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Nanobioremediation: A new and a versatile tool for sustainable environmental clean up - Overview

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Abstract

Population growth, rapid industrialization and urbanization have led to the spread of enormous amounts of pollutants all around. The ultimate goal of environmental scientists across the globe is to achieve environmental sustainability using efficient, eco-friendly and economically viable technologies. Nanobioremediation is a newly emerging environment friendly clean up technology which entails the application of biosynthesized nanomaterials for the detoxification of pollutants. This methodology possesses a huge potential for large scale environmental cleanup with reduced cost and minimum generation of harmful byproducts. Nanomaterials have received much attention from scientists and researchers in different sectors of environmental sciences attributed to their unique physico-chemical properties. The biogenic production of nanoparticles has the potential to emerge as a safer and promising option to the existing methods. It is simple, cost- and time effective, and involves minimum usage of harmful chemicals.

1. Introduction

A clean and healthy environment is extremely important to not only protect the ecological health but also general public health. As human beings, we all significantly depend on clean air to breathe as well clean water to drink and for use in agriculture and industry [1]. Unfortunately, during the past few decades, the magnitude of environmental pollution has been continuously rising at an alarming pace, majorly due to population explosion, rapid urbanization and industrialization [2].

In the current scenario, it has become a very challenging task to tackle or remediate various forms of environmental pollution by eco-friendly, economical and sustainable technologies [3]. The area of study investigating the removal of contaminants from the environment is called environmental remediation and the methods used to remove or degrade the pollutants are called environmental remediation techniques [4]. One of the most sought after technique for the environment restoration is bioremediation [5]. Solving the problem is referred to as "Remediation" and "bioremediation" is the process which utilizes various biological agents like microorganisms or their enzymes to degrade the environmental pollutants into less toxic forms. Most common bioremediation techniques include bioventing [6], bioloeaching [7], bioaugementation [8], bioreactor [9], composting [10], biostimulation [11], land farming [12], phytoremediation [13] and rhizofiltration [14]. Bioremediation offers many advantages over conventional treatments, which includes its cost effectiveness, high competence, minimal generation of chemical and biological sludge, and selectivity to specific metals, no supplementary nutrient requirements, regeneration of biosorbent, and the possibility of metal recovery [15]. However, this treatment is not feasible for sites contaminated with high concentrations of toxic substances like heavy metals and salts as they are harmful to microorganisms. Therefore, the remediation of contaminants by using existing technology is not much effective for the environmental cleanup.

Nanomaterials: The way ahead

With the rapid development in the area of nanomaterials and nanotechnology, their role in providing innovative and effective solutions to a wide range of environmental challenges is becoming increasingly very important [16,17]. Nanomaterials owing to their unique physico-chemical properties, have garnered much attention from researchers across the globe in different areas of environmental sciences, specifically in bioremediation [18,19]. They possess a large number of special properties relative to bulk material and often have unique visible properties because they are small enough to confine their electrons and produce quantum effects and hence are more reactive [20]. They possess large surface per unit area, exhibit Plasmon resonance and are able to diffuse or penetrate contaminated sites easily. The surface functionality of the nanoparticles can be modified to improve its selectivity for the sample extraction [21].

Nanoparticles can be prepared by various physical and chemical methods [22,23] but their high cost, use of hazardous chemicals and formation of toxic byproducts has given biogenic nanoparticle synthesis an upper edge [24]. Literature reveals a number of research papers on the biogenic production of several nanoparticles like Fe, Zn, Cu, Ag, and Au using microorganisms (bacteria, yeasts, fungi, algae, actinomycetes and plant extracts) which are emerging as nano-factories [25-29]. With various biological entities being used in the process, biosynthesis of nanoparticles is a quickly developing research area in the green nanotechnology [30]. Biosynthesis of nanoparticles is a bottom-up approach where the main reaction is reduction/oxidation. The reduction of metal compounds into their respective nanoparticles is usually attributed to the presence of microbial enzymes or the phytochemicals of the plants containing antioxidants or reducing properties. Nanoparticles of desired morphologies and sizes can be obtained quite fast and cleanly with certain optimization of the process parameters [31]. In the recent past, many research groups have focused on developing nanotechnology as more specific, cost effective and a sustainable remediation tool [32,33]. Nanomaterials have been used widely for treating the toxic contaminants present in small amounts in air, water and soil. They are ideally capable of monitoring, recognizing and removing them. For removing a particular pollutant, nanomaterials can be fabricated to decompose them even if they are present in micro levels [34]. Nanomaterials can also be engineered to develop highly miniature, accurate and sensitive pollution-monitoring devices: nano-sensors which after detecting the pollutants may later interact with them and decompose them to less toxic species [35]. A large surface to volume ratio of nanoparticles compared to bulk materials makes them a potential catalyst, which can be further aimed at manipulating such manufacturing processes which not only reduce the amount of material used, but also employ less toxic starting material and reduce the production of harmful wastes [36].

Nanomaterials have given new dimensions to the environmental cleanup and have proved to be an effective alternative for site remediation [37]. These nanomaterials have properties that enable both chemical reduction and catalysis to mitigate the pollutants of concern. They have found applications in bioremediation of heavy metal pollution [38], solid waste [39], hydrocarbons and uranium contamination and ground water and waste water remediation [40]. The following reports establish the efficacy of these nanoparticles in achieving a sustainable environment. Some of such examples include bioremediation of radioactive wastes from nuclear power plants and nuclear weapon production, such as uranium, has been achieved using nanoparticles. Cells and S-layer proteins of *Bacillus sphaericus* JG-A12 have been found to have special capabilities for the cleanup of uranium contaminated wastewaters [41]. Hence, nanoparticles have the unique capability to remediate such toxic environments which will not only have less toxic effect on microorganisms, but will also improve the microbial activity of the specific waste and toxic material which will reduce the overall time consumption as well as the overall cost. In this context, nanobioremediation has emerged as a new promising strategy for controlling pollution using biosynthetic nanoparticles. It is still a budding area but growing rapidly into the field of nanotechnology. This article is an overview of the recent advances in the field of nanobioremediation of various polluted areas of the environment.

The Science of Nanobioremediation

The removal of environmental contaminants (such as heavy metals, organic and inorganic pollutants) from contaminated sites using nanoparticles/nanomaterials produced by plants or microorganisms (fungi, bacteria) with the help of nanotechnology is called nanobioremediation (NBR). NBR is attracting major attention as a versatile technique for sustainable environmental cleanup [42]. The most recent technologies available for remediation of contaminated sites include chemical and physical remediation, incineration and bioremediation. With recent advances, bioremediation offers an environmental friendly and economically feasible alternative to remove contaminants from the environment [43]. Bioremediation works via three main approaches, the use of microbes, plants and the enzymatic remediation.

In the past two decades, nanomaterials emerged as good alternative to existing treatment methods due to its high efficiency, cost effectiveness and environmentally benign nature [44]. Iron NPs are considered to be the first nanoparticle to be used for environmental clean-up [17]. Several promising iron-based technologies are available for the treatment of contaminated land or groundwater remediation. Zn NPs have been extensively studied and explored by the researchers across the globe owing to their excellent capacity to degrade organic dyes. Zn NPs, being a semiconductor photocatalyst, can lead to the complete degradation of a wide variety of compounds from dyes to phenols and pharmaceutical drugs [45]. Among all nanoparticles, noble metal nanoparticles like gold and silver have enormous applications in diverse areas, most important being the degradation of organic dyes [46]. Copper nanoparticles have also exhibited good results in the degradation of organic dyes [47].

Nanotechnology also increases phytoremediation efficiency [48]. Nanoparticles can also be used for remediation of soils, water contaminated with heavy metals, organic and inorganic pollutants. Recent studies have shown that organic contaminants such as atrazine, molinate and chlorpyrifos can be degraded with nano-sized zerovalent ions [49,50]. Nanoparticles in enzyme-based bioremediation can also be used in combination with phyto-remediation [51,52]. For example, several complex organic compounds, such as long-chain hydrocarbons and organochlorines, are particularly resistant to microbial and plant degradation. A combined approach involving nanotechnology and biotechnology could overcome this limitation: complex organic compounds would be degraded into simpler compounds by nano-encapsulated enzymes, which in turn would be rapidly degraded by the joint activities of microbes and plants.

In order to address the environmental problems, to date, extensive research has been carried out to design the efficient and cost-effective technologies. A number of remediation technologies have been continually grown, evolved and developed to treat contaminated soil, leachate, wastewater and ground water, using the *in-situ* [53] and *ex-situ* [54] methods. Most of the conventional remediation techniques available are based on the classical *ex-situ* approach which involves excavation of contaminated material or toxic substances and then treating it using conventional methods. These methods are highly energy intensive, therefore costly and may also leave concentrated hazardous wastes residues which may require further treatment and disposal. Nanomaterials have highly desirable properties for *in-situ* applications. Due to their minute size and innovative surface fabrication, they may be able to invade very small spaces in the subsurface and remain suspended in groundwater, allowing the particles to travel farther and achieve wider distribution [17]. For nanoremediation, *in situ*, no ground water is pumped out for above ground treatment and no soil is transported to other places for treatment and disposal [55].

The following table enlists the nanoparticles for the remediation of various pollutants.

Nanoparticle used	Contaminant removed	References
Iron (Fe)	Total petroleum hydrocarbons	[56]
	As(III), Cr(VI)	[57]
	2,4-dichlorophenol	[58]
	Trichloroethene	[59]
	Dissolved sulfides	[60]
	Cd^{2+}	[61]
	Ni^{+2}, Co^{+2}	[62]
	Cr(VI) and Cd(II)	[63]
	Uranium	[64]
	Dichloroethane	[65]

	Trichloro ethylene	[66]
	Cationic and anionic Dyes	[67]
	Nitrate	[68]
	Chlorobenzene	[69]
	Cr(VI)	[70]
	Cu(II), Pb(II)	[71]
	Pb(II), Hg(II)	[72]
	Metalachlor	[73]
	Pyrene	[74]
	Alachlor and atrazine	[75]
	As(V), Cr(VI)	[76]
	Cu(II), Cr(VI)	[77]
	Atrazine	[78]
	Polychlorinated biphenyls (PCBs)	[79]
	Lindane, atrazine	[80]
	RDX (hexahydro-1,3,5-trinitro-1,3,5-triazine)	[81]
	Dibenzo-p-dioxins and furans	[82]
	4,4′- dinitrostilbene-2,2′-disulfonic acid	[83]
	Brominated methanes	[84]
	Alachlor, pretilachlor	[85]
	Ni(II)	[86]
	Chlorinated ethanes	[87]
	Perchlorate	[88]
	Pentachlorophenol	[89]
ZINC (Zn)	Malachite green	[90]
	Organic dyes	[91]
	Formaldehyde	[92]
	Brown CGG dye	[93]
	Methylene blue	[94]
	Direct red 23	[95]
	Eriochrome Black T	[96]
	Cd(II)	[97]
	Methylene blue	[97]
	Phenol	[98]
	Rhodamine B	[99]
	Congo red and Benzopurpurine 4B	[100]
	Fuchsine	[101]
	Resorcinol	[102]
	p-chloro catechol	[103]
Copper (Cu)	Methylene blue	[104]
	Methyl orange	[105]
	Dichloromethane	[106]
Gold (Au)	Methylene blue	[107]
	Tertiary dye effluent (Methyl orange, Acid red 88, Acid orange 10)	[108]
	Methylene blue	[109]
	p-nitrophenol	[110]
Silver (Ag)	Congo red	[111]
	Organic dyes	[112]
	Coomassie brilliant blue G-250	[113]
	p-nitrophenol	[114]
	Textile effluent	[115]
	Methylene blue	[116]

Conclusion

The field of nanotechnology has witnessed a tremendous growth during the past few decades. Nanotechnology may provide effective solutions for many pollution-related problems such as heavy metal contamination, oil pollution, adverse effects of chemical pollutants, soil pollution and so on. Nanobioremediation is one such promising technology to tackle various harmful pollutants present in the environment. The unique characteristics of nanoparticles have rendered them very useful in various fields, especially in environmental remediation. Biogenic synthesis of nanoparticles coupled with remediation is the new ray of hope for clean environment and a sustainable future. A large number of nanoparticles (Au, Ag, Cu, Fe, Zn) have been obtained from biological sources like bacteria, fungi and plant extracts. Biosynthesis of nanoparticles is simple and cost-effective with minimal use of harmful chemicals, and moreover requires less time. Many potent environmental pollutants like heavy metals; organic compounds; toxic dyes etc. have been sequestered by these nanoparticles. Considering their tremendous potential in reducing the environmental pollution, it is of utmost interest to the researchers to find novel and efficient methods for the biosynthesis of various nanoparticles.

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