; Mehta et al. 2012), organic solvent method (Mezni et al. 2012) and microwave method (Nehru et al. 2012). However biological synthesis using bacteria, fungi, algae and plant extracts is the method of choice and many researchers have been successful in synthesizing ZnNPs (Table 1).

3 Biosynthesis of Silver Nanoparticles (AgNP's)

Nanobiotechnological developments have led to the development of environmentally benign nanoparticles. AgNP's have applications in non-linear optics, as intercalation materials for electrical batteries, optical receptors, as a catalyst and as an antibacterial. The antimicrobial activity of silver nanoparticles has many uses like the production of AgNP coated blood collecting vessels, coated capsules, bandaids etc. (Geoprincy et al. 2011). Biosynthesis of AgNp's using biological entities is tabulated in Table 2.

Table 2 Biosynthesis of AgNP's

Materials	Organism	References
Plant	*Euphorbia hirta, Nerium indicum*	Priya et al. (2011)
	Cleome viscosa	Yamini et al. (2011)
	Trigonella foenumgraecum	Singh et al. (2011)
	Cycas	Jha and Prasad (2010)
	Ocimum	Mallikarjuna et al. (2011)
	Sinapis arvensis	Khatami et al. (2015)
	Iresine herbstii	Dipankar and Murugan (2012)
	Lantana camara	Kumar et al. (2015)
	Citrus limon	Prathna et al. (2011)
	Artemisia nilagirica	Vijayakumar et al. (2013)
	Pithophora oedogonia	Sinha et al. (2015)
	Butea monosperma	Chaturvedi and Verma (2015)
	Nerium oleander	Subbaiya et al. (2014)
Bacteria	*Morganella psychrotolerans*	Ramanathan et al. (2010)
	Bacillus licheniformis	Kalimuthu et al. (2008)
	Streptomyces sp. LK3	Karthik et al. (2014)
	Staphylococcus aureus	Nanda and Saravanan (2009)
	Brevibacterium casei	Kalishwaralal et al. (2010)
	Streptomyces rochei	Selvakumar et al. (2012)
Fungi	*Aspergillus fumigates*	Bhainsa and D'souza (2006)
	Aspergillus tamarii	Kumar et al. (2012)
	Schizophyllum commune (mushroom fungus)	Arun et al. (2014)
	Trichoderma reesei	Vahabi et al. (2011)
	Cladosporium cladosporiodes	Balaji et al. (2009)
	Fusarium oxysporum	Birla et al. (2013)
	Aspergillus clavatus	Verma et al. (2010a, b)
Algae	*Navicula atomus, Diadesmis gallica, Stauroneis sp. Sargassum wightii, Fucus vesiculosus*	Asmathunisha and Kathiresan (2013)
	Turbinaria conoides	Rajeshkumar et al. (2012)
	Sargassum longifolium	Devi et al. (2013)
	Caulerpa racemosa	Kathiraven et al. (2015)
	Cystophora moniliformis	Prasad et al. (2013)
	Sargassum muticum	Azizi et al. (2013)

4 Biosynthesis of Gold Nanoparticles (AuNP's)

Gold nanoparticles show high chemical reactivity on comparison with bulk gold. It exhibits surface plasm on oscillations which can be used in fields like labeling, imaging and sensing. AuNPs are biocompatible and hence can be used in disease diagnosis and therapy. AuNPs have been biosynthesized from plant extracts, bacteria, fungi and algae. Table 3 focuses on the biological synthesis of AuNP's.

Table 3 Biosynthesis of AuNP's

Materials	Organism	References
Plant	*Sorbus aucuparia*	Dubey et al. (2010)
	Chenopodium album	Dwivedi and Gopal (2010)
	Maduca longifolia	Fayaz et al. (2011)
	Rosa hybrida	Noruzi et al. (2011)
	Ocimum sanctum	Philip and Unni (2011)
	Magnolia kobus, Diopyros kaki	Song et al. (2009)
	Sesbania drummondii	Sharma et al. (2007)
Bacteria	*Rhodopseudomonas capsulate*	He et al. (2007)
	Escherichia coli DH5a	Du et al. (2007)
	Thermomonospora sp.	Kasthuri et al. (2009)
	Rhodococcus sp.	Park et al. (2011)
	Delftia acidovorans	Johnston et al. (2013)
	Pseudomonas aeruginosa	Narayanan and Sakthivel (2010)
	Geobacillus sp. strain ID17	Correa-Llantén et al. (2013)
	Klebsiella pneumonia	Malarkodi et al. (2013)
	Marinobacter pelagius	Sharma et al. (2012)
Fungi	*Candida albicans*	Chauhan et al. (2011)
	Fusarium semitectum	Sawle et al. (2016)
	Epicoccum nigrum	Sheikhloo et al. (2011)
	Cylindrocladium floridanum	Narayanan and Sakthivel (2011)
	Aspergillus clavatus	Verma et al. (2010a, b)
	Neurospora crassa	Castro-Longoria et al. (2011)
	Aspergillus oryzae	Binupriya et al. (2010)
	Hormoconis resinae	Mishra et al. (2010)
	Penicillium brevicompactum	Mishra et al. (2011)
	Saccharomyces cerevisiae	Sen et al. (2011)
Algae	*Sargassum wightii*	Singaravelu et al. (2007)
	Shewanella oneidensis	Suresh et al. (2011)
	laminaria japonica	Ghodake and Lee (2011)
	tetraselmis kochinensis	Senapati et al. (2012)
	Klebsormidium flaccidium	Dahoumane et al. (2012)
	Centella asiatica	Das et al. (2010)
	Lemanea fluviatilis	Sharma et al. (2014)
	Sargassum muticum	Namvar et al. (2015)
	Padina gymnospora	Singh et al. (2013a)

5 Synthesis of Iron Nanoparticles (FeNP's)

The three major forms of iron oxides found in nature are magnetite (Fe_3O_4), maghemite (γ-Fe_2O_3), and hematite (α-Fe_2O_3) (Cornel and Schwertmann 1996). Of all the different kinds of iron oxides, magnetite have aroused the interest of many researchers owing to the fact that it can be easily synthesised, can be modified or coated and has superparamagnetic characteristics (McHenry and Laughlin 2000). This property makes it easy to separate these supermagnetic particles from aqueous solution and complicated matrices by applying an external magnetic field. Some problems associated with using FeNP's are its intrinsic instability resulting in the formation of agglomerates and its high chemical activity which promotes oxidation, subsequent loss of magnetism and dispersion. Hence for application in various fields these nanoparticles have to be coated with either inorganic substances like silica, carbon etc., or with organic species like surfactants and polymers (Wu et al. 2013). Iron nanoparticles have been synthesized by various chemical and physical methods (Afonso et al. 2011). Some emerging methods of synthesis of iron nanoparticles are the use of microorganisms and plant extracts which exclude the use of harmful chemicals and toxic byproducts (Table 4).

Table 4 Biosynthesis of FeNP's

Materials	Organism	References
Plant	*Sorghum sp.*	Njagi et al. (2010)
	Green tea	Shahwan et al. (2011)
	Musa paradisiaca	Herlekar et al. (2014)
	Dodonaea viscosa	Daniel et al. (2013)
	Musa paradisiaca	Venkateswarlu et al. (2013)
	Terminalia chebula	Kumar et al. (2013)
	Eucalyptus tereticornis, Melaleuca nesophila, and *Rosemarinus officinalis*	Wang et al. (2014)
	Aloe vera	Phumying et al. (2013)
Bacteria	*Bacillus subtilis*	Sundaram et al. (2012)
	Shewanella oneidensis	Perez-Gonzalez et al. (2010)
	E. coli	Lee et al. (2008a, b)
	Klebsiella oxytoca	Arčon et al. (2012)
Fungi	*Fusarium oxysporum*	Bharde et al. (2006)
	C. globosum	Kaul et al. (2012)
	Plerotus Sp.	Mazumdar and Haloi (2011)
	Alternaria alternata	Mohamed et al. (2015)
Algae	*Sargassum muticum*	Mahdavi et al. (2013)
	Sargassum myriocystem	Sangeetha and Kumaraguru (2014)

6 Synthesis of Copper Nanoparticles (CuNP's)

Copper is one of the most widely used materials in the world owing to its usage in fields like electricity, optics, catalysis, biomedical and antimicrobial applications. Many researchers have been successful in the biosynthesis of copper nanoparticles using the seed, flower, leaves and fruit skin of plants (Table 5). The nanoparticles synthesized from plant extracts were found to be covered by the medicinal properties of the plant. CuNP is an antimicrobial agent used in food packaging and water treatment.

Table 5 Biosynthesis of CuNP's

Materials	Organism	References
Plant	*Magnolia kobus*	Lee et al. (2013)
	Pterocarpus marsupium	Sharma et al. (2015a)
	Malva sylvestris	Awwad et al. (2015)
	Calotropis gigantea	Sharma et al. (2015b)
	Tamarix gallica	Nasrollahzadeh et al. (2015)
	Aloe barbadensis miller	Kumar et al. (2015)
	Tabernaemontana divaricate	Sivaraj et al. (2014a, b)
	Pyrus pyrifolia	Sundaramurthy and Parthiban (2015)
	Acalypha indica	Sivaraj et al. (2014b)
	Nerium oleander	Gopinath et al. (2014)
	Tridax procubens	Gopalakrishnan et al. (2012)
	Calotropis procera L	Harne et al. (2012)
Bacteria	*M. psychrotolerans* and *M. morganii RP42*	Ramanathan et al. (2011)
	Pseudomonas stutzeri	Varshney et al. (2010)
	Pseudomonas fluorescens	Shantkriti and Rani (2014)
	Serratia	Saif Hasan et al. (2008)
	Streptomyces sp.	Usha et al. (2010)
	Escherichia coli	Singh et al. (2010)
Fungi	*Hypocrea lixii*	Salvadori et al. (2013)
	Penicillium aurantiogriseum, Penicillium citrinum, Penicillium waksmanii	Honary et al. (2012)
	Aspergillus Sp.	Cuevas et al. (2015)
Algae	*Bifurcaria bifurcata*	Abboud et al. (2014)

7 Nano Bioremediation

Population growth, rapid industrialization and long term droughts has resulted in the spread of wide range of pollutants in surface and ground water system (Chong et al. 2010). The major contaminants include heavy metals, inorganic compounds, organic pollutants and many other complex compounds (Li et al. 2011). It is imperative to remove these toxic substances as they are harmful not only to human beings but also to the ecological environment (Pang et al. 2011). Waste water treatment processes like photo catalytic oxidation, adsorption/separation processing and bioremediation (Huang et al. 2006; Zelmanov and Semiat 2008) have been tried and tested. But factors like efficiency, operational method, energy requirements and high cost have restricted their usability (Huang et al. 2006; Zelmanov and Semiat 2008). In the past two decades nano scale materials have been used as an alternative to existing treatment materials due to its efficiency, cost effectiveness and eco-friendly nature (Dastjerdi and Montazer 2010).

Iron NPs is considered to be the first nanoparticle to be used in environmental clean-up (Tratnyek and Johnson 2006). Current applications of iron-based technologies in contaminated land or groundwater remediation can be broadly divided into two groups, based on the chemistry involved in the remediation process: technologies which use iron as a sorbent (adsorptive/immobilization technologies) and as an electron donor to break down or to convert contaminants into a less toxic or mobile form (reductive technologies) (Cundy et al. 2008). However, it should be noted that many technologies utilize both these processes.

Zn NPs a semiconductor photo catalyst have been extensively studied by researchers around the globe owing to its capacity to degrade organic dyes. ZnNPs can photo catalyse and cause the complete degradation of a wide variety of compounds from dyes to phenols and pharmaceutical drugs (El-Kemary et al. 2010).

Among all nanoparticles noble metal nanoparticles like gold and silver have enormous applications in diverse areas. In recent times researchers have analyzed the potential of Au and Ag nanoparticles in the degradation of organic dyes. Copper nanoparticles also can be used in the degradation of organic dyes with good results. Table 6 focusses on the degradation and subsequent remediation of various environmental pollutants.

Table 6 Remediation by metal nanoparticles

Metal nanoparticles	Remediation	References
Iron	Pentachlorophenol	Kim and Carraway (2000)
	Chlorobenzene	Lee et al. (2011)
	Dissolved sulfides	Chaung et al. (2014)
	Pyrene	Chang and Kang (2009)
	Dibenzo-*p*-dioxins and furans	Kim et al. (2008)
	Nitrate	Ryu et al. (2011)
	RDX (hexahydro-1,3,5-trinitro-1,3,5-triazine)	Naja et al. (2008)
	Cationic and anionic dyes	Shahwan et al. (2011)
	Alachlor, pretilachlor	Kim et al. (2006)
	Perchlorate	Moore et al. (2003)
	Brominated methanes	Lim et al. (2007)
	Chlorinated ethanes	Song and Carraway (2005)
	4,4′- dinitrostilbene-2,2′-disulfonic acid	Fan et al. (2007)
	Uranium	Fan et al. (2012)
	Lindane, atrazine	Joo and Zhao (2008)
	Alachlor and atrazine	Bezbaruah et al. (2009)
	Polychlorinated biphenyls (PCBs)	Choi et al. (2008)
	Atrazine	Satapanajaru et al. (2008)
	Cr(VI)	Cutting et al. (2010)
	Ni(II)	Li and Zhang (2006)
	As(V), Cr(VI)	Pradeep (2009)
	Cu(II), Pb(II)	Mahdavian and Mirrahimi (2010)
	Pb(II), Hg(II)	Ambashta and Sillanpää (2010)
	Cu(II), Cr(VI)	Huang and Chen (2009)
	Cr(VI) and Cd(II)	Li et al. (2013)
	Trichloro ethylene	Smuleac et al. (2011)
	Cd2+	Boparai et al. (2013)
	Metalachlor	Santornchot et al. (2010)
	Dichloroethane	Wei et al. (2012)

(continued)

Table 6 (continued)

Metal nanoparticles	Remediation	References
Zinc	4-chloro catechol	Kamat (2002)
	Cd(II)	Srivastava et al. (2013)
	Brown CGG dye	Islam (2015)
	Methylene blue	Srivastava et al. (2013)
	RhodamineB	Ali et al. (2013)
	Organic dyes	Sanna et al. (2016)
	Direct red 23	Kumar et al. (2014)
	Eriochrome black-T dye	Kazeminezhad and Sadollahkhani (2014)
	Methylene blue	Jain et al. (2014)
	Formaldehyde	Darvishi Cheshmeh Soltani et al. (2015)
	Phenol	Kruefu et al. (2012)
	Congo Red and Benzopurpurine 4B	Elaziouti and Ahmed (2011)
	Malachite green	Khezami et al. (2016)
	Resorcinol	Pardeshi and Patil (2009)
	Rhodamine B	Zhao and Wang (2011)
	fuchsine	Zhou et al. (2009)
Gold	Methylene blue	Suvith and Philip (2014)
	Tertiary dye effluent (Methyl orange, Acid red 88, Acid orange 10)	Sathishkumar et al. (2013)
	4-nitrophenol	Huang et al. (2009)
	Methylene blue	Gupta et al. (2010)
Copper	Methylene blue	Sinha and Ahmaruzzaman (2015)
	Methyl orange	Soomro and Nafady (2015)
	Dichloromethane	Huang et al. (2012)
Silver	Organic dyes (methyl violet, saffranin, eosin methylene blue, methyl orange)	Bhakya et al. (2015)
	Methylene blue	Morones et al. (2005)
	4-nitrophenol	Gangula et al. (2011)
	Congored	Modi et al. (2015)
	Coomassie Brilliant Blue G-250	Arunachalam et al. (2012)
	Textile Effluent	Corso and Almeida (2009)

8 Conclusions

Nanotechnology is revolutionizing the way we live. The unique characteristics of nanoparticles have made them the particle of choice in many fields including remediation of environmental pollutants. Ecofriendly synthesis of nanoparticles coupled with remediation can go a long way in promoting sustainability. Biosynthesis helps minimize the use of harmful chemicals and solvents and is simple, cost effective and time saving. Zn, Ag, Au, Fe and Cu nanoparticles have been synthesized by many researchers using various biological methods. Although there are many studies on the synthesis of Au, Ag, Cu and Zn nanoparticles, very few have concentrated on the biosynthesis of FeNPs using bacteria, fungi and algae. Green synthesis of metal NPs using plant extract seems to be the subject of choice of a majority of researchers, however only a few is documented in this review. On comparing the bioremediation properties of these NPs it was noted that FeNPs has a wider application, degrading pollutants like pesticides, dyes, hydrocarbons, TCE etc. Most of the other NPs find applications in the photocatalytic degradation of dyes. Considering the wide applications of FeNPs in remediation it is necessary to find novel methods to biosynthesize FeNPs on a large scale.

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