Application of Microbes in Remediation of Hazardous Wastes: A Review

Chapter · January 2018

DOI: 10.1007/978-981-10-7485-1_11

3 authors:

Moni Kumari
Magadh University
11 PUBLICATIONS **208** CITATIONS

SEE PROFILE

Pooja Ghosh
Indian Institute of Technology Delhi
58 PUBLICATIONS **1,815** CITATIONS

SEE PROFILE

Indu SHEKHAR Thakur
Jawaharlal Nehru University
284 PUBLICATIONS **7,390** CITATIONS

SEE PROFILE

Chapter 11
Application of Microbes in Remediation of Hazardous Wastes: A Review

Moni Kumari, Pooja Ghosh and Indu Shekhar Thakur

Abstract Currently, pollution control, environmental management, treatment and recycling of wastes have become critical issues. One of the major reasons behind the growing environmental pollution is illegal disposal of waste. Due to the toxicity of waste, establishing efficient and environmentally friendly method to degrade and detoxify these wastes represent an important research challenge. Various physio-chemical methods are applied all over the world for solid waste management. The application of microbes to degrade waste is gaining attention due to its environmental and economic benefits. The present review deals with application of microbes in bioremediation of hazardous wastes. This review also outlines the various factors that limit the use of microbial waste bioremediation technologies. Moreover, the prospects of waste valorization for the production of biopolymers, biofuels, biocompost and industrial enzymes are also discussed in the review article.

Keywords Microbes · Bioremediation · Valorization · Waste management
Biofuel · Biocompost

M. Kumari · I. S. Thakur (✉)
School of Environmental Sciences, Jawaharlal Nehru University,
New Delhi 110067, India
e-mail: isthakur@hotmail.com

M. Kumari
e-mail: mona.jnu10@gmail.com

P. Ghosh
Centre for Rural Development and Technology, Indian Institute of Technology,
New Delhi 110016, India

S. J. Varjani et al. (eds.), *Bioremediation: Applications for Environmental Protection and Management*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-10-7485-1_11

11.1 Introduction

Environmental pollution refers to the introduction of hazardous wastes into the environment. This is one of the most severe problems of the twenty-first century facing global attention and priority decision-making. As the year passes, hazardous waste causes grave and irreparable damage to the Earth and thus, it has become an issue of serious international concern (Orloff and Falk 2003).

All the hazardous toxic wastes that are improperly managed are potential threat to mankind and environment. The nature of these wastes could be either liquid, solid, sludge or gas according to the Resource Conservation and Recovery Act (RCRA), enacted in 1976. Based on the regulations set by environment protection agency (EPA), hazardous wastes are categorized into four major groups: (1) ignitability/highly flammable like alcohol, acetone and gasoline, (2) corrosive substance including hydrochloric acid, nitric acid and sulphuric acid, (3) reactivity/ explosive and (4) highly toxicity/poisonous hazardous wastes are toxic in nature even at very low concentration.

Industrial hazardous wastes are produced either intentionally or unintentionally. According to the report of Chinese Nationwide General Investigation in 2007, 25.00 million tons of industrial hazardous waste is generated in China only (Sun and Wu 2007). Industries are major source of hazardous waste and are categorized into three main subcategories: (1) non-specific industrial source, for example halogenated solvents, (2) specific industrial source like wastewater produced in the industries during the course of 2, 4-dichlorophenoxyacetic acid (2, 4-d) production and (3) chemicals that have been used in the production of drugs, detergents, lubricants, dyes and pesticides like benzene. The best-known examples are hazardous chlorinated organic molecules such as polychlorinated naphthalenes (PCNs), polychlorinated dibenzofurans (PCDFs), polychlorinated biphenyls (PCBs), polychlorinated dibenzo-p-dioxins (PCDDs) and chlorophenols. Another group of inadvertently produced hazardous chemicals produced during the course of chemical combustive processes includes chemicals such as PAHs, hexachlorobenzene (HCB), dioxins like PCDDs and furans like PCDFs. Heavy metals such as chromium, nickel, copper, mercury and lead are also contaminants present in sludge, wastewater, vehicles and industrial activities above maximum permissible value. They too are considered as hazardous waste to due their environmental load and health effects.

Hazardous waste produced from agriculture and agro-industries includes fertilizers, pesticides and hazardous veterinary product wastes. Excess use of fertilizers, pesticides and other chemicals used in agriculture and the wastes formed from these cause land and water pollution. Chemicals/pesticides used in agriculture such as atrazine, endosulfan, DDT, toxaphene, aldrin, dieldrin, heptachlor, chlordane and lindane or gamma-hexachlorocyclohexane (γ-HCCH) are well-known hazardous waste. This group of toxic hazardous chemicals has been deliberately used in agriculture for enhanced production. Domestic-produced hazardous waste includes rat poisons, herbicides and pesticides, mosquito repellents, paints, disinfectants and fuels.

Hazardous waste produced in hospitals includes pathological waste, contaminated needle and pharmaceutical waste.

Among all the toxic hazardous wastes, some groups are specially designated as persistent contaminants due to their specific physicochemical properties as well as high toxicity levels. They are synthetic chemicals that have an intrinsic resistance to natural degradation processes and are therefore environmentally persistent. They have recalcitrant nature, long-term transportation, long half-life, adverse toxicological impact and bioaccumulation ability.

The uses of micro-organisms to destroy or reduce the concentration of hazardous wastes or any other contaminants present in the environment are called bioremediation. The two major success stories of bioremediation technologies of the past are the oil spill clean up of Prince William Sound and Gulf of Alaska (Atlas and Bartha 1998). Thereafter, bioremediation is used continuously as a good clean-up, cost-effective, energy efficient and eco-friendly alternative technique over the physicochemical methods. The two major processes to accomplish bioremediation are either by boosting the growth of indigenous microbial community present at the site called biostimulation or via introducing microbes having better bioremediation capabilities (Agnello et al. 2016). During bioremediation, microbes utilize toxic hazardous waste as a source of carbon and energy to destroy them into non-toxic or less toxic by-products. It is a low-cost technique, which generally has a high public acceptance and can often be carried out on site (Boopathy 2000). One of the major advantages of bioremediation is the generation of non-toxic elements such as carbon, nitrogen and hydrogen as the dead end by-products which simply get assimilated back into the environment. It is, however, not always be suitable as the range of contaminants on which it is effective is limited, the timescales involved are relatively long, and the residual contaminant levels achievable may not always be appropriate. Although the methodologies employed are not technically complex, considerable experience and expertise may be required to design and implement a successful bioremediation programme, due to the need to thoroughly assess a site for suitability and to optimize conditions to achieve a satisfactory result. It also has been observed that by utilizing the native microbial community present at the contaminated site, the bioremediation rate is quite slow. Hence, nowadays several advancements have been done in bioremediation strategies in order to increase its rate. This includes (i) adopting genetic engineered microbes/transgenic based bioremediation, (ii) application of exogenous biosurfactants producing microbes which increase the bioavailability of contaminants to the microbes thus rate of bioremediation, (iii) application of mixed microbial culture and (iv) by the application of rhizoremediation despite of bioremediation (Kumari et al. 2016; Sharma et al. 2017). The application of bacto-algal consortia leads to enhanced removal of several persistent organic contaminants present in landfill leachate over individual bacterial and algal treatment. It also has been observed that the bacto-algal consortia are more capable in reduction of cytotoxicity and genotoxicity over individual microbial culture after treatment of landfill leachate (Kumari et al. 2016).

Microbial degradation of hazardous waste involves the activities of several kinds of enzymes including oxidoreductase, oxygenase, dehydrogenase, Cytochrome

Table 11.1 Application of microbial enzymes involved in bioremediation of various hazardous wastes

Enzyme	Reaction	Applications
Oxidoreductases	Oxidative coupling of substrate	The detoxification of toxic organic compounds including phenolic, anilinic, chlorinated compounds
Oxygenases like monooxygenases and dioxygenases	Oxidation of reduced substrates by transferring oxygen from molecular oxygen (O_2) utilizing FAD/NADH/NADPH as a cosubstrate	Desulphurization, dehalogenation, denitrification, ammonification, hydroxylation, biotransformation, oxidation and biodegradation of various aromatic and aliphatic compounds
Laccases	Oxidation of a wide range of organic and inorganic compounds	Phenolic, aromatic, paradiphenols, aminophenols, polyphenols, polyamines, lignins and aryl diamine substrates
Peroxidases	Oxidation of substrate at the expense of hydrogen peroxide (H_2O_2)	Lignin and other phenolic compounds
Hydrolytic enzymes	Disrupt major chemical bonds in the toxic molecules	Reduction of toxicity of hazardous compounds
Lipases	Total hydrocarbon degradation	Bioremediation of oil spill

P450 enzyme, soluble methane monooxygenases (Table 11.1). The detoxification of hazardous contaminants is carried out through oxidative coupling by the action of oxidoreductases present in the microbial system. During such oxidation–reduction process, the hazardous toxic contaminants get transformed into harmless by-products.

11.2 Remediation Methods

11.2.1 Physicochemical Methods

Numerous physicochemical methods including coagulation–flocculation, filtration, precipitation, adsorption, ozonation, sedimentation, chemical precipitations, ion exchange, advanced oxidation and reverse osmosis have been employed for the removal of hazardous waste from the environment (Crini 2006). These methods have been found to be limited because these techniques are executed under controlled environmental conditions. Physicochemical techniques often involve high capital and operational costs, production of large volumes of sludge, high cost of equipments and require skilled manpower.

11.2.2 Biological Methods

Biological methods of treatment also called bioremediation are powered by micro-organisms for the degradation and detoxification of POPs. Bioremediation has distinct advantages over physicochemical remediation methods as it is cost-effective, eco-friendly and could be achieved without destructing indigenous flora and fauna (Timmis and Pieper 1999). During the course of bioremediation processes, micro-organisms use the contaminants as nutrient or energy sources (Tang et al. 2007). There are numerous benefits of using micro-organism for degradation of xenobiotic contaminants due to their ubiquitous presence, diversity and adaptation of variable metabolic pathways.

Since micro-organisms possess high biodegradation potential, they are of considerable biotechnological interest and their application in the degradation and detoxification of various hazardous wastes has been extensively investigated.

11.3 Bioremediation Processes: Two Main Categories

11.3.1 In situ Bioremediation

In situ bioremediation is the application of microbes for the on-site removal of pollutants. This technology of bioremediation depends on activity of contaminated site-specific indigenous microbial consortia (Agarwal 1998). However, this approach of bioremediation is less expensive and there is chance of permanent waste removal. Also, the chances of site disruption are very little, giving greater public acceptance to it. However, this method is often more suitable for remediation of soil with a low level of contaminants. For enhanced in situ bioremediation, effective microbial consortia can be established in the contaminated sites by providing proper temperature, moisture, nutrients and terminal electron acceptor (Hess et al. 1997; Agarwal 1998). During in situ bioremediation, anaerobic micro-organisms play better role over aerobic micro-organisms since they do not require expensive oxygen. It is very well studied that in situ bioremediation is successful in removing several monoaromatic organic pollutants including carbon tetrachloride (CT), tetrachloroethylene (TCA), trichloroethylene (TCE) or pentachlorophenol (PCP)-contaminated groundwater (Dyer et al. 2003; Widdowson 2004). Bioventing, biosparging and bioaugmentation are common in situ bioremediation processes.

11.3.2 Ex situ Bioremediation

Ex situ bioremediation is the major remediation technology and has been employed widely for the treatment of a wide range of xenobiotic hazardous wastes. In this technology, contaminated soil is taken out and treated elsewhere. It has been a topic of considerable research interest since last several decades. Ex situ bioremediation technology has been executed by either bioaugmentation which means micro-organisms are added to the contaminants or biostimulation, i.e. by providing essential nutrients or biosurfactants to stimulate microbial degradation (Sayara et al. 2010). Landfarming, composting, biopiles and bioreactors are commonly applied ex situ bioremediation processes. It is usually observed that the ex situ bioremediation techniques lead to removal of a wide range of pollutants, easily controllable and a faster processes over in situ.

11.4 Microbial Application for the Bioremediation of Hazardous Wastes

Microbes reported for the bioremediation of several classes of hazardous waste are mainly bacteria, algae, actinomycetes and fungi as these groups of micro-organisms have the physiological and metabolic capabilities to degrade the pollutants (Strong and Burgess 2008).

11.4.1 Bacterial Treatment of Wastes

Numerous aerobic and anaerobic bacteria have unique catabolic pathways enabling them to degrade a number of hazardous contaminants, including pesticides, PHA, dioxins and furans present in the environment. These groups of bacterial strains have ability to use pollutants as a sole source of carbon and energy. Bacterial P450 oxygenase system, monooxygenase, dioxygenases, hydroxylases and dehalogenases are key enzymes that participate in biotransformation and mineralization of xenobiotic compounds. Some examples of bacteria possess the ability to degrade chemical belongs to persistent organic contaminants (POPs) are *Pseudomonas*, *Streptomyces*, *Paenibacillus*, *Bacillus* and *Pandoraea* (Arshad et al. 2008; Fuentes et al. 2011; Karigar and Rao 2011; Ali et al. 2014; Singh et al. 2014).

For the bioremediation of industrial wastes containing lignin in huge quantity, bioremediation is efficiently carried out by the bacteria possessing ligninolytic enzymes like laccase. This enzyme is a multicopper oxidase and is involved in degradation of wide-range industrial pollutants. The introduction of molecular oxygen into substrate is carried out by the dioxygenases, a multicomponent enzyme system. The ubiquitous presence of dioxygenases in the bacterial system participates in the transformation of more toxic aromatic hazardous wastes into less toxic aliphatic one.

11.4.2 Algal Treatment of Hazardous Wastes

Most of the published literature on degradation of hazardous contaminants has been focused on either bacteria or fungi, while the innate potential of algae and cyanobacteria has received relatively less attention and has not been fully realized. Microalgal cells possess a complex array of enzymatic antioxidant defence system, which comprises mainly enzymes superoxide dismutase (SOD) and catalase (CAT) (Karigar and Rao 2011). Microalgae are one of the main diazotrophic components of the primary microbiota and significantly contribute to building-up soil fertility (Elizabeth and Harris 2008). Microalgae in their natural habitats are often exposed to various contaminants such as heavy metals, hexachlorobenzene, herbicides, insecticides, endocrine-disrupting chemicals and phenol (Hirooka et al. 2005; Dosnon-Olette et al. 2010), which impose toxic effects on the microalgae. Biodegradation of methyl parathion (MP) by microalgae and cyanobacteria was also reported by Megharaj et al. (1994). The authors have reported that microalgae or cyanobacteria utilized 1 ml of 1000 ppm commercial MP as a carbon and nitrogen source. There are reports on the role of algae in the biodegradation of lindane up to 48.8% by *Anabaena azotica* in 5 days (Zhang et al. 2012). Several algal species including *Scenedesmus* sp., *Chlamydomonas* sp. and *Chlorella* sp. have been identified for the degradation of fenamiphos, DDT and endosulfan (Megharaj et al. 2000; Sethunathan et al. 2004). Anthracenes (2.5 ppm), DDT (0.5 ppm) and Pyrene (0.1 ppm) are reported to be degraded by *Chlorella protothecoides*, *C. vulgaris* and *Scenedesmus quadricauda,* respectively (Lei et al. 2002; Yan et al. 2002).

11.4.3 Fungal Treatment of Hazardous Wastes

Mycoremediation is the technology where fungi are used for the degradation of pollutants. Since fungi are rapidly colonized, and more tolerant to pollutants, they are more efficient in bioremediation over other micro-organisms. Its hyphae can penetrate into soils and reach pollutant much faster than microbes (Reddy and Mathew 2002; Harms et al. 2011). Metabolic enzymes that catalyse xenobiotic biotransformation and detoxification reactions in eukaryotes are classified as phase I and phase II enzymes. Cytochrome P450 monooxygenase (P450s) and epoxide hydrolases constitute two important phase I oxidation enzyme groups. However, the application of various POPs as the source of carbon and energy by fungi has not been reported extensively. A diverse group of lignolytic and non-lignolytic fungi is able to oxidize POPs. Two main groups of enzymes are involved in the initial attack on PAHs by a fungus which includes cytochrome P-450 monooxygenase and lignin-degrading enzyme system. The mechanism of PAH metabolism by non-lignolytic fungi involves the oxidation of aromatic ring by P-450 monooxygenase (Chang et al. 2003). They generally incorporate one atom of oxygen into the aromatic nucleus and reduce the remaining atom to water, followed by enzymatic addition water to yield cis/trans-dihydrodiols (Sutherland et al. 1995). Arene oxide formed can then undergo non-enzymatic rearrangement to form phenol which can further be conjugated with glucose, xylose, gluconeric acid and sulphate. Various non-lignolytic fungi such as *A. niger*, *C. elegans* and *P. janthinellum* used cytochrome P 450 monooxygenase for the oxidative degradation of PAH. The most widely studied non-lignolytic fungus is *C. elegans*.

Many fungi have been tested for their ability to degrade endosulfan, including *Aspergillus terreus*, *Cladosporium oxysporum* (Mukherjee and Mittal 2005), *Mucor thermohyalospora* (Shetty et al. 2000) and *Fusarium ventricosum* (Siddique et al. 2003) (Table 11.2).

Table 11.2 Application of microbial species for the bioremediation of different classes of toxic hazardous wastes

Contaminants	Microbial pure culture	References
Mixture of PAHs	*Pseudomonas putida* (B1)	Chen et al. (2012)
High molecular weight PAHs	*Pseudomonas saccharophila* P15	Chen and Aitken (1999)
Cd, Cr (IV)	*Staphylococcus xylosus*	Ziagova et al. (2007)
Cr (IV)	*Bacillus licheniformis*	Zhou et al. (2007)
Chlorpyrifos	*Enterobacter* Strain B-14	Singh et al. (2004)
Tetrachlorvinphos	*Proteus vulgaris*	Ortiz-Hernández and Sánchez-Salinas (2010)
Diazinon	*Serratia marcescens* DI101	Abo-Amer (2011)
DDT, DDD and DDE	*Sphingobacterium* sp	Fang et al. (2010)
Pb, Ni, Cr	*Aspergillus niger, Aspergillus flavus*	Dwivedi (2012)
Cu, Mn, Zn	*Aspergillus brasiliensis, Penicillium citrinum*	Pereira et al. (2014)
Cd, Pb	*Chlorella vulgaris*	Aung et al. (2012), Edris et al. (2012)
Cd (II)	*Cladophora fascicularis*	Deng et al. (2008)
Cd, Hg, Pb, As, Co	*Spirogyra hyalina*	Kumar and Oommen (2012)
Sr	*Platymonas subcordiformis*	Mei et al. (2006)
Crude oil, a mixed hydrocarbon substrate, n-alkanes and isoalkanes as well as aromatic hydrocarbons	*Prototheca zopfii*	Walker et al. (1975)
Crude oil hydrocarbons	*Aspergillus, Cephalosporium* and *Penicillium*	Singh (2006)
Hazardous contaminants present in landfill leachate	*Pseudomonas* sp. ISTDF1	Ghosh et al. (2014)
Endosulfan	*Paenibacillus* sp. ISTP10	Kumari et al. (2014)
Bromophenol blue, fast blue RR, Congo red, crystal violet	*Trametes* sp. SQ01	Yang et al. (2009)

11.5 Degradation of Hazardous Waste Using Microbial Consortia

As the rate of pollution keeps increasing, the designing and constructing of synthetic microbial consortia has raised extensive attention for improving remediation technology. Microbial mixed cultures have been shown to be more suitable for bioremediation of recalcitrant compounds because of following reasons:

(1) The degradation of hazardous organic wastes by using microbial consortia is highly significant because microbial consortia together enhance the level of bioremediation.
(2) Microbial consortia together reduce treatment time of degradation.
(3) Pure culture of microbes can degrade only limited types of compounds, while some xenobiotic complex compounds can only degrade by cometabolism of more than one microbe present in a mixed culture.
(4) The application of bacto-algal microbial consortia leads to complete degradation of pollutants or toxic metabolites due to synergistic interactions among members of the associations (Kumari et al. 2016).
(5) Mixed microbial consortia easily adapt in the presence of different toxic wastes. The treatment using mixed culture is easy to handle and need minimal maintenance.
(6) Mixed cultures permit better utilization of the substrate.

11.6 Mechanism of Bioremediation

Chlorinated organic compounds such as chlorinated pesticides, solvents, polychlorinated naphthalenes (PCNs), polychlorinated dibenzofurans (PCDFs), polychlorinated biphenyls (PCBs), polychlorinated dibenzo-p-dioxins (PCDDs) and chlorophenols are common hazardous contaminants present in soil and groundwater. These classes of hazardous wastes are mainly bioremediated by micro-organisms by reductive dechlorination, dehydrochlorination, oxidation and isomerization of the parent molecule. Sulphur-containing hazardous wastes undergo bioremediation by sulphur-oxidizing micro-organisms. Such hazardous wastes are utilized as a source of sulphur for the growth of micro-organisms and concurrently produce soluble metal sulphate and sulphuric acids. Micro-organisms initiate degradation of another class of toxic compounds including dioxins and furans by hydroxylation of the aromatic ring with molecular oxygen. Several micro-organisms are known to grow on such class of hazardous compounds and oxidize it completely via salicylic acid to carbon dioxide.

11.7 Factors Affecting Bioremediation

(1) Bioavailability: This is an extremely important factor which determines the rate of biodegradation (Boopathy 2000). The physical nature and chemical composition of the waste determine their availability to the microbes. It is often observed that even though the hazardous wastes are biodegradable in nature, the rate of its degradation is quite low due to their unavailability. As for example, the microbial degradation of hydrophobic hazardous waste naphthalene and phenanthrene are utilized only when present in dissolve state.

(2) Soil nutrient: Nutrient bioavailability in the soil is one of the major factors that determine bioremediation rate. As the soil nutrient increases, it stimulates the indigenous microbial growth and activity in the soil ecosystem for enhanced bioremediation. The presence of adequate soil nutrient such as nitrogen, phosphorous and carbon also helps in building of various necessary enzymes that participate in bioremediation of hazardous waste. The balanced soil nutrients required for the microbial growths are carbon, nitrogen, phosphorous which should be in the ratio of 100:10:1 (Haghollahi et al. 2016).

(3) Soil oxygen: Microbial bioremediation of hazardous waste is too decided by the presence or absence of molecular oxygen (O_2) in the soil microbial environment. The very first enzymes that participate in aerobic are oxygenases, which rely on the molecular oxygen for their activity. Besides that, the presence of molecular oxygen also acts as an electron acceptor that is released on waste bioremediation. Since the solubility of molecular oxygen in the water is relatively low, thus, their presence is considered as a primary limiting factor for the aerobic microbial bioremediation.

(4) Temperature: As the microbial growth and activity are satisfactory only at optimum temperature, it measures the bioremediation of hazardous waste. At both extreme of temperature, microbial metabolism is inhibited which result in inhibition of bioremediation. At low temperature and high temperature, some psychrophilic and thermophilic microbial metabolism is active for the waste bioremediation. As the temperature increases from 4 to 35 °C, the rates of bioremediation increase by the mesophilic micro-organisms. The microbial growth doubles with every 10 °C rise in temperature leading to an increase in rate of bioremediation (Thibault and Elliott 1979).

(5) Soil moisture: All micro-organisms require soil moisture for their growth and function. It helps in circulation of water and nutrients in and out the micro-organisms. However, the presence of excess soil moisture leads to soil saturation creating resistance to oxygen transfer and ultimately diminish the amount of available oxygen required for microbial respiration (Haghollahi et al. 2016). Low levels of moisture content decrease microbial activity. The water holding capacity of the soil, its type, pore size distribution and texture decides the soil moisture content.

(6) Soil pH: The pH of soil gets altered due to both biotic and abiotic factors. By the process of fermentation and redox reactions, soil micro-organisms either consume or release H^+. Similarly due to metal leaching, pH of the soil gets decreased or its soil acidity increased under high rainfall conditions. Very few micro-organisms including acidophilic and basophilic can tolerate the extreme level of pH (very high or very low). As a consequence, pH of the soil influences soil microbial diversity. Soil pH is also important for enzyme activity because alteration in soil pH causes denaturation of microbial enzymes (Bonomo et al. 2001). It is mentioned in Singh et al. (2003) that at acidic pH, the rate of chlorpyrifos bioremediation is quite low; however, it increases significantly with an increase in soil pH.

(7) Type of soil: The texture of soil determines aeration, nutrient availability, water holding capacity and porosity. The sorption of nutrients by either ion exchange or precipitation to the soil is mainly facilitated by both inner surface and outer surface functional group. Clay is an important type of soil, and due to their very small size (<0.002 mm) and large surface area to volume ratio, it is considered as best for nearly all chemical, physical and biological activities (Buffle and De Vitre 1993). Besides that, soil having high clay content leads to more water adhesion or water holding capacity. Overall thus, very high microbial activities are found there (Brady and Weil 2000) (Fig. 11.1).

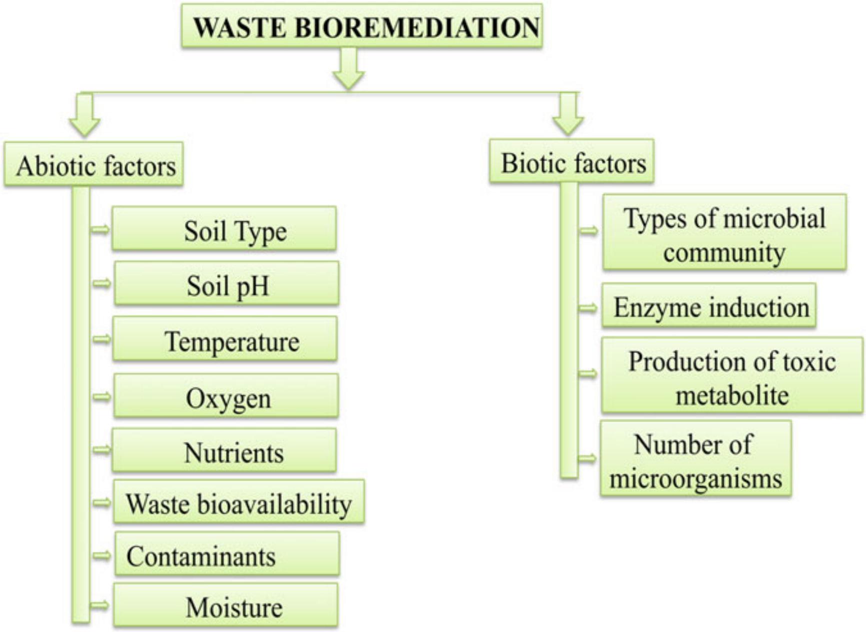

Fig. 11.1 Factors affecting waste bioremediation

11.8 Waste Valorization

Nowadays, the best way to reduce the environmental load of waste generated in such a huge amount is their application for the production of several value-added products such as materials, chemicals, fuels and other energy sources. The initiative of value-added by-products from waste is an approach that facilitates sustainable development.

Waste valorization is a new promising technique in which wastes so produced are treated or used as raw material for the production of a wide range of value-added products at very low capital investment. This emerging approach can not only reduce the environmental load of the waste but also the related negative impacts on the living system and environment. This waste utilization approach could also create new job opportunities and will also be helpful in the conservation of natural resources. The waste so produced from the industrial sector is further utilized for the production of renewable carbon in huge quantities and for the production of sustainable chemical (Koutinas et al. 2014). On the other hand, waste so produced from the agro-industrial could be used as a principal C5 and C6 sugar-based carbon source that can be either used alone or supplemented with various expensive nutrients like yeast extract for the production value-added products such as biodiesel, bioplastic and exopolysaccharides (EPS) at laboratory scale and pilot scale. Several value-added products that have been produced from wastes include biofuels like bioethanol and biohydrogen, short-chain organic acids, building-blocks, including 2, 3-butanediol, 1, 3-propanediol and succinic acid, polymers like bioplastics, i.e. polyhydroxyalkanoates (PHAs) (Koutinas et al. 2014). The major waste generated in pulp and paper industry is cellulose-based fibres which could be further processed for the production of useful products like textile and paper. Another waste generated in pulp and paper industry is spent sulphite liquor (SSL) which is utilized for the production of phenolic compounds mainly aromatics syringic, gallic and vanillic acids (Palmqvist and Hahn-Hägerdal 2000). For the production of several value-added products such as single-cell protein, bioethanol, bioplastics and bacterial cellulose, SSL is utilized as a raw material (Alexandri et al. 2016). Food waste is utilized for the production of another value-added product called hydroxymethylfurfural (HMF). It is utilized as the precursor of medicines, polymers, resins, solvents and biofuels (Mukherjee et al. 2015). Similarly, lignocellulosic waste biomass has been used for the production of phytosterols, polypropylene, acrylic acid and esters (Bardhan et al. 2015). 3.7×10^9 t of agricultural waste is produced worldwide annually. Agricultural waste mainly consists of 40% cellulose, 30% hemicellulose, 20% lignin, 5% proteins and 5% minerals (Pleissner and Venus 2014). This agricultural waste is utilized as a C5 and C6 carbon source after pretreatment for the production of several value-added products.

Another agriculture-based industry in India that generates a number of wastes in a very huge amount like bagasse and bagasse fly ash, sugarcane trash and press mud is the sugar industry. These wastes are used for the production of a number of value-added products like fuels and activated carbon. Either directly or biocomposting with distillery effluent, press mud is used as a fertilizer. Bagasse fly is utilized as an additive in cement and concrete (Balakrishnan and Batra 2011).

There are certain constrains of waste valorization that must be overcome which includes high water contents of wastes so produced, lack of highly efficient conversion techniques for processing of waste, infrastructure and expertise.

11.9 Advantages and Disadvantages of Bioremediation

Disadvantage	Advantage
(1) Not all the toxic hazardous waste is susceptible to rapid and complete microbial degradation	(1) Since bioremediation is a natural process and therefore has wide public acceptance for the treatment of toxic hazardous wastes
(2) Sometimes on microbial degradation, more toxic and persistent intermediate metabolite are formed than the parent compound	(2) It is a relatively economical, low-technology and less energy required technique for clean-up of hazardous waste
(3) Microbial degradation of toxic hazardous waste requires highly specific conditions such as microbial populations, suitable environmental growth conditions and appropriate levels of nutrients and contaminants	(3) On microbial degradation of hazardous wastes, the final residues are harmless products such as carbon dioxide, water and cell biomass
(4) It is very tough to extrapolate the microbial degradation from laboratory scale to pilot scale.	(4) Microbial degradation is useful for the complete destruction of a wide variety of toxic hazardous contaminants
(5) Since bioremediation is a very slow process, it requires months to year to clean-up the environment	(5) Microbes are able to degrade the contaminant, increase in numbers when the contaminant is present; when the contaminant is degraded, the biodegradative population declines
(6) Since microbial degradation of waste is a slow process, thus it needs longer time than the other physiochemical technologies for the complete degradation of toxic hazardous waste	(6) Many compounds that are legally considered to be hazardous can be transformed to harmless products. This eliminates the chance of future liability associated with treatment and disposal of contaminated material

(continued)

(continued)

Disadvantage	Advantage
(7) Regulatory uncertainty remains regarding acceptable performance criteria for bioremediation. There is no accepted definition of “clean”, evaluating performance of bioremediation is difficult, and there are no acceptable endpoints for bioremediation treatments.	(7) Since microbial degradation is an environmentally friendly approach, thus it causes very less disruption of natural environment or minimal environmental impact
(8) Modern technologies like genetic engineering are required to develop highly efficient microbes for the degradation of toxic hazardous waste. A stronger scientific base is required for rational designing of process and success	(8) Bioremediation techniques are potentially ideal for the detoxification of hazardous waste present in the environment
(9) For the successful in situ degradation of toxic hazardous waste, the contaminated site must contain soil with high permeability	

11.10 Hazardous Waste Management

Since the hazardous waste is highly toxic in nature even at very low concentration, thus, the governments of different countries across the world have rules and regulations for the proper management of hazardous waste. It includes policy regarding collection, treatment and disposal of waste material that, when improperly handled, can cause substantial harm to human health and safety or to the environment. Waste management is required for both resource and environment protection and also to cut down the waste production. Some important points for hazardous waste management include:

(a) Identification of various groups of hazardous materials commonly used in industries, laboratory, agriculture, hospital and home.
(b) Proper characterization of wastes so that those wastes having similar composition are processed together.
(c) Guidelines must be provided for the proper storage, processing, transport and regulations of hazardous waste.
(d) Generate a policy regarding negative effects of disposable of hazardous waste.
(e) The movement of hazardous waste from one country to another should be under proper jurisdiction.
(f) There must be proper disposable site far from the city for the dumping of wastes.

(g) Industries must adopt proper approach regarding recycling and reuse of waste produced.
(h) Modernization of equipments in the industries so that the waste production is either stopped or minimized.
(i) Adopting new trends like waste valorization so that the waste so produced is further utilized for the production of useful materials and energy.

11.11 Conclusion

The aim of the present chapter is to raise awareness regarding the hazardous wastes produced from different sectors and how they can be managed using microbial remediation. Bioremediation of waste using microbial consortia has been found as a better option for the fast and efficient approach of waste removal over pure microbial culture. Focus has also been given on production of a number of value-added products from wastes for a bio-based economy in an environmentally friendly manner.

Acknowledgements We would like to express our sincere thanks to Department of Science and Technology, Govt. of India, for providing INSPIRE Faculty fellowship to Ghosh, P [DST/INSPIRE/04/2016/000362].

References

Abo-Amer AE (2011) Biodegradation of diazinon by *Serratia marcescens* DI101 and its use in bioremediation of contaminated environment. J Microbiol Biotechnol 21:71–80

Agarwal SK (1998) Environmental biotechnology, 1st edn. APH Publishing Corporation, New Delhi, India, pp 267–289

Agnello AC, Bagard M, van Hullebusch ED, Esposito G, Huguenot D (2016) Comparative bioremediation of heavy metals and petroleum hydrocarbons co-contaminated soil by natural attenuation, phytoremediation, bioaugmentation and bioaugmentation-assisted phytoremediation. Sci Total Environ 563–564:693–703

Alexandri M, Papapostolou H, Vlysidis A, Gardeli C, Komaitis M, Papanikolaou S, Koutinas AA (2016) Extraction of phenolic compounds and succinic acid production from spent sulphite liquor. J Chem Technol Biotechnol. https://doi.org/10.1002/jctb.4880

Ali U, Syed JH, Malik RN, Katsoyiannis A, Li J, Zhang G, Jones KC (2014) Organochlorine pesticides (OCPs) in South Asian region: a review. Sci Total Environ 476:705–717

Arshad M, Hussain S, Saleem M (2008) Optimization of environmental parameters for biodegradation of alpha and beta endosulfan in soil slurry by *Pseudomonas aeruginosa*. J Appl Microbiol 104:364–370

Atlas RM, Bartha R (1998) Fundamentals and applications. In: Microbial ecology, 4th edn. Benjamin/Cummings, San Francisco, Calif, USA, pp 523–530

Aung WL, Aye KN, Hlaing NN (2012) Biosorption of lead (Pb^{2+}) by using *Chlorella vulgaris*. In: International conference on chemical engineering and its applications, Bangkok, Thailand

Balakrishnan M, Batra VS (2011) Valorization of solid waste in sugar factories with possible applications in India: a review. J Environ Manag 92:2886–2891

Bardhan SK, Gupta S, Gorman ME, Haider MA (2015) Biorenewable chemicals: feedstocks, technologies and the conflict with food production. Renew Sust Energy Rev 51:506–520

Bonomo RP, Cennamo G, Purrello R, Santoro AM, Zappala R (2001) Comparison of three fungal laccases from *Rigidoporus lignosus* and *Pleurotus ostreatus*: correlation between conformation changes and catalytic activity. J Inorg Biochem 83:67–75

Boopathy R (2000) Factors limiting bioremediation technologies. Bioresour Technol 74:63–67

Brady NC, Weil RR (2000) Elements of the nature and properties of soils. Prentice Hall, Upper Saddle River, NJ, USA, pp 463–471

Buffle J, De Vitre RR (1993) Chemical and biological regulation of aquatic systems. Lewis Publishers, p 40

Chang BV, Chang W, Yuan SY (2003) Anaerobic degradation of polycyclic aromatic hydrocarbons in sludge. Adv Environ Res 7:623–628

Chen B, Yuan M, Qian L (2012) Enhanced bioremediation of PAH-contaminated soil by immobilized bacteria with plant residue and biochar as carriers. J Soils Sediments 12:1350–1359

Chen SH, Aitken MD (1999) Salicylate stimulates the degradation of high molecular weight polycyclic aromatic hydrocarbons by *Pseudomonas saccharophila* P15. Environ Sci Technol 33:435–439

Crini G (2006) Non-conventional low-cost adsorbents for dye removal: a review. Bioresour Technol 97:1061–1085

Deng L, Zhu X, Su Y (2008) Biosorption and desorption of Cd^{2+} from wastewater by dehydrated shreds of *Cladophora fascicularis*. Chin J Ocean Limnol 26:45–49

Dosnon-Olette R, Trotel-Aziz P, Couderchet M, Eullaffroy P (2010) Fungicides and herbicide removal in *Scenedesmus* cell suspensions. Chemosphere 79:117–123

Dyer M, Heiningen EV, Gerritse J (2003) A field trial for in-situ bioremediation of 1, 2-DCA. Eng Geol 70:315–320

Dwivedi S (2012) Bioremediation of heavy metal by algae: current and future perspective. J Adv Lab Res Bio 3:195–199

Edris G, Alhamed Y, Alzahrani A (2012) Cadmium and lead biosorption by *Chlorella vulgaris*. In: IWTA, 16th international water technology conference, Istanbul, Turkey

Elizabeth H, Harris (2008) Introduction to *Chlamydomonas* and its laboratory use. In: The chlamydomonas sourcebook, vol 1, 2nd edn. Academic Press. ISBN-10: 0123708745

Fang H, Dong B, Yan H, Tang F, Yu Y (2010) Characterization of a bacterial strain capable of degrading DDT congeners and its use in bioremediation of contaminated soil. J Hazard Mater 184:281–289

Fuentes MS, Sáez JM, Benimeli CS, Amoroso MJ (2011) Lindane biodegradation by defined consortia of indigenous *Streptomyces* strains. Water Air Soil Pollut 222:217–231

Ghosh P, Das MT, Thakur IS (2014) Mammalian cell line-based bioassays for toxicological evaluation of landfill leachate treated by Pseudomonas sp. ISTDF1. Environ Sci Pollut Res 21:8084–8094

Haghollahi A, Fazaelipoor MH, Schaffie M (2016) The effect of soil type on the bioremediation of petroleum contaminated soils. J Environ Manage 180:197–201

Harms H, Schlosser D, Wick LY (2011) Untapped potential: exploiting fungi in bioremediation of hazardous chemicals. Nat Rev Microbiol 9:177–192

Hess A, Zarda B, Hahn D (1997) In situ analysis of denitrifying toluene and m-xylene degrading bacteria in a diesel fuel contaminated laboratory aquifer column. Appl Environ Microbiol 63:2136–2141

Hirooka T, Nagase H, Uchida K, Hiroshige Y, Ehara Y, Nishikawa J, Nishihara T, Miyamoto K, Hirata Z (2005) Biodegradation of bisphenol A and disappearance of its estrogenic activity by the green alga *Chlorella fuscavar* vacuolata. Environ Toxicol Chem 24:1896–1901

Karigar CS, Rao SS (2011) Role of microbial enzymes in the bioremediation of pollutants: a review. Enzyme Res. https://doi.org/10.4061/2011/805187

Koutinas AA, Vlysidis A, Pleissner D, Kopsahelis N, Garcia IL, Kookos IK, Lin CSK (2014) Valorization of industrial waste and by-product streams via fermentation for the production of chemicals and biopolymers. Chem Soc Rev 43:2587–2627

Kumar JI, Oommen C (2012) Removal of heavy metals by biosorption using freshwater alga *Spirogyra hyalina*. J Env Bio 33:27–31

Kumari M, Ghosh P, Thakur IS (2014) Microcosmic study of endosulfan degradation by *Paenibacillus* sp. ISTP10 and its toxicological evaluation using mammalian cell line. Int Biodeter Biodegr 96:33–40

Kumari M, Ghosh P, Thakur IS (2016) Landfill leachate treatment using bacto-algal co-culture: an integrated approach using chemical analyses and toxicological assessment. Ecotoxicol Environ Saf 128:44–51

Lei A, Wong Y, Tam N (2002) Removal of pyrene by different microalgal species. Water Sci Technol 46:195–201

Megharaj M, Kantachote D, Singleton I, Naidu R (2000) Effects of long-term contamination of DDT on soil microflora with special reference to soil algae and algal metabolism of DDT. Environ Pollut 109:35–42

Megharaj M, Madhavi DR, Sreenivasulu C, Venkateswarlu UA (1994) Biodegradation of methyl-parathion by micro-algae and cyanobacteria. Bull Environ Contam Toxicol 53:292–297

Mei LI, Xitao X, Renhao XUE, Zhili LIU (2006) Effects of strontium-induced stress on marine algae *Platymonas subcordiformis* (Chlorophyta: *Volvocales*). Chinese J Oceanol Limnol 24:154–160

Mukherjee A, Dumont MJ, Raghavan V (2015) Sustainable production of hydroxymethylfurfural and levulinic acid: challenges and opportunities. Biomass Bioenergy 72:143–183

Mukherjee I, Mittal A (2005) Bioremediation of endosulfan using *Aspergillus terreus* and *Cladosporium oxysporum*. Bull Environ Contam Toxicol 75:1034–1040

Orloff K, Falk H (2003) An international perspective on hazardous waste practices. Int J Hyg Environ Health 206:291–302

Ortiz-Hernández ML, Sánchez-Salinas E (2010) Biodegradation of the organophosphate pesticide tetrachlorvinphos by bacteria isolated from agricultural soils in México. Rev Int Contam Ambient 26:27–38

Palmqvist E, Hahn-Hägerdal B (2000) Fermentation of lignocellulosic hydrolysates. I: inhibition and detoxification. Bioresource Technol 74:17–24

Pereira ARB, Soares CRFS, da Silva JF, da Silva M, Chalfoun SM (2014) Removal of trace element by isolates of *Aspergillus brasiliensis* EPAMIG 0084 and *Penicillium cirtinum* EPAMIG 0086 in biofilters. African J Biotech 13:3759–3773

Pleissner D, Venus J (2014) Agricultural residues as feedstocks for lactic acid fermentation. In: Obare SO, Luque R (eds) Green technologies for the environment, American Chemical Society, pp 247–263

Reddy C, Mathew Z (2002) Bioremediation potential of white rot fungi. In: Gadd G (eds) Cambridge University Press, Cambridge, UK

Sayara T, Sarra M, Sanchez A (2010) Effects of compost stability and contaminant concentration on the bioremediation of PAHs-contaminated soil through composting. J Hazard Mater 179:999–1006

Sethunathan N, Megharaj M, Chen ZL, Williams BD, Lewis G, Naidu R (2004) Algal degradation of a known endocrine disrupting insecticide, α-endosulfan, and its metabolite, endosulfan sulfate, in liquid medium and soil. J Agric Food Chem 52:3030–3035

Sharma JK, Gautam RK, Nanekar SV, Weber R, Singh BK, Singh SK, Juwarkar AA (2017) Advances and perspective in bioremediation of polychlorinated biphenyl-contaminated soils. Environm Sci Pollut Res 1–21. https://doi.org/10.1007/s11356-017-8995-4

Shetty PK, Mitra J, Murthy NBK, Namitha KK, Savitha KN, Raghu K (2000) Biodegradation of cyclodiene insecticide endosulfan by *Mucor thermohyalospora* MTCC 1384. Curr Sci 79:1381–1383

Siddique T, Benedict CO, Muhammad A, William TF (2003) Biodegradation kinetics of endosulfan by *Fusarium ventricosum* and a *Pandoraea* sp. J Agric Food Chem 51:8015–8019

Singh BK, Walker A, Morgan JAW, Wright DJ (2003) Effects of soil pH on the biodegradation of chlorpyrifos and isolation of a chlorpyrifos-degrading bacterium. Appl Environ Microbiol 69:5198–5206

Singh BK, Walker A, Morgan JAW, Wright DJ (2004) Biodegradation of chlorpyrifos by *Enterobacter* strain B-14 and its use in bioremediation of contaminated soils. Appl Environ Microbiol 70:4855–4863

Singh H (2006) Mycoremediation: fungal bioremediation. Wiley-Interscience, New York, NY, USA

Singh R, Singh P, Sharma R (2014) Microorganism as a tool of bioremediation technology for cleaning environment: a review. Proc Int Acad Ecol Environ Sci 4:1–6

Strong PJ, Burgess JE (2008) Fungal and enzymatic remediation of a wine lees and five wine-related distillery wastewaters. Bioresour Technol 99:6134–6142

Sun L, Wu Sh (2007) Analysis and thought about nationwide general investigation on hazardous waste disposal facilities. Nonferrous Met Eng Res 28:7–17

Sutherland JB, Rafii F, Khan AA, Cerniglia CE (1995) Mechanisms of polycyclic aromatic hydrocarbon degradation: microbial Transformation and degradation of toxic organic chemicals. Wiley-Liss, New York

Tang CY, Criddle QS, Fu CS, Leckie JO (2007) Effect of flux and technique. Biol Med 1:1–6

Thibault GT, Elliott NW (1979) Accelerating the biological cleanup of hazardous materials spills. In: Proceedings oil and hazards materials. Spills: prevention-control cleanup-recovery-disposal

Timmis KN, Pieper DH (1999) Bacteria designed for bioremediation. Trends Biotechnol 17:201–204

Walker JD, Colwell RR, Vaituzis Z, Meyer SA (1975) Petroleum degrading achlorophyllous alga *Prototheca zopfii*. Nature 254:423–424

Widdowson MA (2004) Modeling natural attenuation of chlorinated ethenes under spatially varying redox conditions. Biodegradation 15:435–451

Yan X, Yang Y, Li Y, Sheng G, Yan G (2002) Accumulation and biodegradation of anthracene by *Chlorella protothecoides* under different trophic conditions. Chin J Appl Ecol 13:145–150

Yang XQ, Zhao XX, Liu CY, Zheng Y, Qian SJ (2009) Decolorization of azo, triphenylmethane and anthraquinone dyes by a newly isolated *Trametes* sp. SQ01 and its laccase. Process Biochem 44:1185–1189

Zhang H, Hu C, Jia X, Xu Y, Wu C, Chen L, Wang F (2012) Characteristics of c-hexachlorocyclohexane biodegradation by a nitrogen-fixing cyanobacterium *Anabaena azotica*. J Appl Phycol 24:221–225

Zhou M, Liu Y, Zeng G, Li X, Xu W, Fan T (2007) Kinetic and equilibrium studies of Cr (VI) biosorption by dead *Bacillus licheniformis* biomass. World J Microbiol Biotech 23:43–48

Ziagova M, Dimitriadis G, Aslanidou D, Papaioannou X, Tzannetaki EL, Liakopoulou-Kyriakides M (2007) Comparative study of Cd(II) and Cr(VI) biosorption on *Staphylococcus xylosus* and *Pseudomonas* sp. in single and binary mixtures. Bioresour Tech 98:2859–2865