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REVIEWS

Pesticide relevance and their microbial degradation: a-state-of-art

Jay Prakash Verma · Durgesh Kumar Jaiswal · R. Sagar

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Abstract The extensive use of pesticide causes imbalance in properties of soil, water and air environments due to having problem of natural degradation. Such chemicals create diverse environmental problem via biomagnifications. Currently, microbial degradation is one of the important techniques for amputation and degradation of pesticide from agricultural soils. Some studies have reported that the genetically modified microorganism has ability to degrade specific pesticide but problem is that they cannot introduce in the field because they cause some other environmental problems. Only combined microbial consortia of indigenous and naturally occurring microbes isolated from particular contaminated environment have ability to degrade pesticides at faster rate. The bioaugumentation processes like addition of necessary nutrients or organic matter are required to speed up the rate of degradation of a contaminant by the indigenous microbes. The use of indigenous microbial strains having plant growth activities is ecologically superior over the chemical methods. In this review, we have attempted to discuss the recent challenge of pesticide problem in soil environment and their biodegradation with the help of effective indigenous pesticides degrading microorganisms. Further, we highlighted and explored the molecular mechanism for the pesticide degradation in soil with effective indigenous microbial consortium. This review suggests that the use of pesticide degrading microbial consortia which is an eco-friendly technology may be suitable for the sustainable agriculture production.

Keywords Pesticide · Pesticide degrading microorganism · Microbial degradation · Bioaugumentation · Indigenous · Biodegradation · Sustainable agriculture

J. P. Verma (✉) · D. K. Jaiswal
Institute of Environment and Sustainable Development, Banaras Hindu University, Varanasi 221005, India
e-mail: verma_bhu@yahoo.co.in

R. Sagar
Department of Botany, Banaras Hindu University, Varanasi 221005, India

1 Introduction

During the green revolution, more chemical fertilizers and pesticides were used to enhance the production of food grains needed to meet the needs of the ever expanding human population. Notwithstanding, the green revolution caused many environmental problems such as increased soil fertility loss, soil acidification, nitrate leaching, increased weed species resistance and loss of biodiversity (Tilman et al. 2002; Verma et al. 2013). The pesticides are a diverse group of inorganic and organic chemicals like herbicides, insecticides, nematicides, fungicides, and soil fumigants. In agriculture, these pesticides are applied

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to enhance crop yield and quality and to maximize economic returns by prevention of pest attack. The pesticides are bioactive, toxic substances, and it influences, directly or indirectly, soil fertility and health as well as agroecosystem quality (Lo 2010; Joergensen and Emmerling 2006). These chemicals affect the diversity of soil microbial communities, their metabolic activities, reproduction and growth. Plenty of the studies have discussed the effect of pesticides on soil organisms (e.g. Bunemann et al. 2006; Odukkathil and Vasudevan 2013), including on bacterial populations (Lo 2010; Johnsen et al. 2001).

Pest infestations deplete annual food production by an average of 45 % (Abhilash and Singh 2009). The use of chemical pesticides to control pests and disease vectors have enhanced agricultural yields and limited the spread of insect-borne diseases (e.g., malaria, dengue, encephalitis, filariasis, etc.) that affect human health (Bhatnagar 2001; Rekha and Naik 2006). Effective pest management is essential for maintaining high crop yields in tropical region because high temperatures and humidity in this region facilitate the rapid reproduction of pests, which exert crop loss from insects and diseases more severely (Kannan et al. 1992; Lakshmi 1993). Pesticide pollution of the local environment affects the lives of birds, wildlife, domestic animals, fish and livestock and thus disrupts the ecosystem structure and function through biomagnifications (Anonymous 1991). Unmannered application of pesticide affects the whole ecosystem by entering the residues in food chain and polluting the soil, air, ground and surface water (ICAR report 1967; UN/DESA 2008).

Various treatment methods (e.g. land filling of contaminated sites, recycling, pyrolysis and incineration) have been used for the removal and remediation of these chemicals from the contaminated sites. Phytoremediation has been used for removal of toxic chemical from soil and water. Currently, the pesticide remediation from agriculture fields is one of the important issue because such chemicals are very expensive and problematic as they form toxic chemicals by reaction of various organic and inorganic contents and element present in soils (Jain et al. 2005). Only efficient microbial technology is useful for pesticide removal/degradation from the agricultural soils. Microbial degradation (use of fungi, bacteria, actinomycetes and viruses) can effectively remove pesticides from the contaminated soil (organochlorines, organophosphates and carbamates) through the enzymatic degradation (Porto et al. 2011). The biological degradation; involves the use of effective microorganism to degrade the complex pesticide into simple inorganic chemicals (Wood 2008). Moreover, this technology is less hazardous, environmentally friendly and economically viable and socially acceptable (You and Liu 2004). The indigenous soil microbial consortia are better and effective consortia for microbial degradation of pesticide than the non indigenous strains. Because, the indigenous strains grow very well and have higher adaptability in particular geographical region. Hence, these indigenous microbial consortia have potential to degrade the pesticide and also have plant growth promoting ability like production of plant growth hormones, biological nitrogen fixation, phosphate solubilization, hydrogen cyanide, siderophore and antagonistic properties for enhancing the sustainable agriculture.

The genetically modified indigenous microorganisms are also used for bioremediation because these organisms have particular genes, which are responsible for degradation of the specific pesticide (Sakamoto and Tsutsumi 2004). The natural microorganisms exposed to pesticides; develop resistance power though anti-catabolic processes to remove the toxic compounds. Since the knowledge on microbial bioremediation of pesticides is fragmented (Finley et al. 2010; Porto et al. 2011; Sakamoto and Tsutsumi 2004; You and Liu 2004; Wood 2008). Therefore, the objective of the present study was to elaborate the potential applications of various indigenous microorganisms in degradation and detoxification of pesticide in agricultural soils.

2 Pesticide relevance and problem

The increase in the demand for agro-products and changing regional climate has resulted in an increase in consumption and application rate of pesticide (Shetty et al. 2008). The rates of pesticides consumption in various countries depend on agricultural land. Some country showed higher consumption of total pesticide according to agricultural area. The Worldwide top ten higher pesticide using countries are Italy (63,305 tone/y), Turkey (60,792.4 tone/y), Colombia (48,618.47 tone/y), India (40,379.24 tone/y), Japan (36,557 tone/y), Bolivia (31,566.76 tone/y), Ecuador

Table 1 Worldwide higher pesticide (insecticide, herbicides, fungicides and bactericides) consuming countries with agricultural land area in year 2010

Countries	Worldwide higher consumption of pesticides in year 2010 (tones/year)				Worldwide area agricultural area (Sq km)	
	Insecticides	Herbicides	Fungicides and bactericides	Total pesticide consumption	Total land area	Total agricultural area
Bangladesh	2,681.69	658.54	9,883.70	13,223.93	130,170	31,650
Bolivia	9,843.50	17,263.60	4,459.66	31,566.76	1,083,300	369,650
Cameroon	3,467.28	3,470.20	2,457.46	9,394.94	472,710	96,000
Chile	7,071.00	7,234.00	3,727.00	18,032	743,530	157,430
Colombia	8,717.60	17,587.15	22,313.72	48,618.47	1,109,500	425,030
Costa Rica	2,148.52	4,416.26	7,438.56	14,003.34	51,060	18,800
Dominican Republic	609.43	3,849.66	1,323.83	5,782.92	48,320	24,470
Ecuador	7,689.61	14,394.76	9,118.73	31,203.1	248,360	749,770
El Salvador	750.97	11,007.37	85.41	11,843.75	20,720	15,293.4
Germany	1,243.79	16,675.00	9,666.70	27,585.49	348,570	167,000
Guatemala	2,026.92	8,362.84	4,508.48	14,898.24	107,160	43,950
Honduras	314.00	2,860.90	1,877.60	5,052.5	111,890	32,200
Hungary	1,965.00	4,479.00	2,285.50	8,729.5	90,530	53,430
India	20,618.82	6,704.98	13,055.44	40,379.24	2,973,190	1,797,590
Italy	10,834.00	9,934.00	42,537.00	63,305	294,140	143,228
Japan	2,053.30	12,166.70	22,337.00	36,557	364,500	45,930
Myanmar	6,175.68	661.00	2,141.33	8,978.01	653,260	125,260
Netherlands	1,634.90	2,642.30	3,613.10	7,890.3	33,730	19,087
Norway	5.33	8,321.09	1,479.40	9,805.82	365,268	10,060
Peru	4,352.16	6,160.08	4,045.60	14,557.84	1,280,000	214,700
Portugal	370.97	2,042.29	9,475.36	7,249.2	91,470	36,770
Romania	1,327.70	3,688.90	2,232.60	26,506.74	230,050	141,560
Turkey	8,215.57	745.59	17,545.58	60,792.4	769,630	390,120
Ukraine	8,531.50	40,910.60	11,350.30	13,899.57	579,320	412,670
United Kingdom	889.46	7,488.83	5,521.28	13,223.93	241,930	172,240

Source: FAO (2010), World Bank (2010), Schreinemachers and Tipraqsa (2012)

(31,203.1 tone/y), Germany (27,585.49 tone/y), Romania (26,506.74 tone/y) and Chile (18,032 tone/y) (Table 1). The Worldwide top ten higher agricultural land are: India (1,797,590 sq.km), Ecuador (749,770 sq.km), Colombia (425,030 sq.km), Ukraine (412,670 sq.km), Turkey (390,120 sq.km), Bolivia (369,650 sq.km), Peru (214,700 sq.km), United Kingdom (172,240 sq.km), Germany (167,000 sq.km) and Chile (157,430 sq.km). Total annual pesticide consumption was depend on the total agricultural lands e.g. Turkey, Colombia, India, Bolivia, Ecuador, Germany and Chile showed higher pesticide consumption as well as agricultural area (Table 1).

Pesticides can be classified as either being readily degradable (non-persistent), or as being persistent. The non-persistent pesticides are: insecticides (methoxychlor, sevin, malathion), herbicides (paraquat, dalapon, dacthal, treflan) and fungicides (benlate, mancozeb, zineb, captan), and persistent pesticides are: insecticides (DDT, aldrin, dieldrin and chlordane), herbicides (simazine, turbacil, tordon) fungicides (PMAS, calo-clor, cadmium compounds) (Vargas 1975). Orgnochlorine (OC) insecticides (DDT, hexachlorocyclohexane, aldrin and dieldrin, etc.) and organophosphate insecticides (chlorpyrifos, acephate, diazinon, malathion and disulfoton etc.) are

most commonly used pesticides in developing countries of Asia because of their low cost and broad control spectrum and versatility against various pests (FAO 2005). The intense and frequent use of these chemicals has led to the persistence in soil due to lack of their timely degradation (Odukkathil and Vasudevan 2013). For example; metribuzin was in practice because of its easy transfer as a water soluble compound (Hernandez et al. 1998), and linuron for its persistence in the soil (Guzzella et al. 2006), and fluazinam due to its persistence and wide taxonomic range to inhibit phytopathogenic fungi (Kimyoji et al. 1995). Metribuzin (4-amino-6-tert-butyl-4,5-dihydro-3-methylthio-1,2,4-triazin-5-one) and linuron (3-(3,4-dichlorophenyl)-1-methoxy-1-methylurea) inhibit electron transport at the photosystem II receptor site, were used to control weeds in several crops, including potato (Tomlin 2002). Metribuzin is biodegraded rapidly in soil and its photodecomposition is also efficient in the soil surface as well as in water. Fluazinam (3-chloro-N-(3-chloro-5-trifluoromethyl-2-pyridyl)-a,a,a-trifuoro-2,6-dinitro-p-toluidine has an uncoupling activity on mitochondrial oxidative phosphorylation and is used as a fungicide to protect the crops.

The World Health Organization (WHO 2004) provides an internationally accepted standard for hazard classification. Depending upon their intensity expressed in LD50 value those were (1) IA (Extremely), (2) IB (Highly hazardous), (3) II (Moderately hazardous) and (4) III (slightly hazardous). Currently, in India, there are registered 234 pesticides; among these, four belongs to WHO Class IA, 15 to WHO class IB and 76 to WHO Class II. They constituted 40 % of the registered pesticides. During 2005–2006 and 2009–2010, out of 15 pesticides; sulfur (fungicide, 16,424 mt), endosulfan (insecticide, 15,537 mt), moncojeb (provides, 11,067 mt) and phorate (insecticide, 10,763 mt) are highly used (Table 2) and the total consumption amounted 210,600 mt. According to the Directorate of Plant Protection, Quarantine and Storage, Government of India (2010); during 2005 to 2010, the highest use of pesticide (39,948 mt) has been reported in Uttar Pradesh as compared to other top six pesticide-consuming states of India during 2005 to 2010 (Fig. 1). In India, the average consumption of pesticide is lesser as compared to other developed countries, but the problem of pesticide residue in India is comparatively higher. Presently, the yearly pesticide consumption in India is increasing due to rapid agricultural production (FAO 2010).

Table 2 Most consumed pesticides in India (during 2005–2006 to 2009–2010)

S.No.	Pesticide (Technical Grade)	Quantity consumed (metric tonnes)
1	Sulphur (fungicide)	16,424
2	Endosulfan (insecticide)	15,537
3	Mancozeb (fungicide)	11,067
4	Phorate (insecticide)	10,763
5	Methyl Parathion (insecticide)	08408
6	Monocrotophos (insecticide)	08209
7	Cypermethrin (insecticide)	07309
8	Isoproturon (herbicide)	07163
9	Chlorpyrifos (insecticide)	07163
10	Malathion (insecticide)	07103
11	Carbendazim (fungicide)	06767
12	Butachlor (herbicide)	06750
13	Quinalphos (insecticide)	06329
14	Copper oxychloride	06055
15	Dichlorvos (insecticide)	05833

Source: Total pesticides consumed during 2005–2006 to 2009–2010, as per official data of the Directorate of Plant Protection, Quarantine and Storage, Govt of India. (www.indiaforsafefood.in/farminginindia.html)

In tropical countries; crop loss due to plague is severe because of high temperature and humidity, which facilitates the rapid multiplication of pests (Kannan et al. 1992; Lakshmi 1993). The intensive use of pesticides help for the protection of crops from pests (insects, mites, nematodes and rodents), plant pathogens (fungi, viruses and bacteria), and weeds reduced 30 % crop loss (Porto et al. 2011) and increase the sufficient food grain for the need of ever increasing human population (Acharya 2006). Among different pesticides; pyrethroids, organophosphates and chlorinated compounds (DDT, hexachlorocyclohexane, aldrin and dieldrin) are the most commonly used pesticides in the developing countries because of their low cost, easy availability in local markets and versatility against various pests (Porto et al. 2011). Polycyclic aromatic hydrocarbons (PAHs) form a group of compounds composed of two or more fused aromatic rings. These hydrophobic compounds display a high affinity for organic matter and particles, and accumulate in organic rich soil and marine sediments (Amellal et al. 2001).

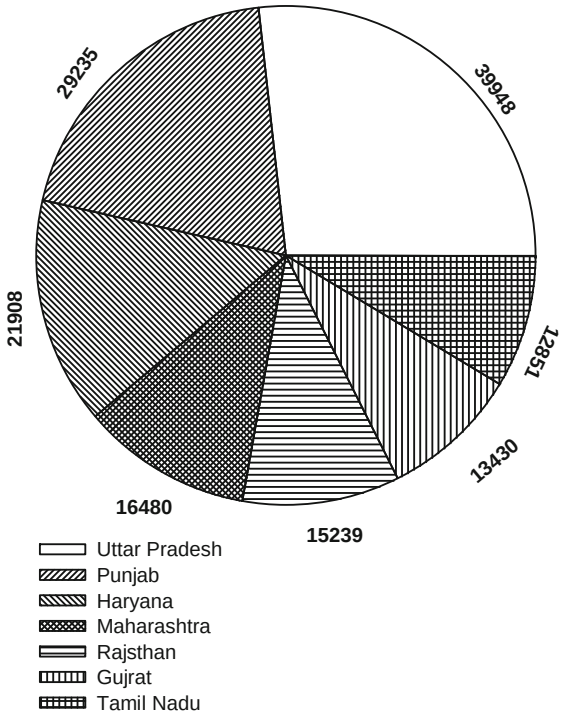

Fig. 1 The maximum pesticide-consuming states e.g. Uttar Pradesh, Punjab, Haryana, Maharashtra, Rajasthan, Gujarat and Tamil Nadu in India during 2005–2006 to 2009–2010. The values near each state is in MT (*Data Source*: Directorate of Plant Protection, Quarantine and Storage, Govt of India) (www.indiaforsafefood.in/farminginindia.html)

Carbamate pesticides are mainly used in the agriculture due to their broad activity spectrum, less toxic to human beings and easy degradation by the microorganism (Wolfe et al. 1978). On the other hand, the application of endosulfan as an insecticide, more than 99 % of it goes to misuse and remains in the environment as pollutants (Mahapatra 2008; Mahapatra and Panigrahi 2013). Organochloride pesticides are recalcitrant and resistant to biodegradation (Diaz 2004; Dua et al. 2002; Chaudhry and Chapalamadugu 1991). Because of indiscriminate and unplanned uses (EI-Bestway et al. 2000), long half-life, nondegradable nature, such poisonous chemical are continuously persisting in the soils of certain agroecosystems (You and Liu 2004; Gavrilescu 2005), contributed to loss of soil fertility, acidification, nitrate leaching and weed invasions (Tilman et al. 2002; Verma et al. 2013). It further enters into the food chain and pollutes the air, ground and surface water (ICAR 1967; Parsek et al. 1995; You and Liu 2004; UN/DESA 2008).

The farmers are not aware of the critical loads of these pesticides on the agricultural crops and soils, and they are used to spray pesticides for controlling the pest. Such pesticide load in soil causes negative consequences on the microbial flora and fauna (You and Liu 2004), which further causes the cascading effects on the agricultural ecosystem structure and function (Gavrilescu 2005). Further, such problem become more complicated due to extensive use of chlorinated pesticide, which is easily available in local markets of India, though banned in developed countries of the world (You and Liu 2004). Because of their unusually long half life and non-biodegradable nature, these poisonous chemicals are likely to persist in the environment and inter into the food chain and cause serious health hazards (Parsek et al. 1995).

Humans are exposed to pesticides by different routes of exposure, such as; inhalation, ingestion and dermal contact (Rekha and Naik 2006). Increasing incidence of cancer (Porto et al. 2011), mutagenicity and circulatory problem (Sinha et al. 1995, 1997), chronic kidney diseases, suppression of the immune system, sterility among males and females (Colosio et al. 2009; Jokanovic and Prostran 2009), endocrine disorders, neurological (IARC 1986; Vaccari et al. 2006; Porto et al. 2011) and behavioral disorders, especially among children, have been attributed by the chronic pesticide poisoning (Agnihotri 1999). Pesticide pollution to the local environment so affects the lives of birds, wildlife, domestic animals, fish and livestock and more pesticide load in environment enhances the resistance ability of microbial strains of soils. Thus, increased amount of pesticides disrupt the whole ecosystem through biomagnifications (Anonymous 1991). Persistent organic pollutants (POPs) are chemicals that remain persistent in the environment for long periods, become widely distributed geographically, accumulate in the fatty tissue of living organisms and are toxic to humans and wildlife (United Nations Environment programs 2011). The Stockholm Convention seeks to restriction as well as elimination of production and releases of nine organochlorine pesticides, viz: aldrin, chlordane, DDT, dieldrin, endrin, heptachlor, hexachlorobenzene, mirex, toxaphene (Stockholm Convention 2009) and Endosulfan (Stockholm Convention 2011). These chemicals are highly hazardous to organism because of their higher degree of halogenations, inclination to bioaccumulation in the lipid component, and resistance to natural

degradation (Weber and Varbelow 2013; Torres et al. 2013a, b; Weber and Varbelow 2013; Abhilash et al. 2013).

3 Microbial degradation of pesticides

Soil microbes perform substantial role in litter degradation (Schneider et al. 2010), promotion of plant growth (Hayat et al. 2010), nutrient cycling (Van Der Heijden et al. 2008) and the degradation of pollutants and pesticides (Pino and Penuela 2011; Zhao et al. 2009). Such functions are significant to the farmers and society; therefore, the applications of pesticide which hamper the ecosystem services need to be minimized. The effect of pesticide on the activity of soil microbes has been observed by testing the efficiency of carbon utilization and nitrification. The success of the nitrification test against the pesticide side effect is likely due to the fact that no soil fungi are known to be involved in the nitrification process and that only few species of bacteria are able to perform the process. Recently, the expressed functional genes (amoA and amoB) involved in the nitrification process have been used to quantify the effect of pesticides on nitrification. One other microbial-driven ecosystem function that has been found to be affected by pesticide use is the degradation of pesticides by increasing the pesticide degrading microbial populations (Bælum et al. 2008; Lancaster et al. 2010). In mRNA quantification study the process of nitrification has been shown too susceptible against certain pesticides, and the nitrification rate was linked with the quantity of mRNA transcript. Other molecular sequencing study suggested that the microbial community structures are influenced by pesticides (Jacobsen and Hjelmsø 2014).

For minimization of soil pollution and soil toxicant in agricultural fields, various treatment methods (i.e., filling of contaminated land sites, recycling, pyrolysis and incineration) have been used (Wang et al. 2005). The physico-chemical remedial strategies to clean up sites containing these compounds are neither cost effective nor adequate enough (Jain et al. 2005). Therefore, biological method would be one of the promising methods to exploit the ability of microorganisms for removal of pollutants from the contaminated sites. This alternative treatment strategy (bioremediation) could be effective, minimally hazardous, economical, environment-friendly, and versatile (Finley et al. 2010; Porto et al. 2011). The microbial based (with the help of fungi, bacteria, actinomycetes and viruses) degradation may ease the pesticide problem (Finley et al. 2010) which is a natural process (Kosaric 2001), does not produce toxic intermediates (Pieper and Reineke 2000; Furukawa 2003) more effective technology, less hazardous and environment-friendly (You and Liu 2004; Wang et al. 2005). Soil microorganisms collectively decompose various xenobiotic compounds and return the item to the mineral salts which are utilized by plants (Fig. 2). Hence, they play an important role in the dissipation of xenobiotic pesticides in the soil. Microorganisms especially bacteria, due to their continuous exposure to such environmental stress, develop a genetically determined system against toxicant (Parsek et al. 1995). The highly diverse microbial communities present in fresh and marine water, sewage and soils are able to transform a wide range of organic chemicals. Compared to chemical methods, the microorganisms that survive in the environment, utilize the pesticides for obtaining the energy seem to be the best candidates for bioremediation of pesticide present in soil or water (Fig. 2).

Pesticide degradation may be carried out by one or more ways described as biotransformation, biomineralization, bioaccumulation, biodegradation, bioremediation and cometabolism (Shakoori et al. 2000; Park et al. 2003; Finley et al. 2010). Microbial degradation involves the use of effective microorganism for the enzymatic breakdown of toxic pesticides (organochlorines, organophosphates and carbamates) into a nontoxic compounds or it may be defined as; microbial mediated degradation of complex organic compound (pesticide) into simple inorganic chemicals on the contaminated sites; soil, ground water, sludge's, industrial water system and gas (You and Liu 2004; Wood 2008; Finley et al. 2010; Porto et al. 2011). Thus, the microorganisms which play substantial role in the in situ removal and detoxification of these toxicants from the concerned environment are of special significance (Desaint et al. 2000; Wang et al. 2005; Wood 2008). Large number of bacterial strains; viz. *Arthobacter* (Aislabie et al. 2005; Patil et al. 1970), *Pseudomonas* (Singh et al. 2003; Lakshmi et al. 2008; Liming et al. 2014), *Ralstonia* (Hay and Focht 2000), *Rhodococcus* (Zaitsev et al. 1995; Park et al. 2003), *Bacillus* (Anwar et al. 2009; Zhu et al. 2010;

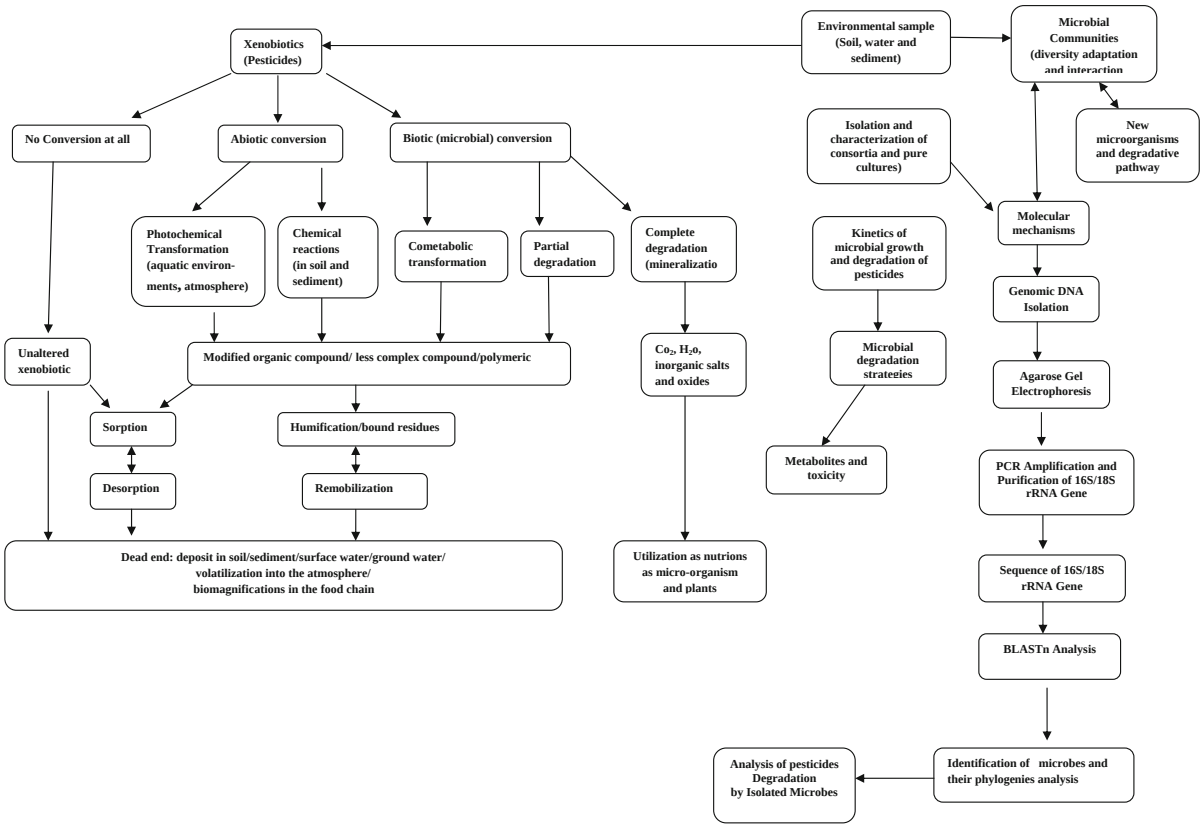

Fig. 2 Microbial degradation of pesticide affected by various environmental factor and characterization of pesticide degrading microbes

Liu et al. 2012; Fawzy et al. 2014), *Nocardiopsis* (Pravin et al. 2012), *Cryptococcus* (Evy et al. 2012) and *Acetobacter* (Shakoori et al. 2000) and *Alcaligenes* (Padmanabhan et al. 2003; Yang et al. 2005) have been isolated from different parts of the world with amazing property to degrade xenobiotic contaminants are listed in Table 3. These microorganisms are appropriately termed as nature's biodegraders and/or scavengers because they recycle most natural waste materials into harmless compounds. The endogenous microbes remove pollutants from soils by their extraordinary ability to use a wide variety of xenobiotics as sole energy and carbon source (Siddique et al. 2003). Such microorganisms are highly adaptable and have the capability to degrade the recalcitrant compounds through evolution of new genes, which encode enzymes that can use these compounds as their primary substrates (Suenaga et al. 2001).

The pesticide degrading genes of soil bacteria reside on plasmids (anti-catabolic plasmid) and encode the pollutant-degrading enzymes (Laemmli et al. 2000). These catabolic plasmids have been reported from different species of *Pseudomonas, Alcaligenes, Actinobacter, Cytophaga, Moraxella, Klebsiella* and *Arthrobacter* (Sayler et al. 1990). *Pseudomonas aeruginosa* MRM6, *Pseudomonas aeruginosa* SFM4 and *Acromobacter xylosoxidans* ES9 dégradé the endosulfan (a broad range of pesticide). The bacteria *Clostridium sporogenes* and *Bacillus coli* produce trace amounts of benzene and mono-chlorobenzene from lindane and can further metabolize it by producing the CO_2 from sub-merged soils. *Pseudomonas putida* and *Acinetobacter* have ability for dehalogenate the chloro-aromatic compounds (Vollmer et al. 1998). A group of brown-rot fungi (*Gloeophyllum trabeum*, *Fomitopsis pinicola*, and *Daedalea dickinsii*) degrades the DDT. *Mucor circinelloides* and *Galactomyces geotrichum* isolated from cattle manure compost (CMC) (Purnomo et al. 2010a) and *Pleurotus ostreatus,* from spent mushroom

Table 3 Pesticide degrading microorganisms have various type pesticides degrading ability

Pesticide	Organism	Nature of study	Reference
Acibenzolar-S-methyl	*B. pumilus* SE34	Biodegradation of soil-applied pesticides by selected strains of plant growth-promoting rhizobacteria (PGPR) and their effects on bacterial growth	Myresiotis et al. (2012)
Aldrin	*Trichoderma viride, Micrococcus* 204, *Bacillus* sp. 458	Comparison of insecticide degradation by soil microorganisms	Patil et al. (1970)
	Aspergillus niger	Evaluation: biotransformation by microorganism	Korte and Porter (1970)
	Bacillus, Micromonospora, Mycobacterium, Nocardia, Streptomyces, Thermoactinomyces and *Pseudomonas*	Epoxidation of aldrin to exo-dieldrin by soil bacteria	Ferguson and Korte (1977)
	Pseudomonas fluorescens	Removal of Aldrin, using activated carbon *Pseudomonas fluorescens* free cell cultures	Erick et al. (2006)
Atrazine	*Arthrobacter nicotinovorans*	Characterization of *Arthrobacter nicotinovorans* HIM, an atrazine-degrading bacterium	Aislabie et al. (2005)
	Cryptococcus laurentii	Biodegradation of atrazine by *Cryptococcus laurentii* isolated from contaminated agricultural soil	Evy et al. (2012)
	Pleurotusostreatus INCQS 40310	Optimized atrazine degradation by *Pleurotusostreatus* INCQS 40310:an alternative for impact reduction of herbicides used in sugarcane crops	Pereira et al. (2013)
	Pichia kudriavzevii strain Atz-EN-01	Atrazine degradation in liquid culture and soil by a novel yeast *Pichia kudriavzevii* strain Atz-EN-01 and its potential application for bioremediation	Evy et al. (2013)
	Raoultella planticola	Atrazine biodegradation by a monoculture of *Raoultella planticola* isolated from a herbicides wastewater treatment facility	Swissa et al. (2014)
Chlorpyrifos	*Micrococcus* sp	Bacterial degradation of chlorpyrifos in pure culture and in soil	Mallick et al. (1999)
	Pseudomonas sp	Effects of soil pH on the biodegradation of chlorpyrifos and isolation of a chlorpyrifos-degrading bacterium	Singh et al. (2003)
	Enterobacter strain B-14	Biodegradation of chlorpyrifos by *Enterobacter* strain B-14 and its use in the bioremediation of contaminated soil	Singh et al. (2004)
	Alcaligenes faecalis DSP3	Isolation and characterization of a chlorpyrifos and 3, 5, 6- trichloro-2-pyridinol degrading bacterium	Yang et al. (2005)
	Serratia sp. and *Trichosporon* sp.	Mineralization of chlorpyrifos by co-culture of *Serratia* and *Trichosporon* sp.	Xu et al. (2007)
	Klebsiella sp.	Biodegradation of chlorpyrifos by *Klebsiella* sp. isolated from an activated sludge sample of waste water treatment plant in Damascus	Ghanem et al. (2007)
	Sphingomonas sp.	Isolation of a chlorpyrifos-degrading bacterium, *Sphingomonas* sp. strain Dsp-2, and cloning of the mpd gene	Li et al. (2007)
	Paracoccus sp. TRP	Biodegradation of chlorpyrifos and 3,5,6-trichloro-2-pyridinol by a newly isolated *Paracoccus* sp. strain TRP	Xu et al. (2008)
	Pseudomonas aeruginosa	Biotransformation of chlorpyrifos and bioremediation of contaminated soil	Lakshmi et al. (2008)
	Verticillium sp. DSP	Fungal degradation of chlorpyrifos by Verticillium sp. DSP in pure cultures and its use in bioremediation of contaminated soil and pakchoi	Fang et al. (2008)

Table 3 continued

Pesticide	Organism	Nature of study	Reference
	Pseudomonas nitroreducens PS-2	Rhizosphere remediation of chlorpyrifos in mycorrhizospheric soil using ryegrass	Korade and Fulekar (2009)
	Bacillus pumilus C2A1	Biodegradation of chlorpyrifos and its hydrolysis product 3,5,6-trichloro-2-pyridinol by *Bacillus pumilus* strain C2A1	Anwar et al. (2009)
	Bacillus licheniformis ZHU-1	Isolation and application of a chlorpyrifos-degrading *Bacillus licheniformis* ZHU-1	Zhu et al. (2010)
	Acremonium sp. GFRC-1	Fungal degradation of chlorpyrifos by *Acremonium* sp. strain (GFRC-1) isolated from a laboratory-enriched red agricultural	Kulshrestha and Kumari (2011)
	Synechocystis sp. strain PUPCCC 64 *(cyanobacterium)*	Chlorpyrifos degradation by the cyanobacterium *Synechocystis* sp. strain PUPCCC 64	Singh et al. (2011)
	Pseudomonas stutzeri B-CP5	Isolation, characterization and fingerprinting of some chlorpyrifos-degrading bacterial strains isolated from Egyptian pesticides-polluted soils	Awad et al. (2011)
	Micrococcus luteus NCIM 2103, *Bacillus subtilis* NCIM 2010 and *Pseudomonas aeruginosa* NCIM 2036	Detoxification of chlorpyriphos by *Micrococcus luteus* NCIM 2103, *Bacillussubtilis* NCIM 2010 and *Pseudomonas aeruginosa* NCIM 2036	Bhuimbar et al. (2011)
	Bacillus cereus	Bacterial degradation of chlorpyrifos by *Bacillus cereus*	Liu et al. (2012)
	Trichoderma harzianum and *Rhizopus nodosus*	Studied the biodegradation of chlorpyrifos by soil fungs	Harish et al. (2013)
	Azospirillum lipoferum and Paenibacillus polymyxa	To compare the capability of *Paenibacillus polymyxa* and *Azospirillum lipoferum* to degrade chlorpyrifos	Romeh and Hendawi (2014)
	Bacillus sp. SMF5, *Penicillium* sp. F09-T10-1 and *Streptomyces thermocarboxydus* strain A-B	Biodegradation of chlorpyrifos by microbial strains isolated from agricultural wastewater	Fawzy et al. (2014)
	Cellulomonas fimi and *Phanerochaete chrysosporium*	Biodegradation of chlorpyrifos by co-culture of *Cellulomonas fimi* and *Phanerochaete chrysosporium*	Barathidasan et al. (2014)
DDT	*Trichoderma viride*	Degradation of DDT by a soil fungus *Trichoderma viride*	Matsumura and Boush (1968)
	Trichoderma viridae, Pseudomonas sp., *Micrococcus* sp., *Arthrobacter* sp., *Bacillus* sp.	Screened DDT contaminated soil for DDT residues and toxicity to microorganisms, microbial biomass and dehydrogenase activity. Isolated two unicellular green algae and three di-nitrogen-fixing cyanobacteria and were tested for their ability to metabolize DDT	Patil et al. (1970)
	Terrabacter sp.	Isolated a *Terrabacter* sp. strain from a 1-1-1-trichloro-2,2-bis(4 chlorophenyl) ethane residue-contaminated agricultural soil and studied the biotransformation of DDE	Aislabie et al. (1999)
	Pseudomonas acidovorans M3GY	Cometabolism of 1, 1-dichloro-2,2-bis (4-chlorophenyl) ethylene by *Pseudomonas acidovorans* M3GY grown on biphenyl	Hay and Foch (1998)
	Ralstonia eutropha strain A5	Transformation of 1,1-dichloro-2,2-(4-chlorophenyl) ethane (DDD) by *Ralstonia eutropha* strain A5	Hay and Focht (2000)
	Eubacterium limosum	Reductive dechlorination DDT by human intestinal bacterium *Eubacterium limosum* under anaerobic conditions	Yim et al. (2008)
	Azoarcus	Biodegradation of DDT by stimulation of indigenous microbial populations in soil with cosubstrates	Ortiz et al. (2013)

Table 3 continued

Pesticide	Organism	Nature of study	Reference
Diazinon	*Serratia marcescens* DI101	Biodegradation of diazinon by *Serratia marcescens* DI101 and its use in bioremediation of contaminated environment	Abo-Amer (2011)
	Serratia liquefaciens and *Serratia marcescens*	Isolation of Bacterial for Degradation of Selected Pesticide	Hussaini et al. (2013)
	Pseudomonas aeruginosa S1, *Bacillus amyloliquefaciens* S2, *Bacillus pseudomycoides* S4 *and Bacillus licheniformis* S5	Diazinon decomposition by soil bacteria and identification of degradation products by GC–MS	Tamer and El-Naggar (2013)
	Pseudomonas peli BG1, *Burkholderia caryophylli* BG4 and *Brevundimonas diminuta* PD6	Degradation of the organophosphorus insecticide diazinon by soil bacterial isolate	Mahiudddin et al. (2014)
Dichlorovos	*Flavobacterium* sp.	In situ enhanced bioremediation of dichlorvos by a phyllosphere *Flavobacterium* strain	Ning et al. (2012)
	Proteus vulgaris, Vibrio sp., *Serratia* sp. and *Acinetobacter* sp.	Biodegradation of dichlorovos (organophosphate pesticide) in Soil by Bacterial Isolates	Agarry et al. (2013)
Dieldrin	*Bacillus* sp.	Dieldrin degradation by soil microorganisms	Matsumura and Boush (1967)
	Pseudomonas sp.	Breakdown of dieldrin in the soil by a microorganism	Matsumura et al. (1968)
	Arthobacter sp., *Bacillus* sp.	Evolution of CO2 from soil incubated with dieldrin-14C	Jagnow and Halder (1972)
	Phlebiabrevispora Nakasone TMIC33929(strain YK543)	Bioconversion of dieldrin by wood-rotting fungi and metabolite detection	Kamei et al. (2010)
	Mucor racemosus strain DDF	Biodegradation of dieldrin by a soil fungus isolated from a soil with annual endosulfan applications	Kataoka et al. (2010)
	Cordyceps militaris KS-92 and *Cordyceps brongniartii* ATCC66779	Biodegradation of Dieldrin by *Cordyceps* Fungi and Detection of Metabolites	Xiao and Kondo (2013)
Difluorobenzens	*Rhodococcus opacus* GM-14	Utilization of halogentad benzenes, phenols, and benzoates by *Rhodococcusopacus* GM-14	Zaitsev et al. (1995)
	Rhodococcus strain MS111	Degradation of alkanes and highly chlorinated benzenes, and production of biosurfactants, by a psychrophilic *Rhodococcus* sp. and genetic characterization of its chlorobenzene dioxygenase	Rapp and Gabriel-Jürgens (2003)
	Labrys portucalensi	Degradation of difluorobenzenes by the wild strain *Labrys portucalensis*	Moreira et al. (2012)

Table 3 continued

Pesticide	Organism	Nature of study	Reference
Endosulfan	*Bacillus subtilis* MTCC1427	Biodegradation of soil-applied endosulfan in the presence Biosurfactant	Awasthi et al. (1999)
	Staphylococcus sp. and *Bacillus* strains	Endosulfan mineralization by bacterial isolates and possible degradation pathway identification	Kumara and Philipa (2006)
	Pseudomonas aeruginosa	Effect of tween 80 added to the soil on the degradation of endosulfan by *Pseudomonas aeruginosa*	Jayashree and Vasudevan (2007)
	Anabaena sp. ATCC 7210	Biodegradation of Endosulfan by *Anabaena*	Shivaramaiah (2010)
	Pseudomonas fluorescens	Biodegradation of endosulfan isomers in broth culture and soil microcosm by *Pseudomonas fluorescens* isolated from soil	Giri et al. (2014)
	Nocardiopsis species MJ435	Degradation of organophosphate pesticide in liquid culture by marine isolate *Nocardiopsis* species	Dudhagara et al. (2012)
	Alcaligenes faecalis JBW4	Biodegradation of organochlorine pesticide endosulfan by bacterial strain *Alcaligenes faecalis* JBW4	Kong et al. (2013)
	Staphylococcus, Micrococcus, Bacillus, Pseudomonas, Mucor, Pencillium, Aspergillus fumigates, Candida	Bioremediation of Endosulfan contaminated Soil	Mohanasrinivasan et al. (2013)
	Klebsiella sp. M3	Biodegradation of Endosulfan in Broth Medium and in Soil Microcosm by *Klebsiella* sp. M3	Singh and Singh (2014)
Endrin	*Trichoderma viride* 12, *Pseudomonas* sp. 27, *Micrococcus* 204, *Arthrobacter* sp. 278, *Bacillus* sp. 4	Comparison of insecticide degradation by soil microorganisms	Patil et al. (1970)
Fenitrothion	*Flavobacterium* sp.	Hydrolysis of selected organophosphorus insecticides by two bacterial isolates from flooded soil	Adhya et al. (1981)
	Burkholderia sp. strain NF100	Involvement of two plasmids in fenitrothion degradation by *Burkholderia* sp. strain NF100	Hayatsu et al. (2000)
Glyphosate	*Penicilliumcitrium*	Biotransformation of 6-nitrochrysene	Pothuluri et al. (1998)
	Pseudomonas aeruginosa and *Bacillus megaterium*	Phyto-Microbial Degradation of Glyphosate in Riyadh Area	Al-Arfaj et al. (2013)
HCN	*Pseudomonas aeruginosa* WH-2	Aqueous phase partitioning of hexachlorocyclohexane (HCH) isomers by biosurfactant produced by *Pseudomonas aeruginosa* WH-2	Sharma et al. (2009)
	Sphingomonas sp. NM05	Surfactant biodegradation of hexachlorocyclohexane (HCH) isomers by *Sphingomonas* sp. NM05	Manickam et al. (2012)
Heptachlor	*Phanerochaete chrysosporium*	Biodegradation of Heptachlor by *Phanerochaete chrysosporium* ME 446	Arisoy and Kolankaya, (1998)
	Phlebia sp.	Metabolism of Organochlorine Pesticide Heptachlor and its Metabolite Heptachlor Epoxide by White-rot Fungi, Belonging to Genus *Phlebia*	Xiao et al. (2011)
Methomyl	*Stenotrophomonas maltophilia* M1	Degradation of methomyl by the novel bacterial strain *Stenotrophomonas maltophilia* M1	Mohamed (2009)

Table 3 continued

Pesticide	Organism	Nature of study	Reference
Methyl parathion	*Pseudomonas* sp.	Isolation of a methyl parathion-degrading Pseudomonas sp. that possesses DNA homologous to the opd gene from a *Flavobacterium* sp.	Chaudry et al. (1988)
	Bacillus sp.	Effect of yeast extract on the degradation of organophosphorus insecticides by soil enrichment and bacterial cultures	Sharmila et al. (1989)
	Pseudomonas fluorescens	Organophosphonate utilization by the wild-type strain of *Pseudomonas fluorescens*	Zboinska et al. (1992)
	Plesiomonas sp. strain M6	Isolation of methyl parathion-degrading strain M6 and cloning of the methyl parathion hydrolase gene	Cui et al. (2001)
	Stenotrophomonas maltophilia M1	Degradation of methomyl by the novel bacterial strain *Stenotrophomonas maltophilia* M1	Mohamed (2009)
	Cyanobacteria	Biodegradation and Utilization of Organophosphorus Pesticide Malathion by *Cyanobacteria*	Ibrahim et al. (2014)
	Pseudomonas sp. strain WBC-3	Bioaugmentation of a methyl parathion contaminated soil with *Pseudomonas* sp. strain WBC-3	Wang et al. (2014)
Monocrotophos (MCP)	*Arthrobacter atrocyaneus* MCM B-425 and *Bacillus megaterium* MCM B-423	To study biomineralization of monocrotophos (MCP) and identify the metabolites formed during biodegradation	Bhadbhade et al. (2002)
	Paracoccus sp. M1	Isolation of a monocrotophos-degrading bacterial strain and characterization of enzymatic degradation	Jia et al. (2007)
	Aspergillus niger MCP1	Isolation and characterization of monocrotophos degrading activity of soil	Jain et al. (2012)
	Pseudomonas stutzeri MTCC 2300	Microbial degradation of monocrotophos by pseudomonas stutzeri	Barathidasan and Reetha (2013)
Parathion	*Flavobacterium* sp. ATCC27551	Degradation of Parathion by bacterial strain *Flavobacterium* that degrade parathion ATCC27551	Sethunathan and Yoshida (1973)
	Bacillus sp. and *Pseudomonas* sp.	Degradation of parathion by bacteria isolated from flooded soil	Siddaramappa et al. (1973)
	Pseudomonas stutzeri	Parathion utilization by bacterial symbionts in a chemostat	Daughton and Hsieh (1977)
	Arthrobacter spp., *Bacillus* spp	Biologically induced hydrolysis of parathion in soil: kinetics and modelling	Nelson et al. (1982)
PCBs	*Desulfomonile tiedjei, Desulfitobacterium, Dehalobacter restrictus*	Polychlorinated biphenyls and their biodegradation	Borja et al. (2005)
Polycyclic aromatic hydrocarbons (PAHs)	*Arthrobacter* sp. strain GLP-1	Isolation and characterization of a mutant of Arthrobacter sp. strain GLP-1 which utilizes the herbicide glyphosate as its sole source of phosphorus and nitrogen	Pipke and Amrhein (1988)
	Arthrobacter atrocyaneus MCM B-425 and *Bacillus megaterium* MCM B-423,	Biomineralization of an organophosphorus pesticide, Monocrotophos, by soil bacteria	Bhadbhade et al. (2002)
Propamocarb hydrochloride	*B. amyloliquefaciens* IN937a *B. pumilus* SE34	Biodegradation of soil-applied pesticides by selected strains of plant growth-promoting rhizobacteria (PGPR) and their effects on bacterial growth	Myresiotis et al. (2012)
Thiamethoxam	*B. amyloliquefaciens* IN937a, *B. pumilus* SE34 *B. subtilis* FZB24	Biodegradation of soil-applied pesticides by selected strains of plant growth-promoting rhizobacteria (PGPR) and their effects on bacterial growth	Myresiotis et al. (2012)
2,4,Dichlorophenoxy acetic acid	*Aspergillus niger*	Metabolism of 2,4-Dichlorophenoxyacetic Acid ('2,4-D') by *Aspergillusniger* van Tiegh	Faulkner and Woodcock (1964)
	Cupriavidus pinatubonensis JMP134	Simultaneous assessment of the effects of an herbicide on the triad: rhizobacterial community, an herbicide degrading soil bacterium and their plant host	Kraiser et al. (2012)

waste (SMW), degrade the DDT (Purnomo et al. 2010b). Several pesticides were degraded through amide or ester hydrolysis mediated by the soil microorganism. Pentachlorobenzene was reduced to pentachloroaniline by specific microbes (Chacko et al. 1966).

Seo et al. (2007) reported five distinct bacterial strains (C3, C4, P1-1, JS14, and JS19b1) for degradation of polycyclic aromatic hydrocarbons (PAH). P1-1 can degrade carbofenothion, chlorfenvinphos, diazinon, fonofos, and pirimiphos-methyl. JS14 can transform chlorfenvinphos and diazinon. JS19b1 can break down diazinon, pirimiphos-methyl, and temephos. Other genera *Burkholderia* (Kang et al. 2003), *Pseudomonas* (Prabha and Phale 2003), *Sphingomonas* (Ye et al. 1996; Van Herwijnen et al. 2003) and *Stenotrophomonas* as Gram negative and *Mycobacterium* and *Rhodococcus* as Gram positive were so isolated and characterized for biodegradation of PAHs varying from two-ring PAHs to five ring PAHs (Beate et al. 1993; Moody et al. 2004). *Arthrobacter, Agrobacterium, Burkholderia, Enterobacter* (Cui et al. 2001; Johnsen et al. 2005; Bhadbhade et al. 2002; Pipke and Amrhein 1988) *Plesiomonas* and *Pseudomonas* (Horne et al. 2002a, b) have ability to degrade of a highly toxic and powerful inhibitory acetylecholinesterase organophosphorus pesticides (OPS) such as chlorpyrifos (Singh et al. 2003), coumaphos, diazinon, fenitrothion monocrotophos and parathion (Cui et al. 2001) (Table 3). Barragan-Huerta et al. (2007) isolated *Pseudomonas aeruginosa, P. putida, Stenotrophomonas maltophilia, Flavimonas oryzihabitans,* and *Morganella morganii* from coffee beans and identified as pesticide-degrading microorganism. *P. aeruginosa* and *F. oryzihabitans* have ability to degrade the DDT and endosulfan (Barragan-Huerta et al. 2007). Degradation of methomyl by the novel bacterial strain *Stenotrophomonas maltophilia* M1 observed by Mohamed (2009). Ortiz-Hernández and Sánchez-Salinas (2010) isolation *Stenotrophomonas malthophilia, Proteus vulgaris, Vibrio metschinkouii, Serratia ficaria, Serratia* spp. and *Yersinia enterocolitica* from agricultural soils and characterized as tetrachlorvinphos {phosphoric acid, ethenyl dimethyl ester 2-chloro-1-(2,4,5-trichlorophenyl)} degrading bacteria.

Matsumura and Boush (1966) isolated various microorganisms from the agricultural soils of northern Ohio, which have the ability for degradation of malathion through the action of a carboxylesterase. The cleavage of the aromatic ring is a common reaction when soil microorganisms degrade pesticide which is not usually encountered in higher animals. Thomas and Parkins (1995) categorized atrazine degraders into two groups; one degrades the side chains and other degrades the rings. Few microorganisms can condense or conjugate pesticides (Burchfield and Storrs 1957). Several recent studies have been reported that the different microbial strains have different potential for pesticide degradation in lab and field condition (Table 3). Ibrahim et al. (2014) reported that Cyanobacteria showed significant degradation of malathion. Similarly Liming et al. (2014) observed that the *Pseudomonas* sp. strain WBC-3 showed efficient degradation of methyl parathion (Table 3). The *Burkholderia* spp., *Achromobacter* spp., *Alcaligenes* spp., *Ralstonia* spp., and *Rhodanobacter* spp. bacterial species have the ability for rapid degradation of aromatic hydrocarbons (Bacosa et al. 2010, 2013). The degradation of n-hexadecane by a microbial consortium in the presence of electric field in soil has been evaluated up to 53.7 %, and it can be enhanced by 20.3 % without electric field. The mechanism of n-hexadecanoic acid what supposed to be intracellular β-oxidation (Yuan et al. 2013). Thus, the availability of such microbes under pesticide stress may provide efficient, cheaper and environmentally friendly solution for bioremediation of xenobiotic contaminated soil (Pallud et al. 2004).

4 Molecular approaches for pesticide degradation

The microbial degradation of pesticide involves various types of enzyme. These methods are based on various types of genes coded with plasmid or chromosomal DNA. Pesticidal degradative genes in microbial strains have been found to be located on plasmids, transposons, and/or on chromosomes. Current studies have provided clues to the evolution of degradative pathways and the organization of catabolic genes, thus making it much easier to develop genetically engineered microbes for the purpose of pesticide degradation. Genetically engineered microorganisms have substantial ability to degrade the pesticide because they secrete various specific enzymes which have a specific catabolic gene into plasmids. The recombinant DNA studies have made it

possible to develop DNA and RNA probes that are being used to identify microbes from diverse environmental communities with a unique ability to degrade pesticides (Kumar et al. 1996). With the help of quantitative measurements of soil DNA and RNA; Bælum et al. (2008) inferred that the repeated application of the soil herbicide MCPA (2-methyl-4-chlorophenoxyacetic acid) resulted in an increased population of microorganisms that could degrade the compound. Similarly, Lancaster et al. (2010) applied five rounds of the herbicide glyphosate to soil and found that the microbial biomass incorporated the herbicide faster after four rounds of applications.

4.1 Mechanism of enzyme based pesticide degradation by microbes

Pesticide degradation is a process that involves the complete rupture of an organic compound into inorganic constituents of pesticide by pesticide degrading microbes.. The biodegradation involves transferring the substrates and products within a well-coordinated microbial community, a process referred to as metabolic cooperation under natural environments (Abraham et al. 2002). Enzyme based pesticide degradation process is an innovative treatment technique for removal of pesticide from polluted environments. Fungi and bacteria are considered as the extracellular enzyme-producing microorganisms for degradation of pollutant. White rot fungi have been used as promising bioremediation agents, especially for compounds not readily degraded by bacteria. The production and secretion of extracellular enzymes in microbes by environmental effects could be of interest. Some of these extracellular enzymes are involved in lignin degradation, such as lignin peroxidase, manganese, peroxidase, laccase and oxidases. Several microbial strains that degrade pesticide have been listed in Table 4. Transferases, isomerases, hydrolases and ligases enzymes are responsible for the biodegradation of the pesticides. These enzymes catalyze metabolic reactions including hydrolysis, oxidation, addition of an oxygen to a double bound, oxidation of an amino group (NH_2) to a nitro group, addition of a hydroxyl group to a benzene ring, dehalogenation, reduction of a nitro group (NO_2) to an amino group, replacement of a sulfur with an oxygen, metabolism of side chains, ring cleavage.

The metabolism of pesticides involves three phase process; in first phase process the initial properties of a parent compound are transformed through oxidation, reduction, or hydrolysis to generally produce a more water-soluble and usually a less toxic product than the parent, in second phase process involves conjugation of a pesticide to a sugar or amino acid, which increases the water solubility and reduces toxicity compared with the parent pesticide, and in third phase process helps in conversion of second phase metabolites into secondary conjugates, which are also non-toxic. In these processes fungi and bacteria are involved producing intracellular or extra cellular enzymes including hydrolytic enzymes, peroxidases, oxygenases, etc. (Van Herwijnen et al. 2003; Ortiz-Hernández et al. 2011).

Hydrolases are a broad group of enzymes which helps in pesticide biodegradation. It catalyzes the hydrolysis of several major biochemical classes of pesticide (esters, peptide bonds, carbon–halide bonds, ureas, thioesters, etc.) (Scott et al. 2008). Organophosphate hydrolases (OPH or Phosphotriesterase) enzyme isolated from *Pseudomonas diminuta* and *Flavobacterium* sp. (Table 4). The first isolated phosphotriesterase belongs to the *Pseudomonas diminuta* strain MG, this enzyme encoded by a gene called *opd* (organophosphate-degrading) and shows a highly catalytic activity towards organophosphate pesticides. These enzymes specifically hydrolyze phosphoester bonds, such as P–O, P–F, P–NC, and P–S (Ortiz-Hernández et al. 2003). Other microbial enzymes such as organophosphorus hydrolase (OPH; encoded by the *opd* gene), methyl-parathion hydrolase (MPH; encoded by the *mpd* gene), and hydrolysis of coroxon (HOCA; encoded by the *hocA* gene), were isolated from *Flavobacterium* sp. (Sethunathan and Yoshida 1973), *Plesimonas* sp. strain M6 (Cui et al. 2001) and *Pseudomonas moteilli* (Horne et al. 2002a, b), respectively.

Esterase have been cloned and proteins have sequenced from several microorganism, e.g. two ferulic acid esterases from *Aspergillus tubingensis*, a cephalosporin esterase from the yeast *Rhodosporidium toruloides*, a chrysanthemic acid esterase from *Arthrobacter globiformis*, and several other esterase from *Pseudomonas fluorescens* strain. These enzymes used for biodegradation of various types of organophosphate, and other herbicide and insecticide. Cytochrome P450 oxidoreductases helps in degradation of

Table 4 Pesticide degrading enzyme of various microbial strains and their co factors

Enzyme	Cofactor requirements	Source organism(s)	Documented target pesticide(s)	Current bioremediation strategies employed
Oxidoreductases				
Gox	Flavin (FAD)	*Pseudomonas* sp LBr; *Agrobacterium* strain T10	Glyphosate	In plant
Monooxygenases				
Esd	Flavin and NADH	*Mycobacterium* sp.	Endosulfan and Endosulfate	Not yet in use
Ese	Flavin (FMN)	*Arthrobacter* sp	Endosulfan and Endosulfate	Not yet in use
Cyp1A1/1A2	Heme and NADH	Mammalian (Rat)	Atrazine, Norfl urazon and Chlortoluron	In plant
Cyp76B	Heme and NADH	*Helianthus tuberosus*	Linuron, Chlortoluron and Isoproturon	In plant
P450	Heme and NADH	*Pseudomonas putida*	Hexachlorobenzene and Pentachlorobenzene	Transgenic *Sphingobium chlorophenolicum*
Dioxygenase				
TOD	Fe^{2+} and NADH	*Pseudomonas putida*	Trifl uralin herbicides	Not yet in use against Pesticides
E3	None	*Lucilia cuprina*	Synthetic pyrethroids and phosphotriester insecticides	Not yet in use
Phosphodiesterases				
PdeA	None	*Delftia acidovorans*	Organophosphorus compounds	Free-enzyme bioremediation
Phosphotriesterases				
OPH	Fe2+ and Zn2+	*Agrobacterium radiobacter*	Insecticides phosphotriester	Free-enzyme bioremediation
OpdA	Fe2+ and Zn2+	*Pseudomonas diminuta* *Flavobacterium* sp.	Parathion, methyl parathion, malathion, coumaphos, others	
Phosphonatase				
Phn	None	*Escherichia coli* *Sinorhizobium meliloti*	Organophosphorus compounds	
Haloalkane dehalogenase				
LinB	None	*Sphingobium* sp.; *Sphingomonas* sp	Hexachlorocyclohexane (β− and δ− isomers)	Bioaugementation with *Sphingobium indicum*
AtzA	Fe2+	*Pseudomonas* sp. ADP	Chloro-s-triazine herbicides	In plant and GM bacteria
TrzN	Zn2+	*Nocardioides* sp.	Chloro-s-triazine herbicides	Not yet in use
LinA	None	*Sphingobium* sp.; Shingomonas sp.	Hexachlorocyclohexane (γ-isomer)	Bioaugementation with *Sphingobium indicum*

Table 4 continued

Enzyme	Cofactor requirements	Source organism(s)	Documented target pesticide(s)	Current bioremediation strategies employed
TfdA	α- ketoglutarate and Fe	*Ralstonia eutropha*	2,4-dichlorophenoxyacetic acid and pyridyl-oxyacetic	Not yet in use
DMO	NADH and a Rieske Fe–S centre	*Pseudomonas maltophilia*	Dicamba	Not yet in use
C–P-lyase				
Glp A&B	None	*Pseudomonas pseudomallei*	Organophosphorus compounds	Not yet in use
ND				
hocA	None	*Pseudomonas monteilli*	Organophosphorus compounds	Not yet in use
mpd	None	*Pseudomonas*	Organophosphorus compounds	Not yet in use

Source: Singh and Walker (2006), Scott et al. (2008), Riya and Jagatpati (2012)

atrazine, norflurazon and chlortoluron from soils. Cytochrome CYP76B1 isolated from *Helianthus tuberosus* was cloned into tobacco and Arabidopsis. This enzyme has capability to catalyse the oxidative dealkylation of phenylurea herbicides such as linuron, chlortoluron and isoproturon (Didierjean et al. 2002). Prokaryotic cytochrome P450 s isolated from *Pseudomonas putida* (Chen et al. 2002) and *Sphingobium chlorophenolicum* have great potential to degrade chlorinated pentachlorobenzene and hexachlorobenzene (Yan et al. 2006). Toluene dioxygenases (TOD) enzyme isolated from *P. putida* F1 that is highly used as degradation of toluene, polychlorinated hydrocarbons, ethylbenzene and p-xylene (Table 4).

Haloalkane dehalogenases (Dh1A) enzyme incoded gene *LinB* isolated from *Xanthomonas thobacter autotrophicus* GJ10; haloacetate dehalogenase (DehH1) from *Moraxella* sp.B; and 2-hydroxymuconic semialdehyde hydrolase (DmpD) from *Pseudomonas* sp. CF600 which is responsible for degradation of hexachlorocyclohexane (HCN). Oxidoreductase is an enzyme that catalyses oxidation and reduction reaction. It is important enzyme like glyphosate oxidase (GOX) for glyphosate degradation. This enzyme is a flavoprotein amine oxidase from *Pseudomonas* sp. LBr that catalyses the oxidation of glyphosate to form aminomethylphosphonate (AMPA) and releases the keto acid glyoxylate (Scott et al. 2008).

Mycobacterium tuberculosis ESD strains secrete endosulfan monooxygenase II enzyme which degrade the beta-endosulfan to the monoaldehyde and hydroxyether but transforms alpha-endosulfan to the more toxic endosulfan sulfate. Alternatively, hydrolysis of endosulfan in some bacteria (*Pseudomonas aeruginosa*, *Burkholderia cepaeia*) yields the less toxic metabolite endosulfan diol (Kumar et al. 2007). Endosulfan can spontaneously hydrolyze to the diol in alkaline conditions, so it is difficult to separate bacterial from abiotic hydrolysis. *Phanerochaete chrysosporium* and *T. versicolor* have ability to degrade simazin, dieldrin and trifluralin pesticides independently by laccase activity (Magan and Fragoeiro 2005).

4.2 Mechanism of catabolic based pesticide degradation by microbes

The pesticide has been degraded by various microbial strains for detoxification of pollutant that may be used

as energy source. The ubiquitous nature of microbes on the earth has capability to catalyze the mechanism of pesticide degradation (Paul et al. 2005). The microbes degrade toxic material because they have some specific genes in their genetic material (chromosomal or plasmid DNA) (Table 5). First catabolic plasmid DNA was isolated from *Pseudomonas putida* as CAM plasmid. This plasmid controls the oxidation of the naturally occurring terrene and camphor (Rheinwald et al. 1973). Such catabolic plasmid with encoded gene degrades the synthetic molecules. The plasmid (pJP1) encoded with gene degrades the notorious organochlorine herbicide 2, 4-D (Pemberton and Fisher. 1977). The intensively studied 2,4-D plasmid (pJP4) isolated by *Ralstonia eutropha* strains JMP134 have very broad host range and one or more clusters of degradative genes have been encoded for the degradation of the organochlorines 2,4-D and 3-chlorobenzoate (3-CBA) (Pemberton and Schmidt 2001). In certain cases these catabolic gene clusters occur within transposable elements and therefore each one move unfettered among plasmids and the main chromosome. *Ralstonia eutropha* (Tn4371), *Burkholderia cepacia* (Tn5530), *Pseudomonas putida* (Tn4654) and *Alcaligenes* sp. (Tn5271) have various transposan for degradation of biphenyl 4-chlorobiphenyl, 2,4-D, Toluene, 3-Chlorobenzoate and Carbofuran, respectively (Table 5). The evolution of microbial genes involved in the biodegradation of xenobiotic molecules could be a powerful and positive development in the fight against environmental pollution.

4.3 Catabolic bio-degradation pathway and its operon system

Catabolism of aromatic compounds in bacteria has revealed that the various enzymes (e.g. monooxygenase, dehydrogenase, hydrolase, oxygenase and isomarase etc.) involve for conversion of toxic chemical of pesticide into various intermediate product such as protocatechuate and (substituted) catechols (Clarke 1984; Gibson and Subramanian 1984; Reineke 1984; Fewson 1988; Reineke and Knackmuss 1988; Commandeur and Parsons 1990; Chaudhry and Chapalamadugu 1991). These dihydroxylated intermediates (protocatechuate and catechols) are directly enter into one of two possible pathways, either a meta cleavage-type or an ortho cleavage-type pathway which supply central metabolic routes such as the tricarboxylic acid cycle (Harayama et al. 1989; van der Meer et al. 1992) (Fig. 3). The aromatic ring fission catalysed by dioxygenases enzyme of these pathways occurs between the hydroxyl groups (intradiol or ortho cleavage), or adjacent to one of the hydroxyls (extradiol or meta cleavage) (Fig. 3). Meta cleavage pathways such as; the lower pathway on plasmid pWWO, pNAH7 and VI150 (from a *Pseudomonas* strain that uses phenol, cresols and 3,4-dimethylphenol as sole carbon and energy sources) show homology for similar cleavage. Such meta-cleavage pathways degrade the methylated catecholic substrates. The TOL plasmid pWW0 isolated from the *Pseudomonas putida* has various gene and encodes a set of enzymes involved in the conversion of toluene and xylenes to their carboxylic acid derivatives. TOL plasmids are self-transmissible and contain two or more operons which encode enzymes required for the degradation of methylbenzenes, such as toluene, xylenes, and 1, 2, 4 trimethylbenzene, via methylbenzoates (Williams and Worsey 1976; Frantz and Chakrabarty 1986; Burlage et al. 1989; Harayama et al. 1989; Assinder and Williams 1990; Harayama and Rekik 1990; Saint et al. 1990). The pathways of TOL degradation consist two parts: first one is upper pathways that have skill to convert toluene and xylene into carboxylic acid derivatives (Harayama et al. 1989) and second one is a lower (or meta-cleavage) pathway transfer the carboxylic acid to the precursors of Krebs cycle intermediates (Harayama and Rekik 1990).

The TOL plasmid pWW0 bears one operon (xylCMABN) of upper-pathway which encodes for secretion of benzaldehyde dehydrogenase (xylC), xylene monooxygenase (xylMA), benzyl alcohol dehydrogenase (xylB) enzymes and the gene xylN is an outer membrane porin involves in m-xylene uptake. These enzymes oxidize methylbenzenes to methylbenzoates (Harayama et al. 1986, 1989) that is the upper pathway, while the "lower-pathway" includes meta operon having 13 genes. These genes encoded by the operon (xylXYZLTEGFJQKIH) are responsible for conversion of methylbenzoates to pyruvate, acetaldehyde, and acetate via (methyl) catechols (Franklin et al. 1983; Harayama and Rekik 1990) (Fig. 4). The gene xylXYZ (benzoate dehydrogenase), xylT (ferredoxin) xylE (catechol 2,3-oxygenase), xylG (2-hydroxymuconic semialdehyde dehydrogenase), xylF (2-hydroxymuconic semialdehyde), xylJ (2-Oxopent-

Table 5 Pesticide degrading gene found in plasmid/chromosome of various microbial strains

Bacterium	Substrate degraded	Gene	Location	Reference
Alcaligenes eutrophus	2,4-D	*tfdA/tfdB/tfdC/tfdD/tfdE/tfdF/tfdR*	Plasmid and Chromosomal	Don and Pemberton (1981)
Alcaligenes sp.	PCB	*bphA/bphB/bphC/bphD*	Plasmids	Shields et al. (1985)
Alcaligenes faecalis AFK2	Phenanthrene	*phnAa/phnAc/phnAd/ phnB/phnC/phnD/phnE/ phnF/phnG phnH/phnI*	Plasmid	Habe and Omori (2003), Chauhan et al. (2008)
Arthrobacter keyseri 12B	Pthalate	*ptrD/ptrA/ptrB/ptrC/phtAa/phtAb/ phtAc/Phtad*	Plasmid	Vamsee and Phale (2008)
Burkholderia PS12	1,2,4,5-tetrachlorobenzene	*tecAB*	Plasmids	Beil et al. (1999)
Comamonas testosterone T-2	Paratoluenesulfonicacid	*tsa*	Plasmid	Tralau et al. (2001)
Nocardioides KP7	Phenanthrene	*phd*	Chromosome	Habe and Omori (2003)
Pseudomonas putida	Napthalene	*pahA/pahAb/pahB/pahC/pahD/pahE/ pahF*	Chromosome	Habe and Omori (2003), Chauhan et al. (2008)
Sphingomonas sp. P2	Biphenyl, Napthalene, Phe naphthalene, Anthacene, Dibenzofuran, Fluorene, Fluroranthene, Pyrene	*ahd, bph, nah, xyl,*	No report	Pinyakong et al. (2000, 2003)
Sphingobium yanoikuyae B1	Tolune, Xylene, Biphenyl, Naphthalene	*bph/nap/xyl*	Chromosome	Gibson et al. (1973), Zylstra and Kim (1997), Gibson (1999)
Sphingobium yanoikuyae Q1	Tolune, Xylene, Biphenyl, Naphthalene,	*bph*	Chromosome	Furukawa et al. (1983)
Sphingobium sp. LB126	Fluorene	*fld*	No report	Bastiaens et al. (2000), Wattiau et al. (2001)
Sphingobium agrestis HV3	Tolune, Napthalene	*cmp*	Plasmid	Klipi et al. (1980), Yrjala et al. (1997)
Sphingomonas paucimobilis Var.EPA505	Pyrene	*pbhD*	Chromosome	Kanaly and Harayama (2000)
Sphingobium indicum B90A	HCH	*linA/linA2/linX1 linB/linC/linX2/linX3*	Chromosome	Malhotra et al. (2007)
Sphingomonas paucimobilis Var.EPA505	Pyrene	*pbhD*	Chromosome	Kanaly and Harayama (2000)
GMMs degrading organic compound				
Burkholderia cepacia L.S.2.4	Toluene	pTOD plasmid	Plasmid	Barac et al. (2004)

Table 5 continued

Bacterium	Substrate degraded	Gene	Location	Reference
Burkholderia cepacia VM1468	Toluene	pTOM-Bu61 plasmid	Plasmid	Taghavi et al. (2005)
Escherichia coli AtzA	Atrazine	Atrazine chlorohydrolase	Gene	Strong et al. 2000)
Pseudomonas fluorescens HK44	Naphthalene	luxCDABE	Gene	Sayler et al. (2000)
Pseudomonas putida KT2442(Pnf142::TnMo-d-OTc)	Naphthalene	pNF142 plasmid, gfp	Plasmid	Filonov et al. (2005)
Pseudomonas fluorescens F113rifpcbrm BP 1::gfp-mut 3	Chlorinated biphenyls	Operon bph, gfp	Plasmid	Boldt et al. (2004)

4-enoate hydratase), xylQ (acetyl dehydrogenase), xylK (4-Hydroxy-2-oxovalerate aldolase), xylI (4-Oxalocrotonate decorboxylate) and xylH (4-Oxalocrotonate tautomerase) encoded by respective enzymes are the part of meta cleavage pathway (Fig. 4). Catabolic pathways are controlled by specific regulatory proteins, which recognize inducer molecules and interact with promoter-operator regions of the catabolic operons. In the TOL-encoded pathways, xylR and xylS coordinately regulate the full transcription of the xyl operons (Spooner et al. 1986; Nakazawa et al. 1990). xylR is responsible for activation of regulatory gene while the xylS only activate the lower pathway for the degradation of toluene and xylene polyaromatic hydrocarbon (Holtel et al.1990).

The modified ortho cleavage pathwayshelps for catabolism of chlorobenzoates, chlorobenzene and chlorophenoxyacetate which produce chlorinated catechol intermediates. These are dealt with plasmid-borne gene (Harwood and Parales 1996); tfd pathway for the degradation of 2,4-D carried by pJP4 plasmid which was isolated from the bacterial strains *Alcaligenes eutrophus* JMP134 (*Ralstonia eutropha*). The size of plasmid is 88 kb which is a self-transmissible broad—host—range, catabolic plasmid. The five operons are responsible for ortho-cleavage pathway. The largest operon is tfdCDEF and tfdCIIDIIEIIFII which contain genes of a modified ortho cleavage pathway (Fig. 5). tfdA, tfdB and tfdBII also encode enzymes, while tfdK encodes a transporter protein involved in the uptake of 2,4-D (Pemberton and Schmidt 2001). The *tfdA* gene encodes a dioxygenase that converts 2, 4-D to 2, 4-dichlorophenol (Fukumori and Hausinger 1993). The *tfdB* gene encodes a 2, 4-dichlorophenol monooxygenase that hydroxylates 2, 4-dichlorophenol to 3, 5dichlorocatechol (Perkins et al. 1990). Two different gene clusters, *tfdC*I*DIEIF*I and *tfdD*II*C*II*E*II*F*II, encode enzymes for the catabolism of chlorocatechols to 3-oxoadipate (Fig. 5). The enzymes from both modules are active during degradation of 2, 4-D (Leveau et al. 1999; Laemmli et al. 2000) and 3-CB (Pelrez-Pantoja et al. 2000). Two identical regulatory genes, *tfdR* and *tfdS* control the whole function of operons (Matrubutham and Harker 1994). According to Genthner et al. (1989) the order of degradability of monochlorophenol was meta > ortho > para. Themel et al. (1996) reported anaerobic dehalogenation of 2-chlorophenol, a common intermediate of polychlorophenol degradation, by mixed

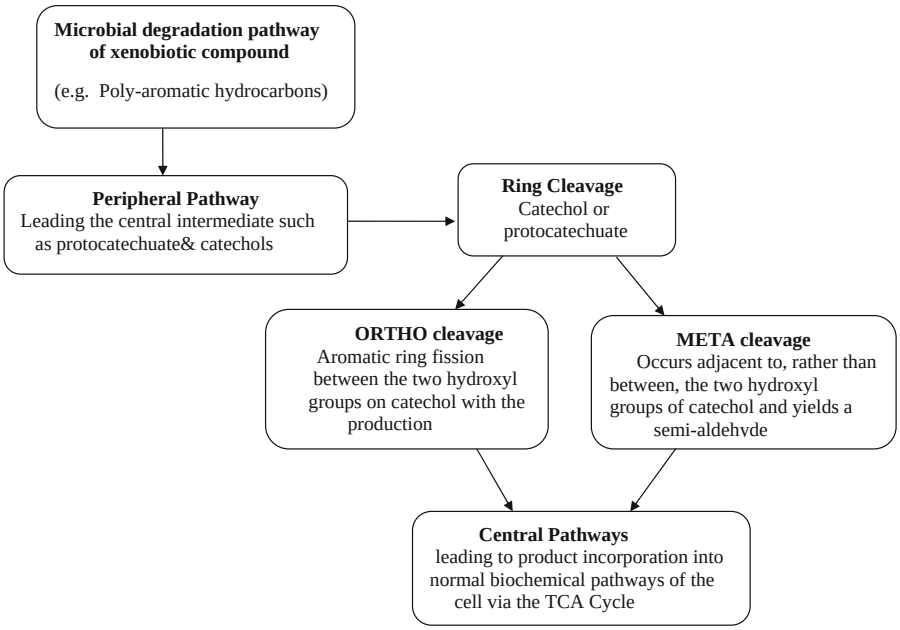

Fig. 3 Microbial degradation pathway of xenobiotic compound

bacterial cultures. Masunaga et al. (1996) proposed dechlorination pathway of chlorophenols in contaminated sediment (Table 6).

5 Genetically modified microbes (GMMs) for pesticide degradation

For more than a century, microbes have been consciously introduced into the environment for specific purposes. The scientists have attempted to produce microbes or plants with enhanced capability to degrade toxic compounds and organic pollutants in the environment. Biodegradation is largely considered as a less expensive alternative to physical and chemical disposal of pollutants (Amarger 2002). Current knowledge on microbial genetics allows us to construct new strain with exciting capabilities. Such genetically modified microorganisms (GMMs) have been postulated to be applicable in agriculture for effective degradation of pesticides, control of plant pathogen (biocontrol), and to improve plant growth (biofertilizers) (Amarger 2002). Wasilkowski et al. (2012) stated that the combination of conventional microbiology, biochemistry, ecology and genetic engineering is a very effective tools and techniques for in situ bioremediation. Several reports showed that GMMs had higher tendency to crumble of various organic pollutant as compared with natural or indigenous strains (Cases and de Lorenzo 2005).

Kuritz and Wolk (1995) reported that the two cyanobacteria have natural ability to degrade a highly chlorinated aliphatic pesticide and lindane (gamma-hexachlorocyclohexane). Studies have shown that such abilities may be enhanced by genetic engineering to degrade another chlorinated pollutant, 3-chlorobenzoate. The genetically engineered *E. coli* degrades organophosphate pesticides with surface-expressed organophosphorus hydrolase (Mulbry and Kearney 1991; Chen and Mulchandani 1998). A novel approach to convalescing the capability of soil microbes to degrade 2,4-D was by natural conjugative transfer of plasmids encoding degradation ability (Top et al. 1998). *E. coli* with plasmids were introduced to 2,4-D contaminated soil and transfer of the plasmids to indigenous soil bacteria established, with augmented consumption of 2,4-D.

When GMMs are introduced in field condition, then, so many biotic and abiotic factors affect their survival in nature. Among the physiological factors; high clay content, high pH and relatively high moisture content can have a positive effect on

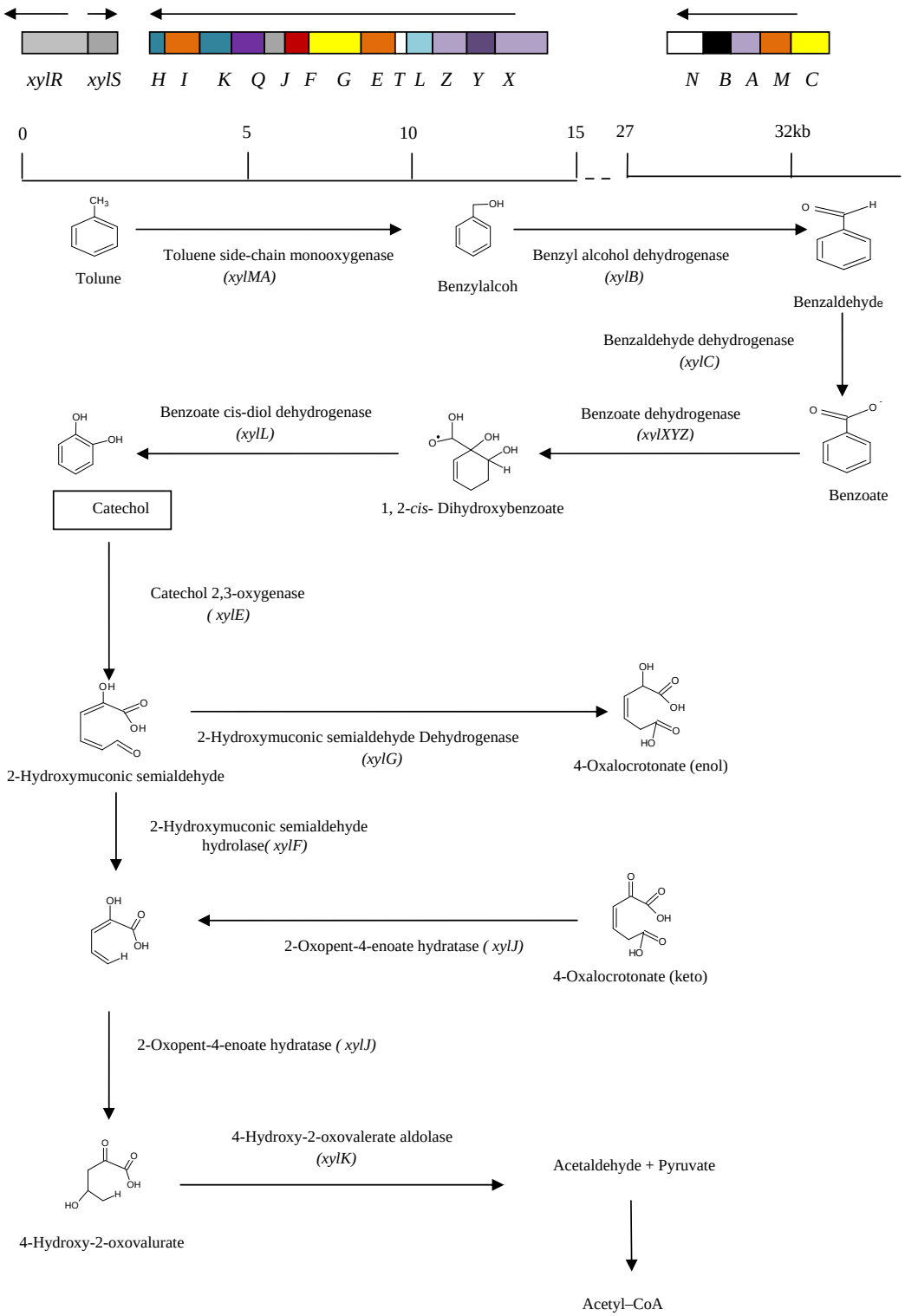

Fig. 4 Meta-cleavage pathway of organic pollutant (e.g. Toluene). Adopted from Pemberton and Schmidt (2001)

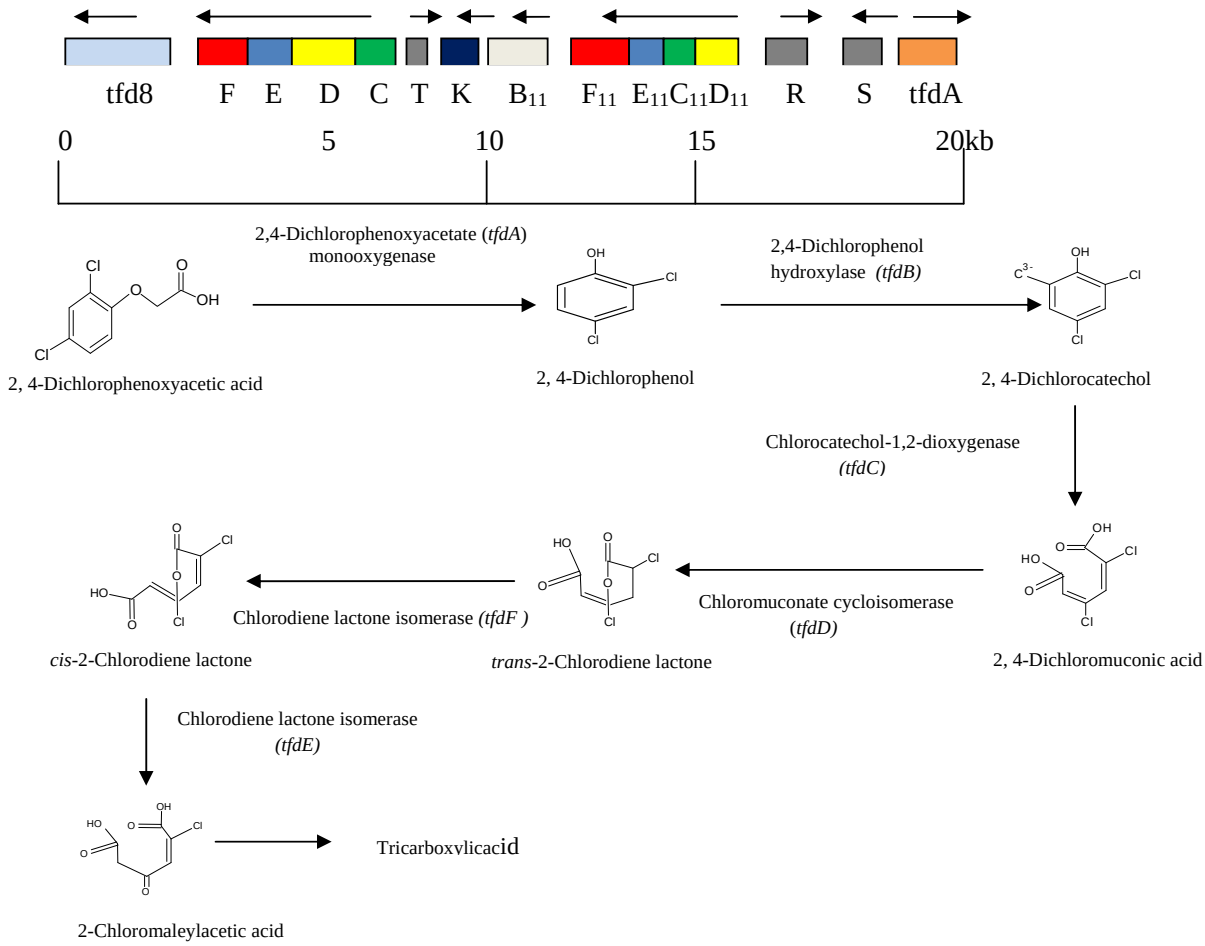

Fig. 5 Ortho-cleavage pathway for degradation of pesticide (e.g. 2,4-Dichlorophenoxy). Adopted from Pemberton and Schmidt (2001)

Table 6 Few examples of catabolic transposons

Bacterium	Phenotype (substrate degraded)	Transposon	Reference
Pseudomonas sp. (pP51)	Chlorobenzene (CB)	Tn5280	Van der Meer et al. (1991)
Alcaligenes sp. strain BR60	Chlorobenzoates	Tn5271	Nakatsu et al. (1995)
P. putida ML2 (pHMT112)	Benzene	Tn5542	Tan (1999)
R. eutropha NH9 (pENH91)	3CBA	Tn5707	Tan (1999)
P. putida mt-2 (pWWO)	Toluene, xylene	Tn4651	Tsuda et al. (1999)
P. putida mt-2 (pWWO)	Toluene, xylene	Tn4653	Tsuda et al. (1999)
P. putida MT53 (pWW53)	Toluene, xylene	Tn4656	Tsuda et al. (1999)
P. putida G7 (NAH7)	Naphthalene	Tn4655	Tsuda et al. (1999)
R. oxalatica A5	Biphenyl/4-chlorobiphenyl	Tn4371	Merlin et al. (1999)
Ralstonia eutropha A5	(Chloro)biphenyl	Tn4371	Springael et al. (2001)
P. putida KF715	Biphenyl/salicylate	bph-sal element	Nishi et al. (2000)
Pseudomonas sp. B13	Chlorocatechol	clc element	van der Meer et al. (2001)
Burkholderia cepacia 2a (pIJB1)	2,4-dichlorophenoxyacetate	Tn5530	Poh et al. (2002)

microbial survival (Da and Deng 2003; Heijnen et al. 1988; Van Elsas et al. 1986). Factors that negatively affect the number of introduced microes include; dry periods, presence of competing microorganisms, and predation by protozoa and lysis by bacteriaophage (Ashelford et al. 2000; Eberl et al. 1997; Johansen et al. 2002). On the other hand, GMMs could evolve and adapt to the prevailing environmental conditions via natural selection. Velicer (1999) reported that the evolutionary adaptation of microorganism to degrade the herbicide 2,4-dichlorophenoxyacetic acid could result in increased competitive fitness to use succinate as a substrate. Although an innumerable of different GM strain has been constructed for bioremediation but their successful applications in the field are rare (Haro and de Lorenzo 2001; Morrissey et al. 2002; Van Limbergen et al. 1998). Moreover, difficulties to scale up the laboratory experiments, low bioavailability of compound, and legislative problems with applying GM strain have precluded wide-scale use.

Halden et al. (1999) studied that the degradation of 3-phenoxybenzoic acid in soil and could increase GMM survival and 3-phenoxybenzoic acid degradation six orders of magnitude by adding phosphate and nitrogen. An example of a field scale remediation is the study of Strong et al. (2000), *P. fluorescens* HK44 with a lux gene fused to a naphthalene-degradative pathway and it was the first GM strain approved for field release in the US (Ripp et al. 2000; Strong et al. 2000). *P. fluorescens* HK44 having pUTK21plasmid, which was made by transposon Tn4431insertion into NAH7 plasmid from *P. fluorescens* 5R. This transposon originated from *Vibrio fischeri* which having luxCDABE gene cassette (Sayler and Ripp 2000). The other GMM strain e.g. *P. putida* KT2442 (pNF142::Tn*Mod*-OTc) have ability to degrade naphthalene in soil (Filonov et al. 2005). *P. putida* KT2442 has been constructed by three strains of *Escherichia coli* S17-1 with pTn*Mod*-OTc plasmid (carrying tetracycline resistance gene), *Pseudomonas* sp. 142NF (pNF142) able to degrade naphthalene and *P. putida* KT2442 with *gfp* gene localized in chromosome. Other study, Lipthay et al. (2001) reported the degradation of 2,4-dichlorofenoxyacetic acid (2,4-D) by bacteria *Ralstonia eutropha* and *Escherichia coli* HB101 carrying pRO103 plasmid which having gene encoding 2,4-dichlorophenoxyacetic acid/2-oksoglutaric dioxygenase. GMM *R. eutropha* (pRO103) showed significant degradation of 2,4-D in soil. Similarly, Rodrigues et al. (2006) developed two genetically modified strains *Rhodococcus* sp. RHA1 (pRHD34::*fcb*) and *Burkholderia xenovorans* LB400 (pRO41) for degradation of mixture of PCBs and Aroclor 1242 in soil. A combined inoculation of microorganism and its host plant by providing extra nutrients could enhance microbial survival and activity (Brazil et al. 1995). Such use of a dual microorganism-plant system, in which the plant supports microbial growth and the microorganism performs the bioremediation is known as rhizoremediation (Kuiper et al. 2004; Yee et al. 1998).

The GMMs have been used for successful bioremediation of pollutants in soil and water under laboratory scale; however, field applications are limited. Long term field studies are now needed to evaluate their effectiveness. Transfer of genetic material from GMOs to indigenous micro-organisms can have an environmental impact as it alters genotypic diversity. Its genotypic diversity results in unanticipated changes in the phenotypic expression of the recipient micro-organism(s) that may have a harmful impact on the environment (Doyle et al. 1995). According to Singh et al. (2011); application of GE bacteria based remediation of various heavy metal pollutants is in the forefront due to eco-friendly and lesser health hazards compared to physico-chemical based strategies, which are less eco-friendly and hazardous to human health. *P. putida* SM1443 carrying a 2,4-D degradative plasmid pJP4 was used as the donor strain. The bioaugmented aerobic granule system with *P. putida* SM1443 gained 2,4-D degradation ability faster and maintained a more stable microbial community than the control in the presence of 2,4-D under fed batch test (Quan et al. 2010). Nancharaiah et al. (2008) first studied bioaugmentation of aerobic microbial granules with *P. putida* carrying a TOL plasmid in batch tests and observed a significant increase in the degradation of benzyl alcohol. Therefore, the GMMs can be applied not only in degradation of pesticide and toxic compounds but also in promotion of plant growth. Generally, plant growth-promoting bacteria (PGPB) are not competent for promotion of plant growth in the existence of various toxic compounds (Cases and de Lorenzo 2005; Davison 2005; Pimentel et al. 2011). Due to this, Yang et al. (2011) attempted to design genetically modified bacteria strain P13 which have ability to promote maize growth as well as degrade phenol. This strain

had been development by recombination of *Pseudomonas aeruginosa* SZH16 and *Pseudomonas fluorescens by* horizontal gene transfer methods.

In Indian scenario; each technology developer is required to have their own Institutional Bio Safety Committee (IBSC) which must include at least one member appointed by the Department of Biotechnology (DBT). The IBSC'sformulate requests for approval for testing, which goes to the Research Committee on Genetic Modification (RCGM). This is the responsibility of DBT and includes representatives from the Ministries of Health, Science and Technology (the parent Ministry for DBT) and Agriculture. The RCGM can approve field trials and other tests and reviews reports on these tests for further action. Approvals for commercial releases must come from the Genetic Engineering Approval Committee (GEAC) which is chaired by the Ministry of the Environment and includes representatives from the Ministries of Health, Science and Technology and Agriculture. To date; India has approved Bt cotton for commercial use in India (March 2002). There is still some discussion within India, on how to treat applications for food approvals in respect to imported commodities. Since this happens rarely in India, hence, the system is not yet defined completely.

6 Role of indigenous microbes for pesticide degradation and plant growth promotion

The indigenous microbes are native microorganism which is isolated from the local environmental sample. These microbes have capability to grow very fast in certain environment and perform their potential for pesticide degradation and plant growth promotion ability. The bioaugmentation (introduction of specific competent microorganisms) has been well thought-out a valuable tool for increasing the rate and extent of biodegradation of pesticide pollution (Coppotelli et al. 2008). The combined inoculation of competent and indigenous microbes directly isolated from the same soil is often called as bioaugumentation (Phelps et al. 1994; Otte et al. 1994). Many studies have shown that biotic and abiotic environmental factors influence the effectiveness of bioaugmentation (Mrozi and Piotrowska-Sege 2010). Therefore, it would be more practical when using bioaugmentation to use autochthonous microorganisms (Hosakawa et al. 2009). Autochthonous bioaugmentation (ABA) is defined as a bioaugmentation technology that uses microorganisms indigenous to the site (soil, sand and water) to be decontaminated (Ueno et al. 2007).

In India, farmers use the pesticide for crop production but they are not known about their toxic effects for environmental pollution as well as loss of soil fertility and health (Fig. 6). For minimization of soil pollution and soil toxicant in agricultural field, degradation of pollutants with indigenous microbial consortia could be very useful because they easily survive and multiply in same environmental condition (Wang et al. 2005). Large numbers of bacteria that are able to degrade carbamate pesticides have been isolated from soil around the world (Desaint et al. 2000). Isolation of indigenous bacteria capable of metabolizing organophosphate compounds has received considerable attention because such bacteria provide an environmentally friendly method of detoxification (You and Liu 2004; Wang et al. 2005; Wood 2008). Large numbers of indigenous microorganisms have been used in many studies for the removal and detoxification of toxicants from the certain environments (Desaint et al. 2000; Wang et al. 2005). The use of various microorganisms to enhance the rate of biodegradation as well as plant growth promoting activities (production, plant growth hormones biological nitrogen fixation, phosphate solubilization, hydrogen cyanide, siderophore and antagonistic properties) are well documented in various studies (Glick 1995; Vessey 2003; Sakamoto and Tsutsumi 2004; Verma et al. 2012; Isaac et al. 2013) (Fig. 6).

The indigenous microbial strains e.g. *Pseudomonas, Marinobacter Salinibacterium* and *Brevibacterium* are able to colonize plant root system and promote plant growth, thus, referred to plant growth promoting microbes. These isolated bacteria from polluted sediment samples degraded the phenanthrene, naphthalene, phenanthrene, and pyrene (Isaac et al. 2013). Archetypical naphthalene and catechol dioxygenase genes were found in two isolates belonging to genus *Pseudomonas* (*Pseudomonas monteilii* P26 and *Pseudomonas xanthomarina* N12) which degrades the polycyclic aromatic hydrocarbons (Isaac et al. 2013). Pesticide degrading microorganism is an effective indigenous plant growth promoting microorganism (PGPM), which is generally free-living, soil-borne bacterium, isolated from the rhizosphere, when

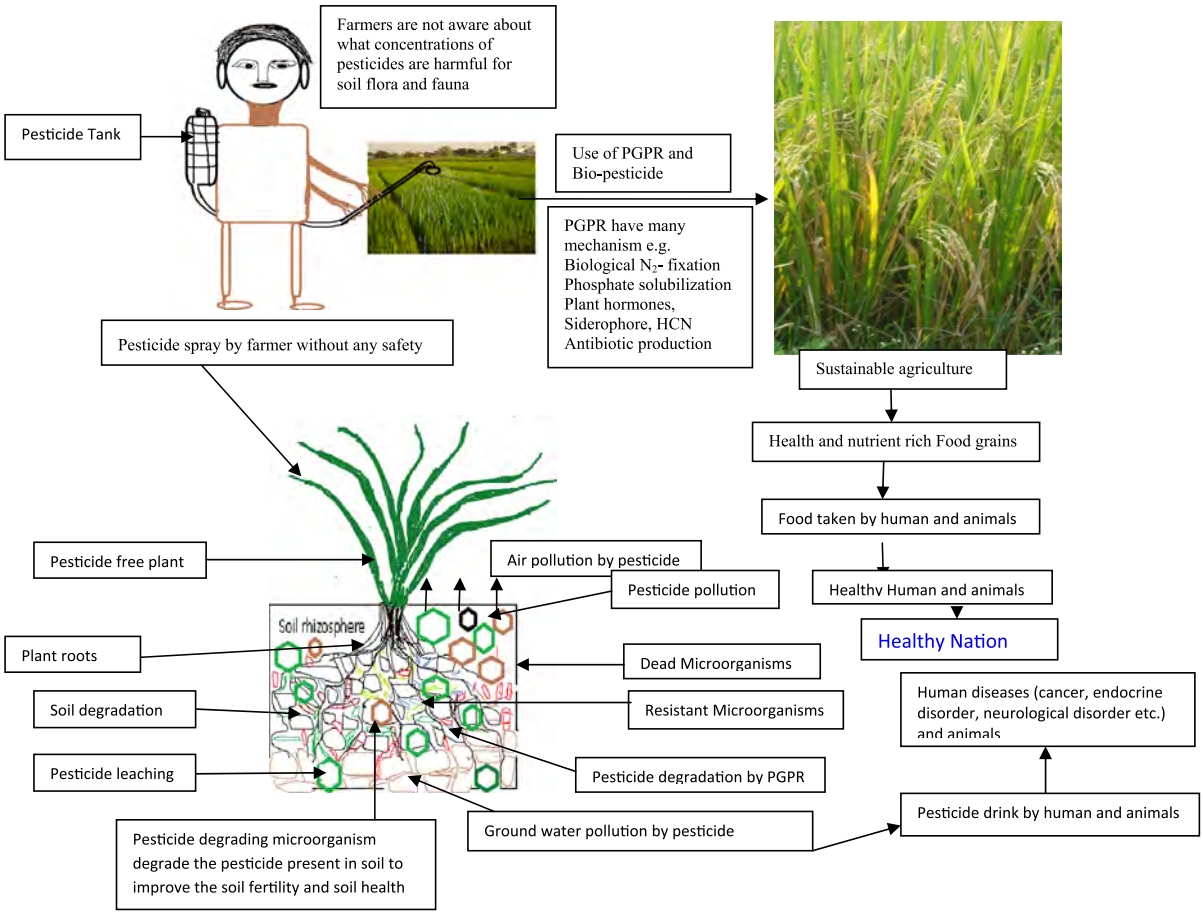

Fig. 6 Schematic diagram of pesticide application by the unaware farmers in agricultural crops and its effect on soil flora and fauna as well as soil, water and air pollution. The pesticide residue has been degraded by pesticide degrading microorganism to enhanced sustainable agriculture

applied to seeds or crops, enhanced the growth of the plant through suppression of plant disease (bioprotectants), improved nutrient acquisition (biofertilizers), production phytohormones (biostimulants) and acting as biopesticides (Vessey 2003) (Fig. 6). The direct mechanisms of plant growth by pesticides include the provision of phosphorus solubilization and its uptake by plants, biological nitrogen fixation, sequestration by siderophores, production of plant hormones like auxins, cytokinins and gibberellins and Lowe ring of ethylene levels in plant (Verma et al. 2012) (Fig. 6). The indirect mechanisms used by PGPM include; production of useful antibiotic against pathogenic microorganisms, reduction of iron availability to phytopathogens in the rhizosphere, synthesis of fungal cell wall lysis enzymes and competition with detrimental microorganisms for sites on plant root (Glick 1995). Yu et al. (2006) investigated the impact of the fungicide chlorothalonil (1.5 mg kg^{-1}) on soil micro-organisms by enumerating bacteria, fungi and actinomycetes using the most probable number method, and by measuring acid phosphatase, alkaline phosphatase, urease, catalase, and invertase activities.

According to Wang et al. (2007) an endophytic bacterium *Bacillus cepacia* strain FX2 isolated from a corn plant (*Z. mays*) has ability to degrade toluene and phenol because this possess a large plasmid encoding the catechol 2, 3-dioxygenase (C23O), a key enzyme in the degradation pathway of monocyclic aromatic compounds. Wang et al. (2010) conducted greenhouse and field trials to investigate the potential applications of strain FX2 to important crop plants (CORN and

wheat). The study showed increased plant growth and biomass. Cultivable endophytic bacteria is a indigenous or native microbes which able to grow on toluene as the only source of carbon and containing a C23O gene were found in the plants inoculated with strain FX2 but not in their non-inoculated controls. Many strains of these bacteria were often reported to be isolated from different plants, able to promote host plant growth, produce antifungal metabolite, degrade organic pollutants and possess C23O genes (Nejad and Johnson 2000; Sessitsch et al. 2004; Taghavi et al. 2005; Kavino et al. 2007; Mendes et al. 2007; Wang et al. 2007). Furthermore, a greater number of phosphate-solubilizing and siderophore producing endophytic bacteria were found in the corn and wheat inoculated with strain FX2 than in their controls. Phosphorus is one of the major essential macronutrients for biological growth and development and phosphate-solubilizing microorganisms may therefore play an important role in supplying phosphate (Wang et al. 2007; Taghavi et al. 2005) to plants in a more environmentally-friendly and sustainable manner (Rodrigues et al. 2006; Khan et al. 2007). Production of siderophores by bacteria becomes important in the suppression of plant pathogens and induction of systemic resistance in plants (Compant et al. 2005). Wang et al. (2010) reported that the horizontal gene transfer (HGT) required for the efficient degradation of a pollutant by the endophytic population might not only contribute to pollutant degradation, but also have other beneficial effects on plant, such as growth promotion and disease suppression. HGT, associated with an endophytic bacterium containing a transferable plasmid carrying the genetic information encoding the desired metabolic properties, is very important for agronomic and environmental applications in crop plants.

6.1 Field studied of pesticide degradation by microbial consortium

Ghazali et al. (2004) isolated consortium first (*Pseudomonas aeruginosa* strains S4.1, S53 and *Bacillus* sp. strain S3.2) and consortium second (*Pseudomonas aeruginosa* strains S4.1, S53, *Bacillus* sp. strain S3.2, 113i, O63 and *Micrococcus* sp) from hydrocarbon-contaminated soils. Consortium second was more efficient for removing the medium- and long-chain alkanes in the diesel-contaminated soil as compared to consortium first under field condition. A potent polycyclic aromatic hydrocarbons (PAHs) degrading microbial consortium of five fungi (*Phanerochaete chrysosporium*, *Cuuninghamella* sp., *Alternaria alternate* (Fr.) Keissler, *Penicillium chrysogenum*, and *Aspergillus niger*) and three bacteria (*Bacillus* sp., *Zoogloea* sp., and *Flavobacterium* sp.) were isolated from PAH contaminated which has great potential to PAH degradation under field condition (Lin et al. 2004; Su et al. 2006). Abbondanzi et al. (2005) conducted an experiment to determine PAHs concentration and changes in microbial populations in brackish sediments. Abbondanzi et al. (2005) suggested that the PAH degrading bacteria degraded the PAHs (phenanthrene, anthracene and fluoranthene) in MPN tubes with increasing concentration of microbial population after incubation in optimal conditions.

Chemical analyses and microbiological counts suggested a potential for PAHs biodegradation by natural occurring populations of sediment microorganisms, thus indicated an ''optimal range'' in sediment PAHs concentrations, outside of which the natural selection of the indigenous microflora did not occur. Chirnside et al. (2007) isolated indigenous microbes (*Alcaligenes xylosoxydans* subsp. *denitrificans*, *Alcaligenes xylosoxydans* subsp. *xylosoxydans*, *Pseudomonas putida*, *Pseudomonas marginalis*, and *Providencia rustigianii*) from 100-year-old pesticide-contaminated mix-load site from Pennsylvania. The selective microbial consortium (SMC) was identified by fatty acids methyl ester (FAME) analysis and they showed ability to degrade herbicides, atrazine (2-chloro-4-ethylamino-6-isopropylamino-S-triazine) and alachlor (2-chloro-20, 60-diethyl-N-[methoxymethyl]-acetanilide) under field condition. Jacques et al. (2008) isolated microbial consortium (five bacteria: *Mycobacterium fortuitum*, *Bacillus cereus*, *Microbacterium* sp., *Gordonia polyisoprenivorans*, *Microbacteriaceae* bacterium, Naphthalene-utilizing bacterium; and a fungus identified as *Fusarium oxysporum*) from a PAHs contaminated land farm site to degrade and mineralize different concentrations (0, 250,500 and 1,000 mg kg^{-1}) of anthracene, phenanthrene and pyrene in soil. The microbial consortium degraded on an average, 99, 99 and 96 % of the different concentrations of anthracene, phenanthrene and pyrene in the soil, in 70 days, respectively.

Kim et al. (2009) observed that the bacteria of three species (*Acinetobacter baumannii, Klebsiella oxytoca*,

and *Stenotrophomonas maltophilia*) have ability to degrade phenylephrine (PHE) which was isolated from sludge of a pulp wastewater treatment plant. When a single microorganism was used, phenanthrene degradation efficiency was very low (48.0, 11.0, and 9.0 % for *A. baumannii*, *K. oxytoca*, and *S. maltophilia* respectively, after 360 h cultivation) but in mixed consortia of *A. baumannii* and *S. maltophilia* degraded ~ 80.0 % of phenanthrene and reduced lag time to 48 h as compared to the 168 h of pure *A. baumannii* culture. The results showed that the mixed cultures of microorganisms may be effective in bioremediation, even if the microorganisms in the cultures have low degradation activity in pure culture. Alisi et al. (2009) recorded 75 % degradation of diesel hydrocarbons and complete degradation of n-C12–20 at 42 days due to inoculation of native microbial strains. *Sphingobium chlorophenolicum* strain C3R was isolated from a PAH contaminated soil by enrichment cultures with *phenanthrene* as sole carbon and energy source (Andreoni et al. 2004). *S. chlorophenolicum* strain C3R was effective pesticide degrading microbes for degradation of phenanthrene in agricultural soil co-contaminated by metals and mixtures of PAHs. These C3R strain persisted in inoculated microcosms as monitored by the DGGE analysis and out competed some indigenous bacteria (Colombo et al. 2011). Silva et al. (2009) isolated the microbial (3 *Bacillus* strains B1F, B5A and B3G; *Chromobacterium* sp. 4015; and *Enterobacter aglomerans* sp. B1A) and fungal strains (*Achremonium* sp., *Verticillium* sp. and *Aspergillus* sp.) and developed different types of microbial consortium of native and non native microbes for degradation of PAHs (naphthalene, phenanthrene, anthracene, pyrene, dibenzo[a]anthracene, benzo[a]pyrene). Their experiment suggested that the native microbial consortia rapidly degraded the PAHs from soil as compared to other treatments combinations.

Fagervold et al. (2011) established that the polychlorinated biphenyl (PCB) dehalorespiring bacteria had a considerable effect on the dehalogenating activity of PCB 151 (2,20,3,5,50,6-hexachlorobiphenyl) and Aroclor 1260, in sediment microcosms, inoculated with two indigenous PCB dehalorespiring microorganisms (DEH10 and SF1), and non-indigenous strain (Dehalobium chlorocoercia strain DF-1). In different treatments of microbial combinations, the numbers of dechlorinators increased approximately 100- and 1,000-fold with PCB 151 and Aroclor 1260, respectively. These observations indicate that bioaugmentation with PCB dehalorespiring microorganisms is a potentially tractable approach for in situ treatment of PCB impacted sites (Fagervold et al. 2007). Madueño et al. (2011) isolated and characterized indigenous soil bacteria of PAH-degrading strains (1A, 22A, 22B and 36). The results suggested that the strain 22B was more resistant to C-starvation and drying conditions and this strain was highly suitable for bioaugmentation in PAH-contaminated soils of Central Patagonia, due to its adaptation to the usual environmental conditions.

7 Challenges of microbial degradation of pesticides

The main problem of popularization and use of microbial consortia for degradation of pesticides in soil is; its unavailability and effectiveness. The specific microbial strain for degradation of specific pesticide is unavailable in the local market for the farmers because all microbial strains do not degrade all types of pesticides which need further research. Other significant aspects are; the effective pesticide degrading microorganism and biopesticide preparations are sensitive to heat, desiccation and ultraviolet radiations (Chakoosari 2013). These conditions reduce the effectiveness of the biopesticides. Special formulation of biopesticide and pesticide degrading microbial consortia in non toxic carrier material are essential for the long term storage at normal temperature.

8 Futures prospective

The approaches like integrated nutrient and pest management are necessary to increase sustainable agricultural productivity and conservation of natural resources (Matson et al. 1997). In India; agricultural development, planning and policy are most important objective. In agricultural development; pesticides have gain importance as a plant protection agent for boosting food production. The pesticides are being used indiscriminately resulting in sever environmental contaminations. To reduce the toxic effects of pesticide in soil and water, genetically modified

microorganism could be important bio-inoculants which may be used as effective biodegrading agent. Such microorganisms survive in the environment and utilize the pesticide for obtaining their energy, hence, will be a suitable candidate for bioremediation of pesticides-contaminated soil or water (Glick 2003). This technique is cheaper, effective and natural to combat the residual problem. These isolates have the potential to clean up the environment from pesticide pollutant and minimize the toxic effects of pesticides from the soil and water (Matson et al. 1997; Glick 2003). Further, these pesticide degrading microorganisms have ability to promote plant growth and yield due to production of phytohormones, ammonia, siderophore. The biological nitrogen fixation and phosphate solubilization have the antagonistic activity against phytopathogenic microorganism. These pesticide degrading microorganisms improve the soil health and fertility and thus, enhance the sustainable agriculture.

9 Conclusion

In current scenario, farmers are using higher dose of pesticides and chemical fertilizers in unmanaged manner for higher production of grain yield. Due to which; pesticides and chemical fertilizers pollute the water, soil and air, and cause many human diseases. Biodegradation that involves the capabilities of microorganisms in the removal of pollutants would be the most promising, relatively efficient and cost-effective technology. Effective and indigenous microbial consortia contribute significantly for the removal of toxic pesticides. These pesticides degrading microbial consortium being an effective biofertilizer could minimize use of chemical fertilizer up to 20–30 %. The use of an effective and indigenous microbial consortium as a tool for pesticide degradation on the contaminated sites is needed to adopt in practice at larger scale. These genetically modified microbial strains may develop more effective strains for pesticide degradation by genetic engineering technology and expression of enzymes. These effective microbial consortia need to be grown in large quantity by bioreactors for large scale field application. Conclusively, it is economically viable; and enhances the quality of life for farmers and society as a whole.

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References

Abbondanzi F, Campisi T, Focanti M, Guerra R, Iacondini A (2005) Assessing degradation capability of aerobic indigenous microflora in PAH-contaminated brackish sediments. Mar Environ Res 59:419–434

Abhilash PC, Singh N (2009) Pesticide use and application: an Indian scenario. J Hazar Mater 165(1–3):1–12

Abhilash PC, Dubey RK, Tripathi V, Srivastava P, Verma JP, Singh HB (2013) Remediation and management of POPs-contaminated soils in a warming climate: challenges and perspectives. Environ Sci Pollut Res. doi:10.1007/s11356-013-1808-5

Abo-Amer A (2011) Biodegradation of diazinon by Serratia marcescens DI101 and its use in bioremediation of contaminated environment. J Microbiol Biotechnol 21(1): 71–80

Abraham WR, Nogales B, Golyshin PN, Pieper DH, Timmis KN (2002) Polychlorinated biphenyl-degrading microbial communities and sediments. Curr Opin Microbiol 5: 246–253

Acharya SS (2006) Food security and Indian Agriculture: policies, production performance and marketing environment. Agricult Econom Res Rev 22:1–19

Adhya TK, Barik S, Sethunathan N (1981) Hydrolysis of selected organophosphorus insecticides by two bacterial isolates from flooded soil. J Appl Bacteriol 50:167–172

Agarry SE, Olu-arotiowa OA, Aremu MO, Jimoda LA (2013) Biodegradation of Dichlorovos (Organophosphate Pesticide) in soil by bacterial isolates. J Natural Sci Res 3(8):12–16

Agnihotri NP (1999) Pesticide safety and monitoring. All India Coordinated Research Project on Pesticides Residues, Indian Council of Agricultural Research, New Delhi, India

Aislabie J, Bej AK, Ryburn J, Lloyd N, Wilkins A (2005) Characterization of *Arthrobacter nicotinovorans* HIM, an atrazine-degrading bacterium, from agricultural soil NewZealand. FEMS Microbiol Ecol 52:279–286

Aislabie J, Davison AD, Boul HL, Franzmann PD, Jardine DR, Karuso P (1999) Isolation of Terrabacter sp. strain DDE-1, which metabolizes 1, 1 dichloro-2,2-bis(4 chlorophenyl) ethylene when induced with biphenyl. Appl Environ Microbiol 65(12):5607–11

Al-Arfaj A, Abdel-Megeed A, Ali HM, Al-Shahrani O (2013) Phyto-microbial degradation of glyphosate in Riyadh area. J Pure App Microbio 7(2):1351–1365

Alisi Chiara, Musella Rosario, Tasso F, Ubaldi C, Manzo S, Cremisini C, Sprocati AR (2009) Bioremediation of diesel oil in a co-contaminated soil by bioaugmentation with a microbial formula tailored with native strains selected for heavy metals resistance. Sci Total Environ 407:3024–3032

Amarger N (2002) Genetically modified bacteria in agriculture. Biochimie 84:1061–1072

Amellal N, Jean-M Portal, Vogel T, Berthelin J (2001) Distribution and location of polycyclic aromatic hydrocarbons (PAHs) and PAH-degrading bacteria within polluted soil aggregates. Biodegradation 12(1):49–57

Andreoni V, Cavalca L, Rao MA, Nocerino G, Bernasconi S, Dell'Amico E, Colombo M, Gianfreda L (2004) Bacterial communities and enzymes activities of PAH polluted soils. Chemosphere 57:401–412

Anonymous (1991) Survey of the environment, The Hindu, Government of India, Eleventh Five-Year Plan (2008–2012) Planning Commission of India, New Delhi, http://planningcommission.nic.in/plans/planrel/fiveyr/welcome.html

Anwar S, Liaquat F, Khan QM, Khalid ZM, Iqbal S (2009) Biodegradation of chlorpyrifos and its hydrolysis product 3, 5, 6-trichloro-2-pyridinol by *Bacillus pumilus* strain C2A1. J Hazard Mater 168:400–405

Arisoy M, Kolankaya N (1998) Biodegradation of Heptachlor by *Phanerochaete chrysosporium* ME 446: the toxic effects of Heptachlor and its Metabolites on Mice. Turk J Biol 22:427–434

Ashelford KE, Norris SJ, Fry JC, Bailey MJ, Day MJ (2000) Seasonal population dynamics and interactions of competing bacteriophages and their host in the rhizosphere. Appl Environ Microbiol 66:4193–4199

Assinder SJ, Williams PA (1990) The TOL plasmids: determinants of the catabolism of toluene and the xylenes. Adv Microb Physiol 31:1–69

Awad NS, Sabit HH, Abo-Aba SEM, Bayoumi RA (2011) Isolation, characterization and fingerprinting of some chlorpyrifos-degrading bacterial strains isolated from Egyptian pesticides-polluted soils. Afr J Microbiol Res 5(18):2855–2862

Awasthi N, Kumar A, Makkar R, Cameotra SS (1999) Biodegradation of soil-applied endosulfan in the presence of a biosurfactant. J Environ Sci Health, Part B 34(5):793–803

Bacosa HP, Suto K, Inoue C (2010) Preferential degradation of aromatic hydrocarbons in kerosene by a microbial consortium. Int Biodeterior Biodegrad 64:702–710

Bacosa HP, Suto K, Inoue C (2013) Bacterial community dynamics during the preferential degradation of aromatic hydrocarbons by a microbial consortium. Int Biodeterior Biodegrad 74:109–115

Bælum J, Nicolaisen MH, Holben WE, Strobel BW, Sørensen J, Jacobsen CS (2008) Direct analysis of tfdA gene expression by indigenous bacteria in phenoxy acid amended agricultural soil. ISME J 2:677–687

Barac T, Taghavi S, Borremans B, Provoost A, Oeyen L, Colpaert JV, Vangronsveld J, van der Lelie D (2004) Engineered endophytic bacteria improvephytoremediation of water-soluble, volatile, organic pollutants. Nat Biotechnol 22(5):583–588

Barathidasan K, Reetha D (2013) Microbial degradation of monocrotophos by Pseudomonas stutzeri. Indian Streams Res J 3(5):1

Barathidasan K, Reetha D, John Milton D, Sriram N, Govindammal M (2014) Biodegradation of chlorpyrifos by co-culture of Cellulomonas fimi and Phanerochaete chrysosporium. Afr J Microbiol Res 8(9):961–966

Barragan-Huerta BE, Costa-Perez C, Peralta-Cruz J, Barrera-Cortes J, Esparza-Garcıa F, Rodrıguez-Vazquez R (2007) Biodegradation of organochlorine pesticides by bacteria grown in microniches of the porous structure of green bean coffee. Int Biodeterior Biodegrad 59:239–244

Bastiaens L, Sphingeal D, Wattiau P, Harms H, deWachter R, Verachtert H, Diels L (2000) Isolation of adherent polycyclic aromatic hydrocarbon (PAH)-degrading bacteria using PAH-sorbing carriers. Appl Environ Microbiol 66:1834–1843

Beate B, Andreas T, Christian F (1993) Degradation of phenanthrene, fluorene, fluoranthene, and pyrene by a *Mycobacterium* sp. Appl Environ Microbiol 59:1927–1930

Beil S, Timmis K, Pieper D (1999) Genetic and biochemical analysis of the *tec* operon suggests a route for evolution of chlorobenzene degradation genes. J Bacteriol 181:341–346

Bhadbhade BJ, Sarnaik SS, Kanekar PP (2002) Biomineralization of an organophosphorus pesticide, monocrotophos, by soil bacteria. Appl Environ Microbiol 93:224–234

Bhatnagar VK (2001) Pesticides pollution: trends and perspectives. ICMR Bull 31:87–88

Bhuimbar MV, Kulkarni Ashwini N, Ghosh Jai S (2011) Detoxification of chlorpyriphos by *Micrococcus luteus* NCIM 2103, *Bacillus subtilis* NCIM 2010 and *Pseudomonas aeruginosa* NCIM 2036. Res J Envir Earth Sci 3(5):614–619

Boldt TS, Sørensen J, Karlson U, Molin S, Ramos C (2004) Combined use ofdifferent Gfp reporters for monitoring single-cell activities of a genetically modified PCB degrader in the rhizosphere of alfalfa. FEMS Microbiol Ecol 48(2):139–148

Borja J, Taleon DM, Auresenia J, Gallardo S (2005) Polychlorinated biphenyls and their biodegradation. Proc Biochem J 40:1999–2013

Brazil GM, Kenefick L, Callanan M, Haro A, de Lorenzo V, Dowling DN (1995) Conctruction of a rhizosphere pseudomonad with potential to degrade polychlorinated biphenyls and detection of *bph* gene expression in the rhizosphere. Appl Environ Micorbiol 61:1946–1952

Bunemann EK, Schwenke GD, Van Zwieten L (2006) Impact of agricultural inputs on soil organisms—a review. Aust J Soil Res 44:379–406

Burchfield HP, Storrs EE (1957) Effect of chlorine substitution and isomerism on the intractions of S-triazine derivatives with conidia of *Neurospora sitophilia*. Boyce Thompson Inst Plant Res 18:429–452

Burlage RS, Hooper SW, Sayler GS (1989) The TOL (pWWO) catabolic plasmid. Appl Environ Microbiol 55:1323–1328

Cases V, de Lorenzo V (2005) Genetically modified organisms for the environment: stories of success and failure and what we have learned from them. Int Microbiol 8(3):213–222

Chacko CI, Lockwood JL, Zabik M (1966) Chlorinated hydrocarbon pesticides: degradation microbes. Sci 154:893–895

Chakoosari MMD (2013) Efficacy of various biological and microbial insecticides. J Biol today's World 2(5):249–254

Chaudhry GR, Chapalamadugu S (1991) Biodegradation of halogenated organiccompounds microbiological reviews. Microbiol Mol Biol Rev 55(1):59–79

Chaudry GR, Ali AN, Wheeler WB (1988) Isolation of a methyl parathion degrading *Pseudomonas* sp. that possesses DNA

homologous to the *opd* gene from a *Flavobacterium* sp. Appl Environ Microbiol 54:288–293

Chauhan A, Faziurrahman, Oakeshott JG, Jain RK (2008) Bacterial metabolism of polycyclic aromatic hydrocarbons: strategies for bioremediation. J Ind Microbiol 48:95–113

Chen W, Mulchandani A (1998) The use of live biocatalysts for pesticide detoxification. Trend Biotechnol 16:71

Chen X, Christopher A, Jones JP, Bell SG, Guo Q, Xu F, Roa Z and Wong LL (2002) Crystal structure of the F87W/ Y96F/ V247L mutant of cytochrome P-450 cam with 1,3,5-trichlorobenzene bound and further protein engineering for the oxidation of pentachlorobenzene and hexachlorobenezene. J Biol Chem 277:37519–37526.

Chirnside AEM, Ritter William F, Radosevich M (2007) Isolation of a selected microbial consortium from a pesticide-contaminated mix-load site soil capable of degrading the herbicides atrazine and alachlor. Soil Biol Bioch 39: 3056–3065

Clarke PH (1984) The evolution of degradative pathways. Microbial degradation of organic compounds. Marcel Dekker, New York, pp 11–27

Colombo M, Cavalca L, Bernasconi S, Andreoni V (2011) Bioremediation of polyaromatic hydrocarbon contaminated soils by native microflora and bioaugmentation with Sphingobium chlorophenolicum strain C3R: a feasibility study in solid- and slurry-phase microcosms. Int Biodeter Biodegrad 65:191–197

Colosio C, Tiramani M, Brambilla G, Colombi A, Moretto A (2009) Neurobehavioural effects of pesticides with special focus on organophosphorus compounds: which is the real size of the problem. Neurotoxicol 30(6):1155–1161

Commandeur LCM, Parsons JR (1990) Degradation of halogenated aromatic compounds. Biodegradation 1:207–220

Compant S, Duffy B, Nowak J, Clément C, Barka EA (2005) Use of plant growth promoting bacteria for biocontrol of plant diseases: principles, mechanisms ofaction, and future prospects. Appl Environ Microbiol 71:4951–4959

Coppotelli BM, Ibarrolaza A, Del Panno MT, Morelli IS (2008) Effects of the inoculant strain Sphingomonas paucimobilis 20006FA on soil bacterial community biodegradation in phenanthrene-contaminated soil. Microbial Ecol 55:173–183

Cui Z, Li S, Fu G (2001) Isolation of methyl parathion-degrading strain M6 and cloning of the methyl parathion hydrolase gene. Appl Environ Microbiol 67:4922–4925

Da HN, Deng SP (2003) Survival and persistence of genetically modified *Sinorhizobium meliloti* in soil. Appl Soil Ecol 22:1–14

Daughton CG, Hsieh DP (1977) Parathion utilization by bacterial symbionts in a chemostat. Appl Environ Microbiol 34:175–184

Davison J (2005) Risk mitigation of genetically modified bacteria and plants designed for bioremediation. J Ind Microbiol Biotechnol 32(11–12):639–650

Desaint S, Hartmann A, Parekh NR, Fournier JC (2000) Genetic diversity of carbofuran-degrading soil bacteria. FEMS Microbiol Ecol 34:173–180

Diaz E (2004) Bacterial degradation of aromatic pollutants: a paradigm of metabolic versatility. Int Microbiol 7(3): 173–180

Didierjean L, Gondet L, Perkins R, Lau SMC, Schaller H, O'Keefe DP, Werck- Reichhart D (2002) Engineering herbicide metabolism in tobacco and Arabidopsis with CYP76B1, a cytochrome P450 enzyme from Jerusalem artichoke. Plant Physiol 130:179–189

Don RH, Pemberton JM (1981) Properties of six pesticide degradation plasmids isolated from *Alcaligenes paradoxus* and *Alcaligeneseutrophus*. J Bacteriol 145:681–686

Doyle JD, Stotzky G, McClung G, Hendricks CW (1995) Effects of genetically engineered microorganisms on microbial populations and processes in natural habitats. Adv App. Microbiol 40: 237–287

Dua M, Singh A, Sethunathan N, Johri AK (2002) Biotechnology and bioremediation: successes and limitations. Appl Microbiol Biotechnol 59:143–152

Pravin D, Bhalani S, Bhatt S, Ghelani A (2012) Degradation oforganophosphate and organochlorine pesticides in liquid culture by marine isolate nocardiopsis species and its bio-prospectives. J Envir Res Develop 7(2A):995–1001

Eberl L, Schulze R, Ammendola A, Geisenberger O, Erhart R, Sternberg C, Molin S, Amann R (1997) Use of green fluorescent protein as a marker for ecological studies of activated sludge communities. FEMS Microbiol Lett 149:77–83

EI-Bestway E, Mansy AH, Mansee AH, EL-Koweidy AH (2000) Biodegradation of selected chlorinated pesticides contaminating lake Maruiut ecosystem. Pak J Biol Sci 3:1673–1680

Erick RB, Juan A-O, Paulino P, Torres LG (2006) Removal of aldrin, dieldrin, heptachlor, and heptachlor epoxide using activated carbon and/or pseudomonas fluorescens free cell cultures. J Environ Sci Health, Part B 41:553–569

Evy AAM, Lakshmi V, Das N (2012) Biodegradation of atrazine by Cryptococcus laurentii isolated from contaminated agricultural soil. J Microbiol Biotech Res 2(3):450–457

Evy AA, Jaseetha AS, Das N (2013) Atrazine degradation in liquid culture and soil by a novel yeast Pichia kudriavzevii strain Atz-EN-01 and its potential application for bioremediation. J Appl Pharma Sci 3(06):035–043

Fagervold SK, May HD, Sowers KR (2007) Microbial reductive dechlorination of Aroclor 1260 in Baltimore Harbor sediment microcosms is catalyzed by three phylotypes within the phylum Chloroflexi. Appl Environ Microbiol 73(9):3009–3018

Fagervold SK, Watts JEM, May HD, Sowers KR (2011) Effects of bioaugmentation on indigenous PCB dechlorinatingactivity in sediment microcosms. Water Res 4(5):3899–3907

Fang H, Xiang YQ, Hao YJ, Chu XQ, Pan XD, Yu JQ, Yu YL (2008) Fungal degradation of chlorpyrifos by *Verticillium* sp. DSP in pure cultures and its use in bioremediation of contaminated soil and pakchoi Int. Biodeter Biodegr 61:294–303

FAO (2005) Proceedings of the Asia Regional Workshop, Regional Office for Asia and the Pacific, Bangkok

FAO (2010) (Food and Agriculture Organization of The United Nations) (http://faostat.fao.org/site/424/default.aspx#ancor)

Faulkner JK, Woodcock D (1964) Metabolism of 2, 4-dichlorophenoxyacetic acid ('2, 4-D') by Aspergillus Niger van Tiegh. Nature 203:865

Fawzy IE, Hend AM, Osama NM, Khaled MG, Ibrahim MG (2014) Biodegradation of chlorpyrifos by microbial strains

isolated from agricultural wastewater. J Am Sci 10(3):98–108

Ferguson JA, Korte F (1977) Epoxidation of aldrin to exo-dieldrin by soil bacteria. Appl Environ Microbiol 34(1):7–13

Fewson CA (1988) Microbial metabolism of mandelate: a microcosm of diversity. FEMS Microbiol Rev 54:85–110

Filonov AE, Akhmetov LI, Puntus IF, ESikova TZ, Gafarov AB, Izmalkova TY, Sokolov SL, Kosheleva IA, Boronin AM (2005) The construction and monitoring of genetically tagged, plasmid-containing, naphthalene-degrading strains in soil. Microbiol 74(4):526–532

Finley SD, Broadbelt LJ, Hatzimanikatis V (2010) In silico feasibility of novel biodegradation pathways for 1,2,4-trichlorobenzene. BMC Syst Biol 4:4–14

Frantz B, Chakrabarty AM (1986) Degradative plasmids in *Pseudomonas*. The biology of *Pseudomonas*. Academic Press, Inc, New York, pp 295–323

Furukawa K (2003) 'Super bugs' for Bioremediation. Trends Biotech 21:187–190

Furukawa K, Simon JR, Chakarbarthy AM (1983) Common induction and regulation of biphenyl, xylene/toluene and salicyalete catabolism in Pseudomonas paucimobilis. J Bacteriol 154:1356–1362

Gavrilescu M (2005) Fate of pesticides in the environment and its bioremediation. Eng Life Sci 5:497–526

Genthner BRS, Price WA II, Pritchard PH (1989) Characterization of anaerobic dechlorinating consortia derived from aquatic sediments. Appl Environ Microbiol 55:1472–1476

Ghanem I, Orfi M, Shamma M (2007) Biodegradation of chlorpyrifos by *Klebsiella* sp. isolated from an activated sludge sample of waste water treatment plant in Damascus Folia. Microbiol 52:423–427

Ghazali FM, Rahman Raja Noor ZA, Salleh AB, Mahiran Basri (2004) Biodegradation of hydrocarbons in soil by microbial consortium. Int Biodeter Biodeg 54:61–67

Gibson GT (1999) *Beijerinckia* sp. strain B1: a strain by any other name. J Indain Microbiol Biotechnol 23:284–293

Gibson DT, Subramanian V (1984) Microbial degradation of aromatic hydrocarbons. Microbial degradation of organic compounds. Marcel Dekker, New York, pp 181–252

Gibson GT, Roberts RL, Wells MC, Kobal VM (1973) Oxidation of biphenyl by a *Beijerinckia* sp. Biochem Biophys Res Commun 50:211–219

Giri K, Rawat AP, Rawat M, Rai JPN (2014) Biodegradation of hexachlorocyclohexane by two species of bacillus isolated from contaminated soil. Chem Ecol 30(2):97–109. doi:10.1080/02757540.2013.844795

Glick BR (1995) The enhancement of plant growth by free-living bacteria. Can J Microbiol 41:109–117

Glick BR (2003) Phytoremediation: synergistic use of plants and microbes to clean up the environment. Biotechnol Adv 21:383–393

Guzzella L, Capri E, Di Corcia A, Caracciolo AB, Giuliano G (2006) Fate of diuron and linuron in a field lysimeter experiment. J Environ Qual 35:312–323

Habe H, Omori T (2003) Genetics of polycyclic aromatic hydrocarbon degradation by diverse aerobic bacteria. Biosci Biotechnol Biochem 67:225–243

Halden RU, Tepp SM, Halden BG, Dwyer DF (1999) Degradation of 3-phenoxy-benzoic acid in soil by Pseudomonas pseudoalcaligenes POB310(pPOB) and two modified Pseudomonas strains. Appl Environ Microbiol 65: 3354–3359

Harayama S, Rekik M (1990) The meta cleavage operon of TOL degradative plasmid pWWO comprises 13 genes. Mol Gen Genet 221:113–120

Harayama S, Rekik M, Wubbolts M, Rose K, Leppi RAK, Timmis KN (1989) Characterization of five genes in the upper-pathway operon of TOL plasmid pWWO from *Pseudomonasputida* and identification of the gene products. J Bacteriol 171:5048–5055

Harayama S, Leppik RA, Rekik M, Mermod N, Lehrbach PR, Reineke W, Timmis KN (1986) Gene order of the TOL catabolic plasmid upper pathway operon and oxidation of both toluene and benzyl alcohol by the xyIA product. J Bacteriol 167:455–461

Harish R, Supreeth M, Chauhan JB (2013) Biodegradation of organophosphate pesticide by soil fungi. Adv Bio Tech 12(09):04–08

Haro MA, de Lorenzo V (2001) Metabolic engineering of bacteria for environmental applications: construction of *Pseudomonas* strains for biodegradation of 2-chlorotoluene. J Biotech 85:105–113

Harwood CS, Parales RE (1996) The b-ketoadipate pathway and the biology of self-identity. Annual Revi Microbiol 50:553–590

Hay AG, Foch DD (1998) Cometabolism of 1, 1-dichloro-2, 2-bis (4-chlorophenyl) ethylene by *Pseudomonas acidovorans* M3GY grown on biphenyl. Appl Environ Microbiol 64:2141–2146

Hay AG, Focht DD (2000) Transformation of 1,1-dichloro-2, 2-(4-chlorophenyl) ethane (DDD) by Ralstonia eutrophastrain A5. FEMS Microbiol Ecol 31:249–253

Hayat R, Ali S, Amara U, Khalid R, Ahmed I (2010) Soil beneficial bacteria and their role in plant growth promotion: a review. Ann Microbiol 60:579–598

Hayatsu M, Hirano M, Tokuda S (2000) Involvement of two plasmids in fenitrothion degradation by *Burkholderia* sp. strain NF100. Appl Environ Microbiol 66:1737–1740

Heijnen CE, van Elsas JD, Kuikman PJ, van Veen JA (1988) Dynamics of *Rhizobium leguminosarum* biovar *trifolii* introduced into soil; the effect of bentonite clay on predation by protozoa. Soil Biol Biochem 20:483–488

Hernandez F, Beltran J, Forcada M, Lopez FJ, Morell I (1998) Experimental approach for pesticide mobility studies in the unsaturated zone. Int J Environ Anal Chem 71:87–93

Holtel A, Abril MA, Marques S, Timmis KN, Ramos JL (1990) Promoter-upstream activator sequences are required for expression of the xylS gene and upper-pathway operon on the Pseudomonas TOL plasmid. MolMicrobiol 4: 1551–1556

Horne I, Sutherland TD, Harcourt RL, Russell RJ, Oakeshott JG (2002a) Identification of an *opd* (organophosphorus degradation) gene in an *Agrobacterium* isolate. Appl Environ Microbiol 68:3371–3376

Horne I, Sutherland TD, Oakeshott JG, Russell RJ (2002b) Cloning and expression of the phosphotriesterase gene *hoc*A from *Pseudomonas monteilii* C11. Microbiology 148:2687–2695

Hosokawa R, Nagai M, Morikawa M, Okuyama H (2009) Autochthonous bioaugmentation and its possible

application to oil spills. World J Microbiol Biotechnol 25(9):1519–1528

Hussaini SZ, Shaker M, Iqbal MA (2013) Isolation of bacterial for degradation of selected pesticides. Adv Biores 4(3):82–85

IARC (1986) Monographs on the evaluation of carcinogenic risks to humans volume 41 some halogenated hydrocarbons and pesticide exposures. Lyon Internation Agency Res Cancer, p 434

Ibrahim WM, Karam MA, El-Shahat RM, Adway AA (2014) Biodegradation and Utilization of organophosphorus pesticide Malathion by Cyanobacteria. BioMed Res Inter. doi:10.1155/2014/392682

ICAR (1967) Report of the special committee on harmful effects of pesticides. ICAR, New Delhi 78

Isaac P, Sánchez LA, Bourguignon N, Cabral ME, Ferrero MA (2013) Indigenous PAH-degrading bacteria from oil-polluted sediments in Caleta Cordova, Patagonia Argentina. Int Biodeter Biodegr 82:207–214

Jacobsen CS, Hjelmsø MH (2014) Agricultural soils, pesticides and microbial diversity. Curr Opin Biotechnol 27:15–20

Jacques RJ, Okeke BC, Bento FM, Teixeira AS, Peralba MC, Camargo FA (2008) Microbial consortium bioaugmentation of a polycyclic aromatic hydrocarbons contaminated soil. Bioresour Technol 99(7):2637–2643

Jagnow G, Halder K (1972) Evolution of CO_2 from soil incubated with dieldrin-14C. SoilBiolog Biochem 4:43

Jain RK, Kapur M, Labana S, Lal B, Sarma PM, Bhattacharya D, Thakur IS (2005) Microbial diversity: application of microorganisms for the biodegradation of xenobiotics. Curr Sci 89:101–112

Jain R, Garg V, Singh KP, Gupta S (2012) Isolation and characterization of monocrotophos degrading activity of soil fungal isolate *Aspergillus Niger* MCP1 (ITCC7782.10). Int J Envir Sci 3(2):841–850

Jayashree R, Vasudevan N (2007) Effect of tween 80 added to the soil on the degradation of endosulfan by *Pseudomonas aeruginosa*. Inter J Env Sci Tech 4(2):203–210

Jia KZ, Li XH, He J, Gu LF, Ma JP, Li SP (2007) Isolation of a monocrotophos-degrading bacterial strain and characterization of enzymatic degradation. Huan Jing Ke Xue 28(4):908–912

Joergensen RG, Emmerling C (2006) Methods for evaluating human impact on soil microorganisms based on their activity, biomass, and diversity in agricultural soils. J Plant Nutr Soil Sci 169:295–309

Johnsen AR, Wick LY Harms H (2005) Principles of microbial PAH degradation in soil. Environ Pollut 133:71–84

Johansen JE, Binnerup SJ, Lebolle KB, Masher F, Sorensen J, Keel C (2002) Impact of biocontrol strain *Pseudomonas fluorescens* CHA0 on rhizosphere bacteria isolated from barley (*Hordeum vulgare* L.) with special reference to *Cytophaga*-like bacteria. J Appl Microbiol 93:1065–1074

Johnsen K, Jacobsen CS, Torsvik V, Sørensen J (2001) Pesticide effects on bacterial diversity in agricultural soils—a review. Biolog Fertil Soils 33(6):443–453

Jokanovic M, Prostran M (2009) Pyridinium oximes as cholinesterase reactivators structure-activity relationship and efficacy in the treatment of poisoning with organophosphorus compounds. Curr Med Chem 16:2177–2188

Kamei I, Takagi K, Kondo R (2010) Bioconversion of dieldrin by wood-rotting fungi and metabolite detection. Pest Manag Sci 66(8):888–891

Kanaly RA, Harayama S (2000) Biodegradation of high-molecular weight polycyclic aromatic hydrocarbons by bacteria. J Bacteriol 182(8):2059–2067

Kang H, Hwang SY, Kim YM, Kim E, Kim YS, Kim SK, Kim SW, Cerniglia CE, Shuttleworth KL, Zylstra GJ (2003) Degradation of phenanthrene and naphthalene by a *Burkholderia* species strain. Can J Microbiol 49:139–144

Kannan K, Tanabe S, Ramesh A, Subramanian A, Tatsukawa R (1992) Persistent orgnochlorine residues in food stuffs from India and their implications on human dietary exposure. J Agric Food Chem 40:518–524

Kataoka R, Takagi K, Kamei I, Kiyota H, Sato Y (2010) Biodegradation of dieldrin by a soil fungus isolated from a soil with annual endosulfan applications. Environ Sci Techno 44(16):6343–6349

Kavino M, Harish S, Kumar N, Saravanakumar D, Damodaran T, Soorianathasundaram K, Samiyappan R (2007) Rhizosphere and endophytic bacteria for induction of systemic resistance of banana plantlets against bunchy top virus. Soil Biol Biochem 39:1087–1098

Khan MS, Zaidi A, Wani PA (2007) Role of phosphate-solubilizing microorganisms in sustainable agriculture—a review. Agron Sustain Develop 27:29–43

Kim YM, Ahna CK, Wood SH, Jungb GY, Parka JM (2009) Synergic degradation of phenanthrene by consortia of newly isolated bacterial strains. J Biotechnol 144:293–298

Kimyoji T, Sugimoto K, Mitani S, Matsuo N, Suzuki K (1995) Biological properties of a new fungicide, fluazinam. J Pest Sci Japan 20:129–135

Klipi S, Backstrom V, Korhola M (1980) Degradation of 2-methyl-4-chlorophenoxy acetic acid (MCPA), 2,4-dichlorophenoxyacetic acid (2,4-D), benzoic acid and salicylic acid by Pseudomonas sp. HV3. FEMS Microbiol Lett 8:177–182

Kong L, Zhu S, Zhu L, Xie H, Su K, Yan T, Wang J, Wang J, Wang F, Sun F (2013) Biodegradation of organochlorine pesticide endosulfan by bacterial strain *Alcaligenes faecalis* JBW4. J Environ Sci 25(11):2257–2264

Korade DL, Fulekar MH (2009) Rhizosphere remediation of chlorpyrifos in mycorrhizospheric soil using ryegrass. J Hazard Mater 172:1344–1350

Korte F, Porter PE (1970) Minutes of the fifth meeting of the IUPAC terminal pesticide residues. Erbach, West Germany

Kosaric N (2001) Biosurfactants and their application for soil bioremediation. Food Technol Biotechnol 39:295–304

Kraiser T, Stuardo M, Manzano M, Ledger T, González B (2012) Simultaneous assessment of the effects of an herbicide on the triad: rhizobacterial community, an herbicide degrading soil bacterium and their plant host. Plant Soil. doi:10.1007/s11104-012-1444-8

Kuiper I, Lagendijk EL, Bloemberg GV, Lugtenberg BJJ (2004) Rhizoremediation: a beneficial plant–microbe interaction. Mol Plant-Microbe Interact 17:6–15

Kulshrestha G, Kumari A (2011) Fungal degradation of chlorpyrifos by Acremonium sp. strain (GFRC-1) isolated from a laboratory-enriched red agricultural Biol Fertil. Soils 47:219–225

Kumar S, Mukerji KG, Lal R (1996) Molecular aspects of pesticide degradation by microorganisms. Crit Rev Microbiol 22(1):1–26

Kumar K, Devi SS, Krishnamurthi K, Kanade GS, Chakrabarti T (2007) Enrichment and isolation of endosulfan degrading and detoxifying bacteria. Chemosfere 68(2): 317–322

Kumara M, Philipa L (2006) Endosulfan mineralization by bacterial isolates and possible degradation pathway identification. Bioreme J 10(4):179–190

Kuritz T, Wolk CP (1995) Use of filamentous cyanobacteria for biodegradation of organic pollutants. Appl Envir Microbiol 61:234–238

Laemmli CM, Leveau JHJ, Zehnder AJB, Van der Meer JR (2000) Characterization of a second *tfd* gene cluster for chlorophenol and chlorocatechol metabolism on plasmid pJP4 in *Ralstonia eutropha* JMP134 (pJP4). J Bacteriol 182:4165–4172

Lakshmi A (1993) Pesticides in India: risk assessment to aquatic ecosystems. Sci Total Environ 134:243–253

Lakshmi CV, Kumar M, Khanna S (2008) Biotransformation of chlorpyrifos and bioremediation of contaminated soil. Int Biodeter Biodegr 62:204–209

Lancaster SH, Hollister EB, Senseman SA, Gentry TJ (2010) Effects of repeated glyphosate applications on soil microbial community composition and the mineralization of glyphosate. Pest Manage Sci 66:59–64

Leveau JHJ, Konig F, Fuchslin H, Werlen C, van der Meer JR (1999) Dynamics of multigene expression during catabolic adaptation of *Ralstoniaeutropha*JMP134 (pJP4) to the herbicide 2,4-dichlorophenoxyacetate. Mol Microbiol 33:396–406

Li X, He J, Li S (2007) Isolation of a chlorpyrifos-degrading bacterium, Sphingomonas sp. strain Dsp-2, and cloning of the mpd gene. Res Microbiol 158:143–149

Lin X, Li PJ, Xu HX, Zhou Q X, Zhang HR (2004) Microbial changes in rhizospheric soils contaminated with petroleum hydrocarbons after bioremediation. J Environm Sci 16(6):987–990

Lipthay JR, Barkay T, Sørensen SJ (2001) Enhanced degradation of phenoxyacetic acid in soil by horizontal transfer of the tfdA gene encoding a 2, 4-dichlorophenoxyacetic acid dioxygenase. FEMS Microbiol Ecol 35(1):75–84

Liu Z, Chen X, Shi Y, Su Z (2012) Bacterial degradation of chlorpyrifos by *Bacillus cereus*. Adv Mater Res 356(360): 676–680

Lo CC (2010) Effect of pesticides on soil microbial community. J Environ Sci Health B 45:348–359

Madueño L, Coppotelli BM, Alvarez HM, Morelli IS (2011) Isolation and characterization of indigenous soil bacteria for bioaugmentation of PAH contaminated soil of semiarid Patagonia, Argentina. Int Biodete Biodeg 65:345–3511

Magan N, Fragoeiro S (2005) Enzymatic activities, osmotic stree and degradation of pesticide mixtures in soil extract liquid broth inoculated with phanerochaete chrysosporium and Trametes versicolor. Envir Microbiol 7(3):348–355

Mahapatra GK (2008) Helopeltis management by chemicals in Cashew: a critical concern. Indian J Entomol 70:293–308

Mahapatra GK, Panigrahi M (2013) The case for banning endosulfan. Curr Sci 104:1476–1478

Mahiudddin M, Fakhruddin ANM, Abdullah-Al-Mahin, Chowdhury MAZ, Rahman MA, Alam MK (2014) Degradation of the organophosphorus insecticide diazinon by soil bacterial isolate. The Intern J Biotechn 3(1):12–23

Malhotra S, Sharma P, Kumari H, Singh A, Lal R (2007) Localization of HCH catabolic genes (*lin*) in *Sphingobium indicum* B90A. Ind J Microbiol 71:8514–8518

Mallick K, Bharati K, Banerji A, Shakil NA, Sethunathan N (1999) Bacterial degradation of chlorpyrifos in pure cultures and in soil. Bull Environ Contam Toxicol 62:48–54

Manickam N, Bajaj A, Saini HS, Shanker R (2012) Surfactant mediated enhanced biodegradation of hexachlorocyclohexane (HCH) isomers by *Sphingomonas* sp. NM05. Biodegradation 23:673–682

Masunaga S, Susarla S, Gundersen JL, Yonezawa Y (1996) Pathway and rate of chlorophenols transformation in anaerobic estuarine sediment. Environ Sci Technol 30:1253–1260

Matrubutham U, Harker AR (1994) Analysis of duplicated gene sequences associated with *tfd*R and *tfd*S in *Alcaligeneseutrophus* JMP134. J Bacteriol 176:2348–2353

Matson PA, Parton WJ, Power AG, Swift MJ (1997) Agricultural intensification and ecosystem properties. Science 277(5325):504–509

Matsumura F, Boush GM (1966) Malathion degradation by *Trichoderma viride* and a *Pseudomonas* species. Science 153:1278–1280

Matsumura F, Boush GM (1967) Dieldrin degradation by soil microorganisms. Science 156:959–961

Matsumura F, Boush GM (1968) Degradation of insecticides by a soil fungus *Trichoderma viride*. J Econom Entomol 61:610–612

Matsumura F, Boush GM, Tai A (1968) Breakdown of dieldrin in the soil by a microorganism. Nature 219(5157):965–967

Mendes R, Pizzirani-Kleiner AA, Araujo WL, Raaijmakers JM (2007) Diversity of cultivated endophytic bacteria from sugarcane: genetic and biochemical characterization of Burkholderia cepacia complex isolates. Appl Environ Microbiol 73:7259–7267

Merlin C, Springael D, Toussaint A (1999) Tn4371: a modular structure encoding a phage-likeintegrase, a pseudomonas-like catabolic pathway and RP4/Ti-like transfer functions. Plasmid 41:40–54

Mohamed MS (2009) Degradation of methomyl by the novel bacterial strain *Stenotrophomonas maltophilia* M1. Electron J Biotechnol 12(4):1–6. doi:10.2225/vol12-issue4-fulltext-11

Mohanasrinivasan V, Suganthi V, Selvarajan E, Subathra Devi C, Ajith E, Muhammed FNP, Sreeram G (2013) Bioremediation of endosulfan contaminated soil. Res J Chem Environ 17(11):93–101

Moody JD, Freeman JP, Fu PP, Cerniglia CE (2004) Degradation of benzo[*a*]pyrene by *Mycobacterium* V*anbaalenii*PYR-1. Appl Environ Microbiol 70:340–345

Moreira IS, Amorim CL, Carvalho MF, Castro PML (2012) Degradation of difluorobenzenes by the wild strain *Labrys portucalensis*. Biodegradation 23:653–662

Morrissey JP, Walsh UF, O'Donnell A, Moënne-Loccoz Y, O'Gara F (2002) Exploitation of genetically modified inoculants for industrial ecology applications. A van Leeuwenhoek 81:599–606

Mrozi A, Piotrowska-Sege Z (2010) Bioaugmentation as a strategy for cleaning up of soils contaminated with aromatic compounds. Microbiol Res 165(5):363–375

Mulbry W, Kearney PC (1991) Degradation of pesticides by micro-organisms and the potential for genetic manipulation. Crop Protect 10:334–346

Myresiotis CK, Vryzas Z, Papadopoulou-Mourkidou E (2012) Biodegradation of soil-applied pesticides by selected strains of plant growth-promoting rhizobacteria (PGPR) and their effects on bacterial growth. Biodegradation 23:297–310

Nakatsu CH, Straus NA, Wyndham RC (1995) The nucleotidesequence of the Tn5271 3-chlorobenzoate 3,4-dioxygenase genes (cbaAB)unites the class IA oxygenases in a single lineage. Microbiol 141:485–495

Nakazawa T, Inouye S, Nakazawa A (1990) Regulatory systems for expression of xyl genes on the TOL plasmid. pp 133–141

Nancharaiah V, Joshi HM, Hausner M, Venugopalan VP (2008) Bioaugmentation of aerobic microbial granules with Pseudomonas putida carrying TOL plasmid. Chemosphere 71:30–35

Nejad P, Johnson PA (2000) Endophytic bacteria induce growth promotion and wilt disease suppression in oilseed rape and tomato. Biol Control 18:208–215

Nelson ML, Yaron B, Nye PH (1982) Biologically induced hydrolysis of parathion in soil: kinetics and modelling. Soil Biol Biochem 14:223–228

Ning J, Gang Gang, Bai Z, Qing Hu, Hongyan Qi, Anzhou Ma, Zhuan X, Guoqiang Zhuang (2012) In situ enhanced bioremediation of dichlorvos by a phyllosphere *Flavobacterium* strain. Front Environ Sci Eng 6(2):231–237

Nishi A, Tominaga K, Furukawa K (2000) A 9-kilobase conjugative chromosomal element coding for biphenyl and salicylate catabolism in Pseudomonas putida KF715. J Bacteriol 182:1949–1955

Odukkathil G, Vasudevan N (2013) Enhanced biodegradation of endosulfan and its major metabolite endosulfate by a biosurfactant producing bacterium. J Environ Sci Health B 48(6):462–469

Ortiz I, Velasco A, Borgne SL, Revah S (2013) Biodegradation of DDT by stimulation of indigenous microbial populations in soil with co substrates. Biodegrad 10532(012): 9578–9581

Ortiz-Hernández ML, Sánchez-Salinas E (2010) Biodegradation of the organophosphate pesticide tetrachlorvinphos by bacteria isolated from agricultural soils in México. Revis Internacion de Contamin Ambient 26(1):27–38

Ortiz-Hernández ML, Quintero-Ramírez R, Nava-Ocampo AA, Bello-Ramírez AM (2003) Study of the mechanism of *Flavobacterium*sp. for hydrolyzingorganophosphate pesticides. Fundam Clin Pharmacol 17(6):717–723

Ortiz-Hernández ML, Sánchez-Salinas E, Olvera-Velona A, Folch-Mallol JL (2011) Pesticides in the environment: impacts and its biodegradation as a strategy for residues treatment. Pesticides—formulations, effects, fate, margarita stoytcheva (Ed.) In-Tech. doi:10.5772/13534. http://www.intechopen.com/books/pesticides-formulations-effects-fate/pesticides-in-the-environment-impacts-and-itsbiodegradation-as-a-strategy-for-residues-treatment

Otte MP, Gagnon J, Comeau Y, Matte N, Greer CW, Samson R (1994) Activation of an indigenous mirobial consortium for bioaugmentation of pentachlorophenol/creosote contaminated soils. Appl Microbiol Biotechnol 40:926–932

Padmanabhan P, Padmanabhan S, De Rito C, Gray A, Gannon D, Snap JR, Tsai CS, Park W, Jeon C, Madsen EL (2003) Respiration of ^{13}C-labelled substrates added to soil in the field and subsequent 16S rRNA gene analysis of ^{13}C labeled soil DNA. Appl Environ Microbiol 69:1614–1622

Pallud C, Dechesne A, Gaudet JP, Debouzia D, Grundmann GL (2004) Modification of spatial distribution of 2,4-dichlorophenoxy acetic acid degrader microhabitats during growth in soil columns. Appl Environ Microbiol 70: 2709–2716

Park JH, Feng Y, Ji P, Voice TC, Boyd SA (2003) Assessment of bioavailability of soil-sorbed atrazine. Appl Environ Microbiol 69:3288–3298

Parsek MR, Mc Fall SM, Chakrabarty AM (1995) Microbial degradation of toxic environment pollution: ecological and evolutionary consideration. Int Biodeter Biodegrad 35:175–188

Patil KC, Matsumura F, Boush GM (1970) Degradation of endrin, aldrin, and DDT by soil microorganisms. J App Microbiol 19:879–881

Paul D, Pandey G, Pandey J, Jain RK (2005) Accessing microbial diversity for bioremediation and environmental restoration. Trends Biotechnol 23:135–142

Pelrez-Pantoja D, Guzmaln L, Manzano M, Pieper DH, Gonzallez B (2000) Role of *tfd*CIDIEIFI and *tfd*DIICIIEIIFII gene modules in catabolism of 3-chlorobenzoate by *Ralstoniaeutropha* JMP134 (pJP4). Appl Environ Microbiol 66:1602–1608

Pemberton JM, Fisher PR (1977) 2, 4-D plasmids and persistence. Nature (London) 268:732–733

Pemberton JM, Schmidt R (2001) Catabolic plasmids. Encyclopedia life science. Wiley, New York, pp 1–9

Pereira PM, Sobral Teixeira RS, de Oliveira MAL, da Silva M, Ferreira-Leitão VS (2013) Optimized atrazine degradation by *Pleurotus ostreatus* INCQS 40310: an alternative for impact reduction of herbicides used in sugarcane crops. J Microb Biochem Technol S 12:006. doi:10.4172/1948-5948.S12-006

Perkins EJ, Gordon MP, Calceres O, Lurquin PF (1990) Organization and sequence analysis of the 2,4-dichlorophenol hydroxylase and dichlorocatechol oxidative operons of plasmid pJP4. J Bacteriol 172:2352–2359

Phelps TJ, Segrist RL, Korte NE, Pickering DA, Strong-Guderson JJM, Palumbo AV, Walker JF, Morrissey CM, Mackowski R (1994) Bioremediation of petroleum hydrocarbon in soil column lysimeters from Kwajalein island. Appl Biochem Biotechnol 45(46):835–845

Pieper DH, Reineke W (2000) Engineering bacteria for bioremediation. Curr Opin Biotech 11(3): 262–270

Pimentel MR, Molina G, Dionísio AP, Maróstica MRJr, Pastore GM (2011) The use of endophytes to obtain bioactive compounds and their application in biotransformation process. Biotechnol. Res Int 1–11

Pino N, Penuela G (2011) Simultaneous degradation of the pesticides methyl parathion and chlorpyrifos by an isolated bacterial consortium from a contaminated site. Int Biodeterior Biodegrad 65:827–831

Pinyakong O, Habe H, Supaka N, Pinpanichkarn P, Juntongjin K, Yoshida T, Furihata K, Nojiri H, Yamane H, Omori T (2000) Identification of novel metabolites in the degradation of phenanthrene by *Sphingomonas* sp. strain P2. FEMS Microbiol Lett 191(1):115–121

Pinyakong O, Habe H, Omori T (2003) The unique aromatic catabolic genes in *Sphingomonads* degrading polycyclic aromatic hydrocarbons (PAHs). J Gen Appl Microbiol 49(1):1–19

Pipke R, Amrhein N (1988) Isolation and characterization of a mutant of *Arthrobacter* sp.strain GLP-1 which utilizes the herbicide glyphosate as its sole source of phosphorusand nitrogen. Appl Environ Microbiol 54:2868–2870

Poh RP-C, Smith ARW, Bruce IJ (2002) Complete characterisation of Tn5530 from *Burkholderia cepacia* strain 2a (pIJB1) and studies of2,4-dichlorophenoxyacetate uptake by the organism. Plasmid 48:1–12

Porto AM, Melgar GZ, Kasemodel MC, Nitschke M (2011) Biodegradation of pesticides, pesticides in modern world-pesticides use and management. [online] http://www.intechopen.com/books/pesticides-in-the-modern-world-pesticides-use-and-management/biodegradation-of-pesticides

Pothuluri JV, Chung YC, Xiong Y (1998) Biotransformation of 6-nitrochrysene. Appl Environ Microbiol 64:3106–3109

Prabha Y, Phale PS (2003) Biodegradation of phenanthrene by *Pseudomonas* sp. strain PP2: novel metabolic pathway, role of biosurfactant and cell surface hydrophobicity in hydrocarbon assimilation. Appl Microbiol Biotechnol 61:342–351

Purnomo AS, Mori T, Kamei I, Nishii T, Kondo R (2010a) Application of mushroom waste medium from Pleurotus ostreatus for bioremediation of DDT-contaminated soil. Int Biodeter Biodegr 64:397–402

Purnomo AS, Mori T, Kondo R (2010b) Involvement of Fenton reaction in DDT degradation by brown-rot fungi. Int Biodeter Biodegr 64:560–565

Quan X, Tang H, Xiong W, Yang Z (2010) Bioaugmentation of aerobic sludge granules with a plasmid donor strain for enhanced degradation of 2,4-dichlorophenoxyacetic acid. J Hazard Mater 179(1–3):1136–1142

Rapp P, Gabriel-Jürgens LHE (2003) Degradation of alkanes and highly chlorinated benzenes, and production of biosurfactants, by a psychrophilic *Rhodococcus* sp. and genetic characterization of its chlorobenzene dioxygenase. Microbiol 149:2879–2890

Reineke W (1984) Microbial degradation of halogenated aromatic compounds. Microbial degradation of organic compounds, Marcel Dekker, New York, pp 319–360

Reineke W, Knackmuss HJ (1988) Microbial degradation of haloaromatics. Annu Rev Microbiol 42:263–287

Rekha SN, Naik RP (2006) Pesticide residue in organic and conventional food—risk analysis. Chem Health Safety 13:12–19

Rheinwald JC, Chakrabarty AM, Gunsalus IC (1973) A transmissible plasmid.controlling camphor oxidation in *Pseudomonas putida*. Proc Natl Acad Sci USA 70:885–889

Ripp S, Nivens DE, Werner C, Sayler GS (2000) Bioluminescent most-probable-number monitoring of a genetically engineered bacterium during a long-term contained field release. Appl Microbiol Biotech 53:736–741

Riya P, Jagatpati T (2012) Biodegradation and bioremediation of pesticides in soil: its objectives, classification of pesticides, factors and recent developments. World J Sci Technol 2(7):36–41

Rodrigues JLM, Kachel A, Aiello MR, Quensen JF, Maltseva OV, Tsio TV, Tiedje JM (2006) Degradation of Aroclor 1242 dechlorination products in sediments by Burkholderia xenovorans LB400 (ohb) and Rhodococcus sp. strain RHA1 (fcb). Appl Environ Microbiol 72(4):2476–2482

Romeh AA, Hendawi MY (2014) Bioremediation of certain organophosphorus pesticides by two biofertilizers, Paenibacillus(Bacillus) polymyxa (Prazmowski) and Azospirillum lipoferum (Beijerinck). J Agric Sci Tech 16:265–276

Saint CP, McClure NC, Venables WA (1990) Physical map of the aromatic amine and m- toluate catabolic plasmid pTDN1 in Pseudomonas putida: location of a uniquemetacleavage pathway. J Gen Microbiol 136:615–625

Sakamoto M, Tsutsumi T (2004) Applicability of headspace solid-phase microextraction to the determination of multiclass pesticides in waters. J Chromat A 1028(1):63–74

Sayler GS, Ripp S (2000) Field applications of genetically engineered microorganismsfor bioremediation processes. Curr Opin Biotechnol 11(3):286–289

Sayler GS, Hooper SW, Layton AC, King JMH (1990) Catabolic plasmids of environmental and ecological significance. Microbiol Ecol 19:1–20

Schneider T, Gerrits B, Gassmann R, Schmid E, Gessner MO, Richter A, Battin T, Eberl L, Riedel K (2010) Proteome analysis of fungal and bacterial involvement in leaf litter decomposition. Proteomics 10:1819–1830

Schreinemachers P, Tipraqsa P (2012) Agricultural pesticides and land use intensification in high, middle and low income countries. Food Policy 37:616–626

Scott C, Pandey G, Hartley CJ, Jackson CJ, Cheesman MJ, Taylor MC, Pandey R, Khurana JL, Teese M, Coppin CW, Weir KM, Jain RK, Lal R, Russell RJ, Oakeshott JG (2008) The enzymatic basis for pesticide bioremediation. Indian J Microbiol 48:65–79

Seo JSu, Keum YS, Reneen MH, Li QX (2007) Isolation and characterization of bacteria capable of degrading polycyclic aromatic hydrocarbons (PAHS) and organophosphorus pesticides from PAH-contaminated soil in hilo, Hawaii. J Agric Food Chem 55:5383–5389

Sessitsch A, Reiter B, Berg G (2004) Endophytic bacterial communities of field-grown potato plants and their plant-growth-promoting and antagonistic abilities. Canad J Microbiol 50(4):239–249

Sethunathan N, Yoshida T (1973) A *Flavobacterium* that degrades diazinon and parathion. Can J Microbiol 19:873–875

Shakoori AR, Makhdoom M, Haq RU (2000) Hexavalent chromium reduction by a dichromate-resistant gram-positive bacterium isolated from effluents of tanneries. Appl Microbiol Biot 53:348–351

Sharma S, Singh P, Raj M, Chadha BS, Saini HS (2009) Aqueous phase partitioning of hexachlorocyclohexane (HCH) isomers by biosurfactant produced by *Pseudomonasaeruginosa* WH-2. J Hazard Mater 171:1178–1182

Sharmila M, Ramanand K, Sethunathan N (1989) Effect of yeast extract on the degradation of organophosphorus

insecticides by soil enrichment and bacterial cultures. Can J Microbiol 35:1105–1110

Shetty PK, Murugan M, Sreeja KG (2008) Crop protection stewardship in India: wanted or unwanted. Curr Sci 95(4):457–464

Shields MS, Hooper SW, Sayler GS (1985) Plasmid mediated mineralization of 4-chlorobiphenyl. J Bacteriol 163: 882–889

Shivaramaiah HM (2010) Biodegradation of endosulfan by anabaena pesticide. Res J 22(2):125–128

Siddaramappa R, Rajaram KP, Sethunathan N (1973) Degradation of parathion by bacteria isolated from flooded soil. Appl Microbiol 26(6):846–849

Siddique T, Okeke BC, Arshad M, Frankenberger WT Jr (2003) Biodegradation kinetics of endosulfan by *Fusarium vetricosum* and a *Pandoraea* species. J Agric Food Chem 51:8015–8019

Silva IS, dos Santos EC, de Menezes CR, de Faria AF, Franciscon E, Grossman M et al (2009) Bioremediation of a polyaromatic hydrocarbon contaminated soil by native soil microbiota and bioaugmentation with isolated microbial consortia. Bioresour Technol 100:4669–4675

Singh M, Singh DK (2014) Biodegradation of endosulfan in broth medium and in soil microcosm by *Klebsiella* sp. M3. Bull Environ Contam Toxicol 92(2):237–242

Singh BK, Walker A (2006) Microbial degradation of organophosphorus compounds. FEMS Microbiol Rev 30(3):428–471

Singh BK, Walker A, Morgan JA, 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 JA, Wright DJ (2004) Biodegradation of chloropyrifos by *Enterobacter* strain B-14 and its use in bioremediation of contaminated soil. Appl Environ Microbiol 70(8):4855–4863

Singh DP, Khattar JIS, Nadda J, Singh Y, Garg A, Kaur N, Gulati A (2011) Chlorpyrifos degradation by the *Cyanobacterium Synechocystis* sp. strain PUPCCC 64. Environ Sci Pollut Res 18:1351–1359

Sinha N, Narayan R, Shanker R, Saxena DK (1995) Endosulfan-induced biochemical changes in the testis of rats. Vet Hum Toxicol 37:547–549

Sinha N, Narayan R, Saxena DK (1997) Effect of endosulfan on the testis of growing rats. Bull Environ Contamin Tox 58:79–86

Spooner RA, Lindsay K, Franklin FCH (1986) Genetic, functional and sequence analysis of thexylR and xylS regulatory genes of the TOL plasmid pWWO. J Gen Microbiol 132:1347–1358

Springael D, Ryngaert A, Merlin C, Toussaint A, Max M (2001) Occurrence of Tn*4371*-Related mobile elements and sequences in (chloro)biphenyl-degrading bacteria. Appl Environ Microbiol 67(1):42–50

Stockholm Convention Persistent Organic Pollutants, Government of India, 2009

Stockholm Convention Persistent Organic Pollutants, Government of India, 2011. moef.nic.in/downloads/public-information/NIP-India.pdf

Strong LC, McTavish H, Sadowsky MJ, Wacket LP (2000) Field-scale remediation of atrazine-contaminated soil using recombinant*Escherichia coli* expressing atrazine chlorohydrolase. Environ Microbiol 2:91–98

Su D, Li PJ, Frank S, Xiong XZ (2006) Biodegradation of benzo[a]pyrene in soil by *Mucor* sp. SF06 and *Bacillus* sp. SB02 co-immobilized on vermiculite. J Environ Sci 18:1204–1209

Suenaga H, Mitsuoka M, Ura Y, Watanable T, Furukawa K (2001) Directed evolution of biphenyl dioxygenase: emergence of enhanced degradation capacity for benzene, toluene and alkylbenzenes. J Bacteriol 183:5441–5444

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 Biodeter Biodeg 92:6–11

Taghavi S, Barac T, Greenberg B, Borremans B, Vangronsveld J, van der Lelie D (2005) Horizontal gene transfer to endogenous endophytic bacteria from poplar improves phytoremediation of toluene. Appl Environ Microbiol 71(2):8500–8505

Tamer MAMT, El-Naggar MAH (2013) Diazinon decomposition by soil bacteria and identification of degradation products by GC-MS. Soil Environ 32(2):96–102

Tan HM (1999) Bacterial catabolic transposons. Appl Microbiol Biotechnol 51(1):12

The Directorate of Plant Protection, Quarantine and Storage, Government of India (2010) Total pesticides consumed during 2005–2006 to 2009–2010, as per official data of (www.indiaforsafefood.in/farminginindia.html)

Themel K, Sparling R, Oleszkiewicz J (1996) Anaerobic dehalogenation of 2-chlorophenol by mixed bacterial cultures in absence methanogenesis. Environ Technol 17:869–875

Thomas B, Parkins IB (1995) Assimilative capacity of subsurface for the pesticides, atrazine and alachlor and nitrate. FEDRIP-Data base, National Technical Information Service (NTIS), USA

Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S (2002) Agricultural sustainability and intensive production practices. Nature 418(6898):671–677

Tomlin CDS (2002) The e-Pesticide Manual, Version 2.2. [CD-ROM], 12th edn. The Britich Crop Protection Council, UK

Top EM, van Daele P, de Saeyer N, Forney LJ (1998) Enhancement of 2,4-dichlorophenoxyaceticacid (2,4-D) degradation in soil by dissemination of catabolic plasmids. Anton van Leeuwen 73:87–94

Torres JPM, Fróes-Asmus CIR, Weber R, Vijgen J (2013a) HCH contamination from farmer pesticide production in Brazil—a challenge for the Stockholm Convention implementation. Environ Sci Pollut Res. doi:10.1007/s11356-012-1089-4

Torres JPM, Leite C, Krauss T, Weber R (2013b) Landfill mining from a deposit of the chlorine/organochlorine industry as source of dioxin contamination of animal feed and assessment of the responsible processes. Environ Sci Pollut Res. doi:10.1007/s11356-012-1073-z

Tralau T, Cook AM, Ruff J (2001) Map of the IncPb plasmid pTSA encoding widespread genes (*tsa)* for p-toluenesulfonate degradation in *Comamonas testosteroni* T2. Appl Environ Microbiol 67:1508–1516

Tsuda M, Tan HM, Nishi A, Furukawa K (1999) Mobile catabolic genes in bacteria. J Biosci Bioeng 87:401–410

Ueno A, Ito Y, Yumoto I, Okuyama H (2007) Isolation and characterization of bacteria from soil contaminated with diesel oil and the possible use of these in autochthonous bioaugmentation. World J Microbiol Biotechnol 23:1739–1745

UN/DESA (2008) Changing unsustainable patterns of consumption and production, Johannesburg plan on implementation of the world summit on sustainable development, Johannesburg, 2002 (Chapter III)

United Nations Environment Programme Chemicals (2011) UNEP Persistent Organic

Vaccari DA, Strom PF, Alleman JE (2006) Pollutants. Accessed 5th July 2010, http://www.chem.unep.ch/pops/

Vamsee-Krishna C, Phale PS (2008) Bacterial degradation of phthalate isomers and their esters. Indian J Microbiol 48(1):19–34

Van Der Heijden MGA, Bardgett RD, Van Straalen NM (2008) The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. Ecol Lett 11:296–310

Van der Meer JR, Zehnder AJB, de Vos WM (1991) Identification of a novel composite transposable element Tn5280, carrying chlorobenzene dioxygenase genes of *Pseudomonas sp.* strain P51. J Bacteriol 173:7077–7083

van der Meer J R, Ravatn R, Sentchilo V (2001) The clc element of Pseudomonas sp. strain B13 and other mobile degradative elements employing phage-like integrases. Arch. Microbiol 175:79–85

van der Meer JR, De-Vos WM, Harayama S, Zehnder AJB (1992) Molecular mechanisms of genetics adaptation to xenobiotic compounds. Microbiol Review 56:677–94

Van Elsas JD, Dijkstra AF, Govaert JM, van Veen JA (1986) Survival of *Pseudomonas fluorescens* and *Bacillus subtilus* introduced into two soils of different texture in field microplots. FEMS Microbiol Ecol 38:151–160

Van Herwijnen R, Van de Sande BF, Van der Wielen FWM, Springael D, Govers HAJ, Parsons JR (2003) Influence of phenanthrene and fluoranthene on the degradation of fluorine and glucose by *Sphingomonas* sp. strain LB126 in chemostatcultures. FEMS Microbiol Ecol 46:105–111

Van Limbergen H, Top EM, Verstraete W (1998) Bioaugmentation in activated sludge: current feature and future perspectives. Appl Microbiol Biotechnol 50:16–23

Vargas JM Jr (1975) Pesticide degradation. In: Presented at the international shade tree conference in Detroit, Michigan. J Arboricult 232–233

Velicer GJ (1999) Pleiotropic effects of adaptation to a single carbon source for growth on alternative substrates. Appl Environ Microbiol 65:264–269

Verma JP, Yadav J, Tiwari KN (2012) Enhancement of nodulation and yield of chickpea by co-inoculation of indigenous *Mesorhizobium* spp. and plant growth-promoting rhizobacteria in eastern Uttar Pradesh. Commun Soil Sci Plant Anal 43:605–621

Verma P, Verma P, Sagar R (2013) Variation in N mineralization and herbaceous species diversity due to sites, seasons, and N treatment in a seasonally dry tropical environment of India. For Ecol Manage 297:15–26

Vessey JK (2003) Plant growth promoting rhizobacteria as biofertilizers. Plant Soil 255:571–586

Vollmer MD, Hoier H, Hecht HJ, Schell U, Groning J, Goldman A, Schlomann M (1998) Substrate specificity of and product formation by muconate cycloisomerases: an analysis of wild type enzyme and engineered variants. Appl Environ Microbiol 64:3290–3299

Wang W-D, Niu JL, Cui ZJ (2005) Biodegradation of pesticides: a review. J Heilongj Aug First Land Reclama Univ 17(2):18

Wang Y, Xiao M, Geng X, Liu J, Chen J (2007) Horizontal transfer of genetic determinants for degradation of phenol between the bacteria living in plant and its rhizosphere. Appl Microbiol Biotechnol 77:733–739

Wang Y, Li H, Zhao W, He X, Chen J, Geng X, Xiao M (2010) Induction of toluene degradation and growth promotion in corn andwheat by horizontal gene transfer within endophytic bacteria.Soil Bio. Biochem 42:1051–1057

Wang L, Chi X-Q, Zhang J–J, Sun D-L, Zhou N-Y (2014) Bioaugmentation of a methyl parathion contaminated soil with Pseudomonas sp. strain WBC 3. Inte Biodete Biodeg 87:116–121

Wasilkowski D, Swędzioł Ż, Mrozik A (2012) The applicability of genetically modified microorganisms in bioremediationof contaminated environments. Science 66(8):817–826

Wattiau P, Bastiaens L, van Herwijnen R, Daal L, Parsons J R, Renard M E, Cornelis G R. (2001). Fluorene degradation by *Sphingomonas* sp. LB126 proceeds through protocatechuic acid: a genetic analysis. Res Microbiol 152(10):861–872

Weber R, Varbelow HG (2013) Dioxin/POPs legacy of pesticide production in Hamburg: part 1—securing of the production area. Environ Sci Pollut Res. doi:10.1007/s11356-012-1011-0

WHO (2004) The WHO recommended classification of pesticides by hazard and guidelines to classification, 2004

Williams PA, Worsey MJ (1976) Ubiquity of plasmids in coding for toluene and xylene metabolism in soil bacteria: evidence for the existence of new TOL plasmids. J Bacteriol 125:818–828

Wolfe NL, Zepp RG, Paris DF (1978) Use of structure-reactivity relationships to estimate hydrolytic persistence of carbamate pesticides. Water Resour 12:561–563

Wood TK (2008) Molecular approaches in bioremediation. Curr Opin Biotechnol 19:572–578

World Bank (2010). World Development Indicators; Rising Global Interest in Farmland. Can it Yield Sustainable and Equitable Benefits? Washington. (available from http://data.worldbank.org/data-catalog/world-development-indicators)

Xiao PF, Kondo R (2013) Biodegradation of dieldrin by cordyceps fungi and detection of metabolites. Appl Mecha Mater 295–298:30–34

Xiao P, Mori T, Kamei I, Kondo R (2011) Metabolism of organochlorine pesticide heptachlor and its metabolite heptachlor epoxide by white-rot fungi, belonging to genus phlebia. Microbiol Lett 314(2):140–146

Xu GM, Li YY, Zheng W, Peng X, Li W, Yan YC (2007) Mineralization of chlorpyrifos by co-culture of *Serratia* and *Trichosporon* sp. Biotechnol Lett 29:1469–1473

Xu G, Zheng W, Li Y, Wang S, Zhang J, Yan Y (2008) Biodegradation of chlorpyrifos and 3,5,6-trichloro-2-pyridinol

by a newly isolated *Paracoccus* sp. strain TRP. Int Biodeter Biodegr 62:51–56

Yan DZ, Lui H, Zhou NY (2006) Conversion of *Sphingobium-chlorophenolicum*ATCC 39723 to a hexachlorobenzene degrader by metabolic engineering. Appl Environ Microbiol 72:2283–2286

Yang, Zhao Y, Zhang B, Yang C, Zhang X (2005) Isolation and characterization of a chlorpyrifos and 3,5,6-trichloro-2-pyridinol degrading bacterium. FEMS Microbiol Lett 251:67–73

Yang L, Wang Y, Song J, Zhao W, He X, Chen J, Xiao M (2011) Promotion of plant growth and in situ degradation of phenol by an engineered Pseudomonas fluorescens strain in different contaminated environments. Soil Biol Biochem 43(5):915–922

Ye D, Siddiqi MA, Maccubbin AE, Kuma S, Sikka HC (1996) Degradation of polynuclear aromatic hydrocarbons by *Sphingomonas paucimobilis*. Environ Sci Technol 30:136–142

Yee DC, Maynard JA, Wood TK (1998) Rhizoremediation of trichloroethylene by a recombinant, root-colonizing Pseudomonas fluorescens strain expressing toluene orthomonooxygenase constitutively. Appl Environ Microbiol 64:112–118

Yim YJ, Seo J, Kang SI, Ahn JH, Hur HG (2008) Reductive dechlorination of methoxychlor and DDT by human intestinal bacterium Eubacterium limosum under anaerobic conditions. Arch Environ Contam Toxicol 54:406–411

You M, Liu X (2004) Biodegradation and bioremediation of pesticide pollution. Chin J Ecol 23:73–77

Yrjala K, Paulin L, Romantschuk M (1997) Novel organization of catechol meta-pathway genes in Sphingomonas sp. HV3 pSKY4 plasmid. FEMS Microbiol Lett 154:403–408

Yuan Y, Guo SH, Li FM, Li TT (2013) Effect of an electric field on *n*-hexadecane microbial degradation in contaminated soil. Int Biodeterior Biodegrad 77:78–84

Yu YL, Shan M, Fang H, Wang X, Chu XQ (2006) Responses of soil microorganisms and enzymes to repeated applications of chlorothalonil. J Agric Food Chem 54:10070–10075

Zaitsev G, Uotila JS, Tsitko IV, Lobanok AG, Salkinoja-Salonen MS (1995) Utilization of halogentad benzenes, phenols, and benzoates by *Rhodococcus opacus* GM-14. Appl Environ Microbiol 61:4191–4201

Zboinska E, Lejczak B, Kafarski P (1992) Organophosphonate utilization by the wild-type strain of *Pseudomonas fluorescens*. Appl Environ Microbiol 58:2993–2999

Zhao H-P, Wu Q-S, Wang L, Zhao X-T, Gao H-W (2009) Degradation of phenanthrene by bacterial strain isolated from soil in oil refinery fields in Shanghai China. J Hazard Mater 164:863–869

Zhu J, Zhao Y, Qiu J (2010) Isolation and application of a chlorpyrifos-degrading Bacillus licheniformis ZHU-1. Afr J Microbiol Res 4:2410–2413

Zylstra GJ, Kim E (1997) Aromatic hydrocarbon degradation by Sphingomonas yanoikuyae B1. J Ind Microbiol Biotechnol 19:408–414