

Chapter 21

Environmental Biodegradation of Xenobiotics: Role of Potential Microflora

Manoj Kumar, Ram Prasad, Pankaj Goyal, Priyanku Teotia,
Narendra Tuteja, Ajit Varma, and Vivek Kumar

21.1 Introduction

The term xenobiotic (Greek *xenos* + *bioticos*, which means “strange” and “life-related,” respectively) means a chemical substance that is not a natural component of a living organism exposed to it, i.e., a strange, exogenous substance or anthropogenic material. This definition also covers the substances strange to the target organisms; hence it is used for most poisons and drugs. An important group of xenobiotics are chemical compounds produced by humans, with artificial chemical structure, to which organisms have not adjusted through prior evolution. Both natural and anthropogenic activities result in accumulation of wide ranges of toxic xenobiotic compounds in the environment and thus cause a global concern (Gren 2012). Primarily, xenobiotics are those compounds that are alien to a living individual and have a propensity to accumulate in the environment. Principal xenobiotics include pesticides, fuels, solvents, alkanes, polycyclic hydrocarbons (PAHs), antibiotics, synthetic azo dyes, pollutants (dioxins and polychlorinated biphenyls), and polyaromatic, chlorinated, and nitroaromatic compounds (Guermouche M'rassi et al. 2015). The main concern with xenobiotic compounds is the toxicity threat they pose to public health. It is quite shocking that some xenobiotic compounds (phenols, biphenyl compounds, phthalates, etc.) act as endocrine disruptors (Itoh et al. 2000).

In early times, we had an unlimited abundance of land and resources; today, due to our carelessness and negligence in using them, however, the resources in the world show, in lesser degree (Vidali 2001). The quick growth of various industries

M. Kumar • R. Prasad • P. Goyal • N. Tuteja • A. Varma • V. Kumar (✉)
Amity Institute of Microbial Technology, Amity University, Noida, Uttar Pradesh, India
e-mail: vivekbps@gmail.com

P. Teotia
Department of Botany, CCS University, Meerut, India

in the past century has extremely increased the release of toxic waste effluents into water bodies along with groundwater (Sethy et al. 2011). Environmental pollution caused by the release of these wide range of compounds (i.e., persistent organic pollutants (POPs)) from industries is creating a disturbance to the ecosystem (Gursahani and Gupta 2011), causing climatic changes, reduction of water levels in the ground as well as oceans, melting of icecaps, global warming, ozone layer depletion due to photochemical oxidation, etc. (Sharma et al. 2011), and this made ecologists to focus more on impacts of pollution and its reduction.

Biodegradation is a microorganism-mediated transformation of contaminants into nonhazardous or less hazardous substances (Lin et al. 2010, 2014a). Microorganisms are nature's recyclers, converting toxic organic compounds to innocuous compounds, often carbon dioxide and water (Leys et al. 2005). The appropriate use of various organisms like bacteria, fungi, and algae for efficient bioremediation of pollutants has been reported by Vidali (2001). As per the opinion of Hamzah et al. (2010), most of the organisms, predominantly bacteria, are known for their detoxifying abilities. They mineralize, transform, or immobilize the pollutants. Bacteria play a crucial role in biogeochemical cycles for sustainable development of the biosphere.

The enormous genetic diversity of microorganisms, their metabolic plasticity and high reproduction rates, and the capacity for horizontal gene transfer ensure the development and adaptation of microorganisms to rapidly changing conditions of the environment (Kumar et al. 2016). Bioremediation can be effective only when environmental conditions permit microbial growth and activity. Bioremediation involves the manipulation of environmental parameters (pH, temperature, moisture, and oxygen) to allow microbial growth and degradation procedure at a faster rate (Selvam and Vishnupriya 2013). The development of recombinant genetically modified organisms (GMOs) is very significant for the bioremediation of complex waste; through this we can identify the gene responsible for specific compound degradation (Karpouzias and Singh 2006).

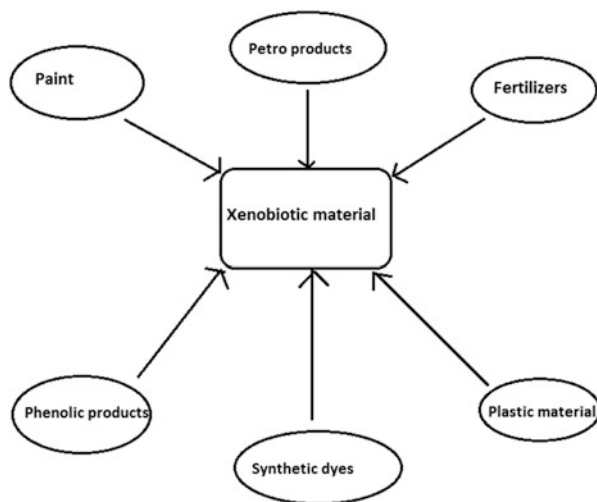
21.2 Xenobiotics Sources

Basically there are two types of sources for occurrence of xenobiotics in environment, direct and indirect.

21.2.1 *Straight Sources*

The prime direct source of xenobiotics is wastewater and solid residual releases from the industries like chemical and pharma, plastics, paper and pulp mills, textile mills, and agricultural (enhancement products like pesticides, herbicides, etc.). Some of the common residual compounds in the wastewater and other effluents

Fig. 21.1 Various sources of xenobiotic compounds in nature



are phenol, hydrocarbons, different dyes, paint effluents, pesticides and insecticides, etc. (Fig. 21.1).

A. Plastic Material “Plastic materials are huge molecules which are held together by strong forces which can be broken only by breaking the energy forces such as light” (Kathiresan 2003). Plastic material is tough, is sturdy, and degrades sluggishly owing to the molecular bonds and interactions. Plastics are made of polystyrene and polyvinyl chloride and polyethylene and its derivatives. Nowadays plastics (from crude oil) are used as fuels in industries since they break down into liquid hydrocarbons (Raaman et al. 2012). Microbial degradation of plastics gained importance in the last few years, but the fragmented compounds released by these also lead to further environmental issues.

B. Paint Material Paints: Volatile organic compounds and additives like emulsifiers and texturizers in paint are considered harmful which can be degraded by different means like chemicals (water as solvent), hygroscopic stresses, and microbial sources (Dixit et al. 2015).

C. Phenolic Components Phenol is one among the most prevalent chemical and pharma pollutants due to its toxicity even at lower concentrations and formation of substituted compounds during oxidation and disinfection processes. Its direct effects on the environment include depletion of ozone layer, effect on the earth’s heat balance, reduced visibility, and adding acidic air pollutants to the atmosphere (Yeom et al. 2010). Phenol removal from the industrial wastewaters is very much necessary, prior to the wastewater discharge, so as to decrease all these effects. Phenol being a carcinogenic compound requires biodegradation method which results in minimum secondary metabolites and harmless end products (Prpich et al. 2006).

D. Petro-products Petroleum effluents mainly contain polycyclic (polynuclear) aromatic hydrocarbons, saturated hydrocarbons, and many nitrogen-, sulfur-, and oxygen-containing organic compounds (Gojgic-Cvijovic et al. 2012). Remediation of such petro-compounds using physicochemical treatments is not cost effective and may lead to further instabilities in environment, thus giving importance to biotreatments, which had an impact on reduction of these recalcitrants. Microorganisms that biodegrade these components are isolated from various environments, particularly from petroleum-contaminated sites (Prakash et al. 2014). Saturated hydrocarbons having the straight chain (*n*-alkanes) are most susceptible to microbial attack than branched alkanes. The aromatic fraction is more difficult to degrade, and susceptibility of biodegradation decreases as the aromaticity increases in the compound (Milić et al. 2009).

E. Dyes and Pigments Dye agglomeration is the major cause for the persistence of xenobiotics, and their presence in aquatic bodies will affect photosynthetic activity in aquatic life due to reduced light penetration even at low concentrations (Kumari et al. 2014). A number of industrial processes, such as textile industries, paper printing, and photography, use synthetic dyes extensively, which usually have complex aromatic molecular structures. Azo (Black B, Turq Blue GN, Yellow HEM, Red HEFB, and Navy HER), anthraquinone, and phthalocyanine dyes are commonly used dyes in these industries (Vigneewaran et al. 2012; Shahid et al. 2013). The degradation of these dyes produces aromatic amines, which may be carcinogenic and mutagenic. Microorganism (living or dead biomass) has the ability not only to decolorize dyes but also detoxify them (Hemapriya and Vijayanand 2014) by adsorption of dyes on microbial surfaces because of the presence of negatively charged ligands in cell wall components.

21.2.2 *Subsidiary Sources*

Subsidiary or indirect sources of xenobiotics include nonsteroidal anti-inflammatory drugs, pharmaceutical products, chemical fertilizers, pesticide residues, etc. Pharmaceutically active compounds, being an indirect source of xenobiotics, are discharged directly by manufacturers of the pharmaceuticals or effluents from hospitals which have performed their biologically intended effect and are passed onto the environment in either their complete or fragmented state. These mainly include hormones, anesthetics, and antibiotics which bioaccumulate in an organism and passed on the other through the common food chain (Iovdijová and Bencko 2010). Biomaterials developed from the synthetic polymers have the biocompatibility, but their degradation into toxic substances in the body is a cause for concern (Baun et al. 2008). Even though they are the indirect sources, they cause adverse effect on the ecological cycle.

Pollution of aquatic bodies and soil is a worldwide problem that can result in uptake and accumulation of toxic chemicals in food chains and also harm to the

flora and fauna of affected habitats. Studies of bioaccumulation characteristics of various ecosystems are essential for long-term planning of industrial waste disposal in ecosystem (Iyovo et al. 2010). Bioaccumulation of pesticides and biomagnification processes lead to toxic behavioral effect on animals and mankind. DDT, having a half-life of 10 years, and BHC are chemicals used in pesticides that accumulate in the plant or in plant parts like fruits and vegetables, though both the pesticides are banned now globally.

Nonsteroidal anti-inflammatory drugs (NSAIDs) are the large miscellaneous chemicals used as drugs in human beings and animals for curing the inflammation, body pain, and fever (analgesic aspects). Diclofenac salt uses in animals has been informed to have led to a sharp fall in the vulture population in Pakistan, 95 % decline in 2003 and 99.9 % decline as of 2008 (Oaks et al. 2004).

21.3 Microbial Role in Bioremediation

Microbes epitomize half of biomass of our globe, and the human activity disturbs the environment and initiated the xenobiotic chemicals on the earth. The microbes exhibit capability to biodegrade xenobiotic compounds using their endo- and exo-enzymes and by using their metabolic pathways for exploiting them as novel carbon sources and to cleanse toxic compounds (Singh et al. 2014). Microbes show eco-friendly behavior to overcome environmental pollution and to help in biodegradation of xenobiotic compounds. Microorganisms apply two modes of action for degradation of xenobiotics compound: (a) aerobic biodegradation and (b) anaerobic biodegradation. Aerobic biodegradation processes require excess oxygen delivery systems, because it is necessary to supply continuous oxygen due to biofouling in subsurface remedial applications (Sharma and Fulekar 2009); when bioreactors are applied, its energy costs and sludge production are high (Kumar et al. 1994a, b). Anaerobic habitats, including sludge digesters, groundwater, sediments, water-laden soils, gastrointestinal contents, feedlot wastes, and landfill sites (Kumar and Singh 1998), and some xenobiotic compounds (e.g., tetrachloroethylene, polychlorinated biphenyls (PCBs), and nitro-substituted aromatics) can be effectively transformed or mineralized by anaerobic bacteria (Zhang and Bennett 2005).

In situ bioremediation procedure consists of basically three vital steps:

1. Bioattenuation: It is related to monitoring of natural progress of biodegradation to guarantee that contaminant declines with sampling time.
2. Biostimulation: The intentional stimulation of natural xenobiotic remediating microbes by electron acceptors, water molecule, nutrient addition, and/or electron donors.
3. Bioaugmentation: It is the addition of laboratory-grown potential bacteria that have suitable and biodegradative abilities.

Normally, the microbes use two pathways for biodegradation of xenobiotics, aerobic and anaerobic conditions.

In aerobic bioremediation, the basic equation will be



In the case of anaerobic bioremediation, it is



In aerobic biodegradation, CO_2 is produced along with some amount of water. In absence of oxygen, anaerobic biodegradation process starts and methane gas is generated instead of CO_2 . The conversion of biodegradable materials to gases like carbon dioxide, methane, and nitrogen compounds is called mineralization. The mineralization process is completed when all the biodegradable biomass is consumed and all the carbon is converted into carbon dioxide (Kyrikou and Briassoulis 2007). Alkanes consisting long carbon chains and straight structures considered to be more prone to aerobic biodegradation. Aerobic degradation pathway of alkane degradation is the oxidation of the terminal methyl group into a carboxylic acid through an alcohol intermediate and after all completes mineralization through β -oxidation (Le and Coleman 2011). Aerobic biodegradation process of aromatic compounds comprises of their oxidation by molecular oxygen; after oxidation steps, intermediates are the outcome, and then they enter into central metabolic pathways, including the Krebs cycle and β -oxidation.

Some xenobiotic pollutants are not mineralized by an aerobic degradation system because they are greatly recalcitrant owing to increase in halogenations in their structures. Replacement of halogen, nitro-, and sulfo-groups on the aromatic ring increases the electrophilicity of the target molecule. These xenobiotic compounds resist the electrophilic attack by enzyme oxygenases in aerobic degradation process. Some of the recalcitrants that persist under aerobic condition are the polychlorinated biphenyls (PCBs), chlorinated dioxins, and some complex and banned pesticides like DDT (Lin et al. 2014). It is essential to overawe the high stubbornness of halogenated xenobiotic compounds from biosphere; in achieving these, the reductive attacks by anaerobic microorganisms are of boundless worth. On the other hand, anaerobic bacteria carried out reductive dehalogenation either by the complimentary reaction or by using a new type of anaerobic respiration. This procedure decreases the degree of chlorination and makes the product more available and manageable for mineralization process by aerobic bacteria (Ferguson and Pietari 2000). During anaerobic degradation process, the reductive dehalogenation is the first step of biodegradation of PCBs (polychlorinated biphenyls); dehalogenation process is carried out under anaerobic conditions where organic substrates act as electron donors.

There are vast numbers of potential microbes, especially the bacteria, which carry out the bioremediation of xenobiotics. The common major groups of anaerobic bacteria that have capability of biodegrading xenobiotic compounds are *Acidovorax* spp., *Bordetella* spp., *Pseudomonas* spp., *Sphingomonas* spp., *Variovorax*

spp., *Veillonella alkalescens*, *Desulfovibrio* spp., *Desulfuromonas michiganensis*, *Desulfitobacterium dehalogenans*, *D. oleovorans*, *G. metallireducens*, and *D. aceticum*. Anaerobic sulfate-reducing bacteria and methanogenic bacterial conditions can be useful to isolate pure culture of anaerobic bacteria to carry out xenobiotic degradation research work (Jiang and Fan 2008; Zhang and Bennet 2005). Anaerobic microbes can also use and exploit substituted and intricate aromatic compounds in a way that do not disturb the benzene nucleus in the ring. On the other hand, sulfate-reducing bacteria (SRB) represent a huge group of anaerobic microorganisms that play a crucial role in numerous biogeochemical cyclic processes and also able to biodegrade the crude oil (Ferradji et al. 2014; Liu et al. 2014a). The sulfate-reducing bacteria are obligated anaerobic bacteria, which utilize sulfate as final electron acceptor during the process of anaerobic respiration and, therefore, generate hydrogen sulfide (H₂S gas) by sulfate reduction. Anaerobic degradation process is also a renewable energy source; here the biogas is generated from the anaerobic digestion. It mainly consists of methane (CH₄) that can be collected easily and applied for eco-friendly power generation or as a fuel, which has been proved on a greater scale (Boetius et al. 2000). Different xenobiotic compounds biodegraded by various microbes are mentioned in Table 21.1.

21.4 Role of Microbial Enzymes in Bioremediation

Bioremediation is a microbial secreted enzymatic process which transforms a xenobiotic pollutant to innocuous products, which blends naturally with the environment; therefore, the toxicity is removed or reduced to a greater extent.

21.4.1 Oxidoreductases

These enzymes slice the chemical bonds and reposition the electrons from a reduced organic compound (called as donor) to another chemical substrate (known as acceptor). During this oxidation reduction process, the chemical pollutants or contaminants are oxidized to inoffensive and harmless compounds (Karigar and Rao 2011). The oxidoreductases cleanse toxic xenobiotic products like phenolic or anilinic compounds, either by the process of polymerization, or copolymerization with other substrates, or binding with the humic substances. The microbial enzymes have also been used in decolorization and bioremediation of azo dyes (Husain 2006; Rani et al. 2014).

Table 21.1 Xenobiotics biodegraded by the microbes

S. no.	Microbe targeting the xenobiotic	Target xenobiotic	Place	References
1	Phenanthrene	<i>Pseudomonas</i> sp. Ph6	China	Sun et al. (2014)
	Phenanthrene	<i>Massilia</i> sp. strain Pn2	China	Liu et al. (2014b)
2	Anthracene	<i>Microbacterium</i> sp. strain SL10	Lagos, Nigeria	Salam et al. (2014)
3	Naphthalene	<i>Streptomyces</i> spp.	Algeria	Ferradji et al. (2014)
4	Pentachlorophenol	<i>Kocuria</i> sp. CL2	India	Karn et al. (2011)
5	Chloroaniline	<i>Acinetobacter baylyi</i> strain GFJ2	Thailand	Hongsawat and Vangnai (2011)
6	Fluoranthene	<i>Herbaspirillum chlorophenicum</i>	China	Xu et al. (2011)
8	1,2,4-Trichlorobenzene (1,2,4-TCB)	<i>Bordetella</i> sp.	Germany	Wang et al. (2007)
9	2-Chlorobenzoic acid	<i>Pseudomonas</i> sp., <i>Enterobacter</i> sp., <i>Acinetobacter</i> sp., and <i>Corynebacterium</i> sp.	Iran	Kafilzadeh et al. (2012)
10	Pyrene	<i>Klebsiella oxytoca</i> PYR-1	China	Zhang and Zhu (2012)
11	HCH/lindane (1,2,3,4,5,6-hexachlorocyclohexane)	<i>Sphingobium czechense</i> LL01	India	Niharika et al. (2013)
12	DDT (dichlorodiphenyltrichloroethane)	<i>Pseudoxanthobacter liyangensis</i> sp. nov.	China	Liu et al. (2014b)
13	DDT (dichlorodiphenyltrichloroethane)	<i>Serratia marcescens</i> DT-1P	India	Bidlan and Manonmani (2002)
14	DDT (dichlorodiphenyltrichloroethane)	<i>Novosphingobium arabidopsis</i> sp. nov.	Taiwan	Lin et al. (2014)
13	Phthalate	<i>Achromobacter denitrificans</i> strain SP1	India	Pradeep et al. (2015)
14	Phthalate	<i>Arthrobacter</i> sp.C21	China	Wen et al. (2014)
15	Phthalate	Wen et al. (2014)	China	Wu et al. (2010)
16	Endosulfan compounds	<i>Paenibacillus</i> sp. ISTP10	India	Kumari et al. (2014)
17	Endosulfan compounds	<i>Stenotrophomonas maltophilia</i> and <i>Rhodococcus erythropolis</i>	India	Kumar et al. (2007)
18	Endosulfan compounds	<i>Klebsiella pneumonia</i>	South Korea	Kwon et al. (2002)

(continued)

Table 21.1 (continued)

S. no.	Microbe targeting the xenobiotic	Target xenobiotic	Place	References
19	Vinyl chloride	<i>Micrococcus</i> species	India	Patil and Bagde (2012)
20	Vinyl chloride	<i>Sphingopyxis</i> sp. PVA3	Japan	Yamatsu et al. (2006)
20	Diuron DCMU (3-(3,4-dichlorophenyl)-1,1-dimethylurea)	<i>Arthrobacter</i> sp. BS2 and <i>Achromobacter</i> sp. SP1	France	Devers-Lamrani et al. (2014)
	Diuron DCMU (3-(3,4-dichlorophenyl)-1,1-dimethylurea)	<i>Pseudomonas</i> sp. and <i>Stenotrophomonas</i> sp.	France	Batissou et al. (2007)
	Atrazine (2-chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine)	<i>Raoultella planticola</i>	Israel	Swissa et al. (2014)
	Atrazine (2-chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine)	<i>Bacillus subtilis</i> strain HB-6	China	Wang et al. (2014)
	Atrazine (2-chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine)	<i>Arthrobacter</i> sp. HB-5	China	Wang et al. (2011)
	Propanil	<i>Xanthomonas</i> sp.	Mexico	Herrera-Gonzalez et al. (2013)
	Propanil	<i>Catellibacterium nanjingense</i> sp. nov.	China	Zhang et al. (2012)
	PCE (tetrachloroethylene or perchloroethylene)	<i>Dehalococcoides</i> spp.	Germany	Kranzioch et al. (2014)
PCE (tetrachloroethylene or perchloroethylene)	<i>Propionibacterium</i> sp. HK-1 and <i>Propionibacterium</i> sp. HK-3	South Korea and Japan	Chang et al. (2011)	

21.4.2 Monoxygenases

These enzymes transfer one atom of molecular oxygen to the organic compound (Karigar and Rao 2011). Monoxygenases can be categorized into two subclasses based on the presence of cofactors, flavin-dependent monoxygenases and P450 monoxygenases. Flavin-dependent monoxygenases contain flavin as prosthetic group and NADP or NADPH as coenzyme. P450 monoxygenases are heme-containing oxygenases that persist in both eukaryotes and prokaryotes. Monoxygenases act as biocatalysts in the bioremediation process and synthetic chemistry because they are highly regionselective and stereoselective on a wide range of substrates (Karigar and Rao 2011). Monoxygenases catalyze enormous reactions such as desulfurization, dehalogenation, denitrification, ammonification, hydroxylation, biotransformation, and biodegradation of various aromatic and aliphatic compounds.

21.4.3 Dehalogenases

Dehalogenase plays an important role in the degradation of chlorinated pollutant (Copley 1998). Some anaerobic microorganisms exploit dehalorespiration and use halogenated compounds as terminal electron acceptors (Le and Coleman 2011). An example of this process is the conversion of either perchloroethylene (PCE), dichloroethylene (DCE) (Schumacher and Holliger 1996), ethylene, or ethane depending on the conditions. Magnuson et al. (1998) reported the partial purification of two reductive dehalogenases from *Dehalococcoides ethenogenes* strain 195; both enzymes are membrane proteins. The first enzyme PCE reductive dehalogenase reduces PCE to TCE, and the second enzyme TCE-reductive dehalogenase reduces TCE, *trans*-DCE, *cis*-DCE, 1,1-dichloroethene, and vinyl chloride (Patil and Bagde 2012).

21.4.4 Phosphotriesterases

Phosphotriesterases (PTEs) are microbial isolated enzyme which hydrolyze and detoxify organophosphate pesticides (OPs). This reduces OP toxicity, and it decreases the ability of OPs to inactivate AchE (Shen et al. 2010; Theriot and Grunden 2010). These enzymes mainly hydrolyze phosphoester bonds like P–O, P–F, P–NC, and P–S, and these hydrolysis mechanisms include water molecule in the phosphorus center (Ortiz-Hernandez et al. 2003).

21.4.5 Dioxygenases

These are multicomponent enzyme systems that incorporate molecular oxygen to the substrate. On the basis of the complexity of the degradation pathways, the biodegradation phenomenon can be categorized into two types: (1) convergent mode and (2) divergent mode of degradation (Eltis and Bolin 1996). In the convergent mode, structurally varied aromatic compounds are converted to aromatic ring cleavage substrates catechol, gentisate, protocatechuate, and their derivatives (Meer et al. 1992). In divergent mode, metal-dependent dioxygenase channels operate, and dihydroxylated intermediates are formed by one of the two possible pathways: the meta-cleavage pathway or the ortho-cleavage pathway (Takami et al. 1997).

21.4.6 Oxygenases

These are classified under the oxidoreductase group of enzymes (E.C. Class 1) (Karigar and Rao 2011). Oxidation reaction is the major enzymatic reaction of aerobic biodegradation and is catalyzed by oxygenases. Oxygenases oxidize the substrates by transferring oxygen from molecular oxygen (O₂) and utilize FAD/NADH/NADPH as the co-substrate. Oxygenases metabolize organic compounds; they increase their reactivity and water solubility and cleave the aromatic ring (Arora et al. 2010). On the basis of the number of oxygen atoms used for oxidation, oxygenases can be further categorized into two groups, (1) monooxygenases and (2) dioxygenases, which have been discussed earlier.

21.5 Future Facets

During the past many years, there has been a boundless work of development in the field of the bioremediation of xenobiotic compounds. Numerous novel microbes bearing bioremediation prospective have been isolated from various ecological niches, and several new remediation pathways have been explicated. However, this information and data is far from complete knowledge. Biotransformation of organosulfide compounds is yet to be explored owing to its complex nature. Efficiency of xenobiotic compound biodegradation can be meaningfully enhanced by addressing vital issues such as tolerance to various xenobiotic compounds, the constitutive expression of catabolic genes and their raw substrate specificity, and the kinetics and stability of the enzyme which has been encoded. Though, the usefulness and efficacy of the constructed organisms in relation to the environmental pollution problem in the ecosystem is yet to be explored and tested.

Most of the microbes, which biodegrade xenobiotic compounds, bear plasmids which encode for the catabolic genes. To depict and describe the suitable genes and to augment the process of biodegradation through improved constructed potential strains, a proper, well-designed management is prerequisite. And due to the same reasons, the microbial degradation machinery is a spanning spectrum from the environmental monitoring point of view which ultimately leads to biodegradation as well. In bioremediation process, presently, molecular techniques and approaches are being applied to characterize the genetic material of numerous bacteria from the several ecological samples. Comparing with the standard and prevalent microbiological techniques and approaches, the molecular procedures provide us with more complete and inclusive interpretation of in situ microorganism population and its response to concocted bioremediation and normal lessening processes. Additional dominant molecular procedure known as metagenomic libraries has been thrived for identification of the desired catabolic genes. Fundamentally, metagenomic technique is a culture-dependent microbial genomic analysis; this technique is either a function-driven tactic or sequence-driven method, of entire microbial

communities, which provides the access to recover unknown sequences. The regular and constant contact with the contaminants and prolonged exposure to their presence is the basics of struggle against xenobiotic compounds, since such processes enable the evolution and progression of new, more or less safe processes of xenobiotic remediation by microorganisms.

21.6 Conclusions

Microbial diversity, the richness of species in environmental sites, provides a huge reservoir of resources which we can utilize for our benefit. However, little is known about the true diversity of bacterial life. Despite the acknowledged value of microorganisms, our understanding of their diversity and many of their key roles in sustaining global life support systems is still very scarce. This is because the vast majority of bacteria are non-culturable by standard methods and we have only recently acquired the skills to explore this aspect of microbial biodiversity. Exploring the range of microbial biodiversity is the key to developing effective and environment-friendly “green” technologies. Bioremediation is one such process that exploits the catabolic abilities of microorganisms to degrade harmful and toxic xenobiotics. We have been able to restore what once were irreversibly polluted sites in some cases, attesting to the usefulness of this clean-up process. However, to maximize the potential benefits of the microbial community in combating pollution problems, it is vital that we have fundamental understanding of a microbe’s degradative potential under various conditions, its biochemical systems, and its molecular biology.

Environmental problems caused by the industrial effluents is mainly due to accumulation of pollutants and other fragmented compounds, which in turn form into other substitutes (natural or manmade), finally forming a xenobiont. There is a quick need to degrade these xenobiotic compounds in an eco-friendly way. Various techniques like microbial remediation, phytoremediation, and photoremediation and their subtypes have been discussed. Each having their own ways of degrading, these xenobionts also have negative impact on the environment (side effects due to fragmentations and bioaccumulations). Photoremediation is a novel equipment-based technique which is rapid but also has a negative impact on the environment. Being a solar-driven technique, phytoremediation is restricted to particular sites containing contaminants. Although slow, on the whole, microbial bioremediation was found to cover a wide range of recalcitrant degradation and is known to be a better choice because of its nature of degradation.

References

- Arora PK, Srivastava A, Singh VP (2010) Application of monooxygenases in dehalogenation, desulphurization, denitrification and hydroxylation of aromatic compounds. *J Bioremed Biodegrad* 1:1–8
- Batisson I, Pesce S, Hoggan PB, Sancelme M, Bohatier J (2007) Isolation and characterization of diuron degrading bacteria from lotic surface water. *Microbial Ecol* 54(4):761–770
- Baun A, Sørensen SN, Rasmussen RF, Hartmann NB, Koch CB (2008) Toxicity and bioaccumulation of xenobiotic organic compounds in the presence of aqueous suspensions of aggregates of nano-C(60). *Aquat Toxicol* 86(3):379–387
- Bidlan R, Manonmani HK (2002) Aerobic degradation of dichlorodiphenyl trichloroethane (DDT) by *Serratia marcescens* DT-1P. *Process Biochem* 38:49–56
- Boetius A, Ravensschlag K, Schubert CJ, Rickert D, Widdel F, Gieseke A, Amann R, Jorgense BB, Witte U, Pfannkuche O (2000) A marine microbial consortium apparently mediating anaerobic oxidation of methane. *Nature* 407:623–626
- Chang YC, Ikeutsu K, Toyama T, Choi DB, Kikuchi S (2011) Isolation and characterization of tetrachloroethylene- and cis-1, 2-dichloroethylene-dechlorinating *Propionibacteria*. *J Ind Microbiol Biotechnol* 38:1667–1677
- Copley SD (1998) Microbial dehalogenases: enzymes recruited to convert xenobiotic substrates. *Curr Opin Chem Biol* 2:613–617
- Devers-Lamrani M, Pesce S, Rouard N, Martin-Laurent F (2014) Evidence for cooperative mineralization of diuron by *Arthrobacter* sp. BS2 and *Achromobacter* sp. SP1 isolated from a mixed culture enriched from diuron exposed environments. *Chemosphere* 117:208–215
- Dixit R, Wasiullah MD, Pandiyan K, Singh UB, Sahu A, Shukla R, Singh BP, Rai JP, Sharma PK, Lade H, Paul D (2015) Bioremediation of heavy metals from soil and aquatic environment: an overview of principles and criteria of fundamental processes. *Sustainability* 7:2189–2212
- Eltis LD, Bolin JT (1996) Evolutionary relationships among extradioldioxygenases. *J Bacteriol* 178:5930–5937
- Ferguson JF, Pietari JM (2000) Anaerobic transformations and bioremediation of chlorinated solvents. *Environ Pollut* 107(2):209–215
- Ferradji FZ, Mnif S, Badis A, Rebbani S, Fodil D, Eddouaouda K, Sayadi S (2014) Naphthalene and crude oil degradation by biosurfactant producing *Streptomyces* spp. isolated from Mitidja plain soil (North of Algeria). *Int Biodeterior Biodegrad* 86(C):300–308
- Gojic-Cvijovic GD, Milic JS, Solevic TM, Beskoski VP, Ilic MV, Djokic LS, Narancic TM, Vrvic MM (2012) Biodegradation of petroleum sludge and petroleum polluted soil by a bacterial consortium: a laboratory study. *Biodegradation* 23:1–14
- Gren I (2012) Microbial transformation of xenobiotics. *Chemik* 66(8):835–842
- Guermouche M'rassi A, Bensalah F, Gury J, Duran R (2015) Isolation and characterization of different bacterial strains for bioremediation of n-alkanes and polycyclic aromatic hydrocarbons. *Environ Sci Pollut Res Int* 22(20):15332–15346
- Gursahani YH, Gupta SG (2011) Decolourization of textile effluent by a thermophilic bacteria *Anoxybacillus rupiensis*. *J Pet Environ Biotechnol* 2:111–120
- Hamzah A, Rabu A, Farzarul R, Yusoff NA (2010) Isolation and characterization of bacteria degrading Sumandak and South Angsi oils. *Sains Malaysiana* 39(2):161–168
- Hemapriya J, Vijayanand S (2014) Ecofriendly bioremediation of a triphenylmethane dye by textile effluent adapted bacterial strain vp-64. *Int J Curr Microbiol Appl Sci* 3(9):983–992
- Herrera-Gonzalez VE, Ruiz-Ordaz N, Galindez-Mayer J, Juarez-Ramirez C, Santoyo-Tepole F, Montiel EM (2013) Biodegradation of the herbicide propanil, and its 3, 4-dichloroaniline by product in a continuously operated biofilm reactor. *World J Microbiol Biotechnol* 29:467–474
- Hongsawat P, Vangnai AS (2011) Biodegradation pathways of chloroanilines by *Acinetobacter baylyi* strain GFJ2. *J Hazard Mater* 186(2/3):1300–1307

- Husain Q (2006) Potential applications of the oxidoreductive enzymes in the decolorization and detoxification of textile and other synthetic dyes from polluted water: a review. *Crit Rev Biotechnol* 26(4):201–221
- Iovdijová A, Bencko V (2010) Potential risk of exposure to selected xenobiotic residues and their fate in the food chain-part I: classification of xenobiotics. *Ann Agric Environ Med* 17(2): 183–192
- Itoh K, Fujita M, Kumano K, Suyama K, Yamamoto H (2000) Phenolic acids affect transformations of chlorophenols by a *Coriolus versicolor laccase*. *Soil Biol Biochem* 32:85–91
- Iyovo GD, Du G, Chen J (2010) Sustainable bioenergy bioprocessing: biomethane production, digestate as biofertilizer and as supplemental feed in algae cultivation to promote algae biofuel commercialization. *J Microb Biochem Technol* 2(4):100–106
- Jiang W, Fan W (2008) Bioremediation of heavy metal contaminated soils by sulfate reducing bacteria. *Ann NY Acad Sci* 1140:446–454
- Kafilzadeh F, Nikvarz M, Jabbari S, Tahery Y (2012) Evaluation of biodegradation of 2-chlorobenzoic acid by isolated bacteria from landfill soils in Shiraz, Iran. *Afr J Microbiol* 6(27):5708–5714
- Karigar CS, Rao SS (2011) Role of microbial enzymes in the bioremediation of pollutants: a review. *Enzym Res* 2011:11, 805187
- Karn SK, Chakrabarti SK, Reddy MS (2011) Degradation of pentachlorophenol by *Kocuria* sp. CL2 isolated from secondary sludge of pulp and paper mill. *Biodegradation* 22:63–69
- Karpouzias DG, Singh BK (2006) Microbial degradation of organophosphorus xenobiotics: metabolic pathways and molecular basis. *Adv Microb Physiol* 51:119–185
- Kathiresan K (2003) Polythene and plastic degrading microbes in an Indian mangrove soil. *Rev Biol Trop* 51(3–4):629–633
- Kranzioch I, Ganz S, Tiehm A (2014) Chloroethene degradation and expression of *Dehalococcoides dehalogenase* genes in cultures originating from Yangtze sediments. *Environ Sci Pollut Res* 22(4):3138–3148
- Kumar ARC, Singh R (1998) Methanogenesis by enrichment cultures from distillery effluent. *Indian J Microbiol* 38:109–110
- Kumar V, Anand RC, Singh R (1994a) Enrichment and isolation of acetoclastic methanogens from distillery effluent. *Ann Biol* 10(2):253–256
- Kumar V, Anand RC, Singh R (1994b) Methanogenesis by pure isolates from distillery effluent digester. *Ann Biol* 10(2):257–260
- Kumar K, Devi SS, Krishnamurthi K, Kanade GS, Chakrabarti T (2007) Enrichment and isolation of endosulfan degrading and detoxifying bacteria. *Chemosphere* 68(2):317–322
- Kumar M, Varma A, Kumar V (2016) Ecogenomics based microbial enzyme for biofuel industry. *Sci Int* 4:1–11
- Kumari M, Ghosh P, Swati, Thakur IS (2014) Microcosmic study of endosulfan degradation by *Paenibacillus* sp. ISTP10 and its toxicological evaluation using mammalian cell line. *Int Biodeter Biodegrad* 96:33–40
- Kwon GS, Kim JK, Kim TK, Sohn HY, Koh SC, Shin KS, Kim DG (2002) *Klebsiella pneumoniae* KE-1 degrades endosulfan without formation of the toxic metabolite, endosulfan sulphate. *Microbiol Lett* 215:255–259
- Kyrikou J, Briassoulis D (2007) Biodegradation of agricultural plastic films: a critical review. *J Polym Environ* 15:125–150
- Le NB, Coleman NV (2011) Biodegradation of vinyl chloride, cis-dichloroethene and 1,2-dichloroethane in the alkene/alkane oxidising *Mycobacterium* strain NBB4. *Biodegradation* 22:1095–1108
- Leyns NM, Bastiaens L, Verstraete W, Springael D (2005) Influence of the carbon/nitrogen/ phosphorus ratio on polycyclic aromatic hydrocarbons degradation by *Mycobacterium* and *Sphingomonas* in soil. *Appl Microbiol Biotechnol* 66:726–736
- Lin C, Gan L, Chen ZL (2010) Biodegradation of naphthalene by strain *Bacillus fusiformis* (BFN). *J Hazard Mater* 182(1/3):771–777

- Lin SY, Hameed A, Liu YC, Hsu YH, Lai WA, Huang HI, Young CC (2014) *Novosphingobium arabidopsis* sp. nov., a DDT resistant bacterium isolated from the rhizosphere of *Arabidopsis thaliana*. Int J Syst Evol Microbiol 64(2):594–598
- Liu H, Yao J, Yuan Z, Shang Y, Chen H, Wang F, Masakorala K, Yu C, Cai M, Blake RE, Choi MMF (2014a) Isolation and characterization of crude oil degrading bacteria from oil water mixture in Dagang oil field, China. Int Biodet Biodegrad 87:52–59
- Liu XM, Chen K, Meng C, Zhang C, Zhu JC, Huang X, Li SP, Jiang JD (2014b) *Pseudoxanthobacter liyangensis* sp. nov., isolated from dichlorodiphenyl trichloroethane contaminated soil. Int J Syst Evol Microbiol 64:3390–3394
- Magnuson JK, Stern RV, Gossett JM, Zinder SH, Burris DR (1998) Reductive dechlorination of tetrachloroethene to ethene by a two component enzyme pathway. Appl Environ Microbiol 64:1270–1275
- Meer JR, van der de Vos WM, Harayama S, Zehnder AJB (1992) Molecular mechanisms of genetic adaptation to xenobiotic compounds. Microbiol Rev 56:677–694
- Milić JS, Beškoski VP, Ilic MV, Ali SAM, Gojic-Cvijovic GD, Vric MM (2009) Bioremediation of soil heavily contaminated with crude oil and its products: composition of the microbial consortium. J Serb Chem Soc 74(4):455–460
- Niharika N, Moskalikova H, Kaur J, Khan F, Sedlackova M, Hampl A, Damborsky J, Prokop Z, Lal R (2013) *Sphingobium czechense* sp. nov. isolated from a hexachlorocyclohexane dump site. Int J Syst Evol Microbiol 63:723–728
- Oaks JL, Gilbert M, Virani MZ, Watson RT, Meteyer CU, Rideout BA, Shivaprasad HL, Ahmed S, Chaudhry MJ, Arshad M, Mahmood S, Ali A, Khan AA (2004) Diclofenac residues as the cause of vulture population decline in Pakistan. Nature 427:630–633
- Ortiz-Hernandez ML, Quintero-Ramirez R, Nava-Ocampo AA, Bello-Ramirez AM (2003) Study of the mechanism of *Flavobacterium* sp. for hydrolyzing organophosphate pesticides. Fundam Clin Pharmacol 17(6):717–723
- Patil R, Bagde US (2012) Isolation of polyvinyl chloride degrading bacterial strains from environmental samples using enrichment culture technique. Afr J Biotechnol 11(31):7947–7956
- Pradeep S, Josh MKS, Binod P, Devi RS, Balachandran S, Anderson RC, Benjamin S (2015) *Achromobacter denitrificans* strain SP1 efficiently remediates di (2-ethylhexyl) phthalate. Ecotoxicol Environ Saf 112:114–121
- Prakash A, Bisht S, Singh J, Teotia P, Kela R, Kumar V (2014) Biodegradation potential of petroleum hydrocarbons (PHCs) by bacteria and mixed bacterial consortium isolated from contaminated sites. Turk J Eng Environ Sci 38(1):31–40
- Pripich GP, Adams RL, Daugulis AJ (2006) Ex situ bioremediation of phenol contaminated soil using polymer beads. Biotechnol Lett 28(24):2027–2031
- Raaman N, Rajitha N, Jayshree A, Jegadeesh R (2012) Biodegradation of plastic by *Aspergillus* spp. isolated from polythene polluted sites around Chennai. J Acad Indus Res 1(6):313–317
- Rani B, Kumar V, Singh J, Bisht S, Teotia P, Sharma S, Kela R (2014) Bioremediation of dyes by fungi isolated from contaminated dye effluent sites for bio-usability. Braz J Microbiol 45(3):1055–1063
- Salam LB, Obayori OS, Olatoye NO (2014) Biodegradation of anthracene by a novel actinomycete, microbacterium sp. isolated from tropical hydrocarbon contaminated soil. World J Microbiol Biotechnol 30(1):335–341
- Schumacher W, Holliger C (1996) The proton/electron ration of themenaquinone dependent electron transport from dihydrogen to tetrachloroethene in *Dehalobacter restrictu*. J Bacteriol 178:2328–2333
- Selvam K, Vishnupriya B (2013) Bioremediation of xenobiotic compounds and heavy metals by the novel actinobacteria. Int Pharm Chem Sci 2(3):1589–1597
- Sethy NK, Jha VN, Sahoo SK, Shukla AK, Tripathi RM (2011) Ground water ingestion dose due to intake of radionuclide (Natural U and 226Ra) to population around uranium mining complex at Jaduguda. J Ecosyst Ecograph 1:104
- Shahid A, Singh J, Bisht S, Teotia P, Kumar V (2013) Biodegradation of textile dyes by fungi isolated from North Indian field soil. Env Asia 6(2):51–57

- Sharma J, Fulekar MH (2009) Potential of *Citrobacter freundii* for bioaccumulation of heavy metal copper. *Biol Med* 1(3):7–14
- Sharma SK, Saxena M, Mandal TK, Ahammed YN, Pathak H (2011) Variations in mixing ratios of ambient ammonia, nitric oxide and nitrogen dioxide in different environments of India. *J Food Process Technol* 1:101
- Shen YJ, Lu P, Mei H, Yu HJ, Hong Q, Li SP (2010) Isolation of a methyl parathion degrading strain *Stenotrophomonas* sp. SMSP-1 and cloning of the *ophc2* gene. *Biodegradation* 21:785–792
- 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):1–6
- Sun K, Liu J, Gao Y, Jin L, GuY, Wang, W (2014) Isolation, plant colonization potential and phenanthrene degradation performance of the endophytic bacterium *Pseudomonas* sp. Ph6-gfp. *Sci Rep* 4(5462): 1–11
- Swissa N, Nitzan Y, Langzam Y, Cahan R (2014) Atrazine biodegradation by a monoculture of *Raoultella planticola* isolated from a herbicides wastewater treatment facility. *Int Biodeterior Biodegrad* 92:6–11
- Takami H, Kudo T, Horikoshi K (1997) Isolation of extradiol dioxygenase genes that is phylogenetically distant from other meta cleavage dioxygenase genes. *Biosci Biotechnol Biochem* 61:530–532
- Theriot CM, Grunden AM (2010) Hydrolysis of organophosphorus compounds by microbial enzymes. *Appl Microbiol Biotechnol* 89:35–43
- Vidali M (2001) Bioremediation. An overview. *Pure Appl Chem* 73:1163–1172
- Vigneswaran M, Prabakaran V, Arthysurendr S (2012) Biodegradation and bioremediation of azo dye entrenched soil by *Pseudomonas* sp. *Int J Chem Anal Sci* 3(5):1381–1384
- Wang F, Grundmanna S, Schmid M, Dorflera U, Rohererb S, Muncha JC, Hartmann A, Jiang X, Schroll R (2007) Isolation and characterization of 1,2,4-trichlorobenzene mineralizing *Bordetella* sp. and its bioremediation potential in soil. *Chemosphere* 67(5):896–902
- Wang J, Zhu L, Liu A, Ma T, Wang Q, Xie H, Wang J, Jiang T, Zhao R (2011) Isolation and characterization of an *Arthrobacter* sp. Strain HB-5 that transforms atrazine. *Environ Geochem Health* 33:259–266
- Wang J, Zhu L, Wang Q, Wang J, Xie H (2014) Isolation and characterization of atrazine mineralizing *Bacillus subtilis* Strain HB-6. *PLoS One* 9(9):1–8
- Wen ZD, Gao DW, Wu WM (2014) Biodegradation and kinetic analysis of phthalates by an arthrobacter strain isolated from constructed wetland soil. *Appl Microbiol Biotechnol* 98:4683–4690
- Wu XL, Wang YY, Liang RX, Dai QY, Chao WL (2010) Degradation of Di-n-butyl phthalate by newly isolated *Ochrobactrum* sp. *Bull Environ Contamin Toxicol* 85:235–237
- Xu HX, Wu HY, Qiu YP, Shi XQ, He GH, Zhang JF, Wu JC (2011) Degradation of fluoranthene by a newly isolated strain of *Herbaspirillum chlorophenicum* from activated sludge. *Biodegradation* 22:335–345
- Yamatsu A, Matsumi R, Atomi H, Imanaka T (2006) Isolation and characterization of a novel poly (vinyl alcohol) degrading bacterium, *Sphingopyxis* sp. PVA3. *Appl Microbiol Biotechnol* 72(4):804–811
- Yeom SH, Daugulis AJ, Lee SH (2010) Bioremediation of phenol contaminated water and soil using magnetic polymer beads. *Process Biochem* 45(9):1582–1586
- Zhang C, Bennett GN (2005) Biodegradation of xenobiotics by anaerobic bacteria. *Appl Microbiol Biotechnol* 67:600–618
- Zhang D, Zhu L (2012) Effects of Tween 80 on the removal, sorption and biodegradation of pyrene by *Klebsiella oxytoca* PYR-1. *Environ Pollut* 164:169–174
- Zhang J, Chen SA, Zheng JW, Cai S, Hang BJ, He J, Li SP (2012) *Catellibacterium nanjingense* sp. nov., a propranol degrading bacterium isolated from activated sludge, and emended description of the genus *Catellibacterium*. *Int J Syst Evol Microbiol* 62:495–499