Chapter 10
Advances in Biological Treatment Technologies for Some Emerging Pesticides

Buzayehu Desisa, Alemayehu Getahun, and Diriba Muleta

Abstract Although pesticides are highly helpful for crop production, environmental contamination with persistent and potentially eco-toxic pollutants discourage their utilization. Soil is full of pesticides with significant environmental and human health problems. The contaminants' behavior, types, complexity, toxicity, and their transformation products have an environmental concern. Pesticides are the known emerging contaminants (ECs) identified in different environmental sources. Tackling these pollutants is vital in creating healthy environment in order to ensure food security and proper water supplies to feed the growing world population. Additional contaminants are released via physical and chemical remediation methods and are considered destructive and highly expensive. Thus, bioremediation is an economical and eco-friendly tool since it uses bacteria, fungi, algae, plants, and their interactions in removing toxicants. Revolutions in genetic engineering techniques aid to explore pollutant-degrading microbes. Therefore, this review mainly focuses on portraying pesticides as ECs, the different types and classes of pesticides, and their fate in the environment. Moreover, the pivotal focus of this review is on the eco-friendly bioremediation technologies available for the removal of these pollutants to maintain a sustainable environment with a healthy and productive ecosystem.

Keywords Bioremediation · Emerging contaminants · In situ · Pesticides · Phytoremediation · Treatment technologies

10.1 Introduction

Global industrialization releases contaminants that can cause harm to all life forms (Quintella et al. 2019). The quality of the environment outlines the quality of life on the planet. As stated by Azubuike et al. (2016), unsafe agricultural and ecological practices can potentially bring environmental pollution. There is also a continuous application of synthetic fertilizers and other agrochemicals to feed a rapidly growing global population (Carvalho 2017). Consequently, several toxic

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contaminants enter into the productive farmlands from multiple sources (Raghunandan et al. 2018). Patel et al. (2020) have indicated emerging contaminants (ECs) that are used on the daily basis including pesticides, plasticizers, pharmaceuticals, personal care products (PCPs), and chemical surfactants. More than 80% of pesticides are in use for a food production system. This amount of pesticides on the total environment needs immediate bioremediation options in the era of sustainable agriculture.

Crops are severely affected by diverse pests. Accordingly, Pimentel et al. (2001) have reported that each year China lost 40 million tons (8.8%) of the country's total grain output. Likewise, India loses also 11–15% of its total output yearly due to pests and other causes (Walter et al. 2016). Thus, to ensure food security, pesticides are extensively used in modern agriculture. Generally, different types of crops are seriously affected by pests with significant yield losses (Fig. 10.1) and need the application of agrochemicals. A growing body of evidence shows that pesticides application can reduce 35–42% crop loss from pests (Pimentel and Burgess 2014). Sharma et al. (2019) have estimated 3.5 million tons of pesticides usage in 2020 with concomitant pollution of the environment. The complex structure and existence at low concentrations make these pollutants untraceable and difficult to remove from the environment (Patel et al. 2020).

The quality of soil and its processes are affected by the use of pesticides in agricultural production systems. Runoff, leaching, and/or vaporization determine the persistence and movements of pesticides in soil, air, and water (Gavrilescu 2005). The function and health of living organisms are greatly influenced by the accumulation and magnification of pesticides in the food chain. Due to these threats, pesticides degradation (remediation) is of great importance (Zulfiqar and Yasmin 2020).

The physical, chemical, and biological pesticides treatment techniques are used (Saleh et al. 2020). The environmental risks of chemical and physical methods may pose low public acceptance, as well as excavation, handling, transportation, and removal costs, are not always sufficient. Thus, eco-friendly remediation approaches are needed to destroy and transform pesticides into harmless substances (Morillo and Villaverde 2017). Likewise, Patel et al. (2020) have presented bioremediation as an important and eco-friendly technology in pollutants treatment. In this paper, the

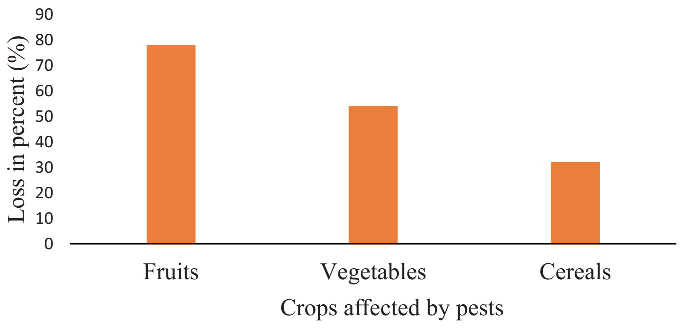

Fig. 10.1 Loss of crop yields by pests. (Modified from Pimentel and Burgess 2014)

negative impact of pesticides on the natural environment is discussed. The chemical and physical treatment options are usually costly and are not eco-friendly as well as aggressive to soil and soil microbiota. Hence, this review provides more insight into the bioremediation techniques using mainly microbes that have proven effectiveness and reliability in removing toxicants from the environment.

10.2 Pesticides as Emerging Contaminants (ECs)

Emerging contaminants (ECs) are unregulated compounds discovered in the environment. ECs are not yet widely regulated by national or international laws and are named emerging for the rising level of concern (Glassmeyer 2007; Sauvé and Desrosiers 2014). Human-induced activities increased the release of ECs into the natural environment (Arihilam and Arihilam 2019). Such contaminants create unique and considerable challenges and deserve attention (Bell et al. 2019). Emerging contaminants cause adverse ecological and human health problems (Patel et al. 2020; Zhang et al. 2019). Neonicotinoids are a first-hand generation of pesticides applied to control pests (Tomizawa and Casida 2003) and (Cloyd and Bethke 2011).

10.2.1 Types of Emerging Pesticides

Pesticide is an umbrella term used to kill, repel, and control some forms of animal and plant life and it can apply to a wide spectrum of chemicals. These synthetic toxicants vary in their characteristics and are classified under their respective groups (Freeman 2020). Figure 10.2 indicates percentages of frequently applied pesticides for agricultural production (Mekouar 2015).

Pesticide classification based on chemical composition is the most common and useful approach that gives clues about the efficacy, physical, and chemical properties of the respective pesticides (Yadav and Devi 2017). The chemical and physical characteristics of pesticides determine their mode of application and need precautions during use (Kaur et al. 2019; Mileson et al. 1998). The chemical classification

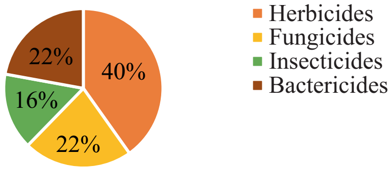

Fig. 10.2 The most applied pesticides (%) for agricultural production. (Adapted and modified from Mekouar 2015)

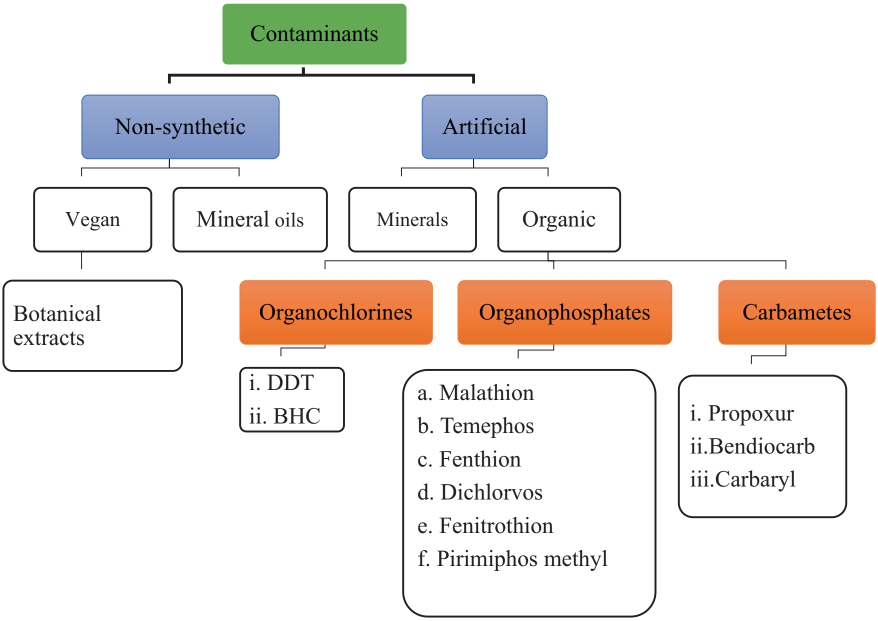

Fig. 10.3 The chemical composition of pesticides. (Adapted and modified from Kaur et al. 2019)

of pesticides is highly useful for its practical application (Gavrilescu et al., 2006; Kaur et al. 2019; Zacharia 2011) (Fig. 10.3).

10.2.2 Common Features of Pesticides

Agrochemicals have proven potential to increase the production and productivity of crops. However, damage to the environment due to the irresponsible use of these synthetic chemicals decreases their application (Meena et al. 2020). Hence, initiatives that address these questions are desirable. Understanding the common features of a pesticide allows a better pesticide formulation to apply for a particular situation to maintain the integrity of the environment. The fate of pesticides is mainly determined by their characteristics (water solubility and persistence) and soil properties (Gavrilescu 2005; Pereira et al. 2016).

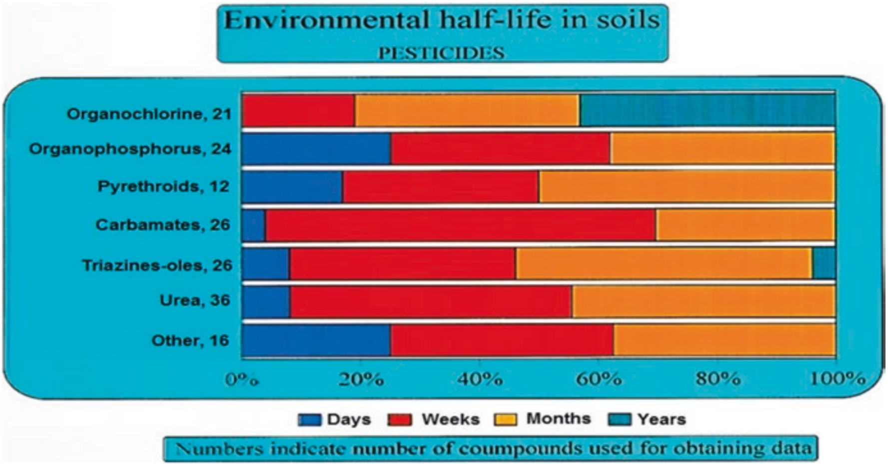

Fig. 10.4 The persistence of some pesticides in soils. (Data are available in Carvalho (2017) modified from Carvalho et al. (1997)

Table 10.1 Persistence and toxicity of pesticides. Adapted from Madigan and Martinko (2006)

Insecticide class	Example	Persistence	Toxicity to mammals
Organochlorides	DDT, dieldrin, toxaphene, chlordane, lindane	High	Relatively low
Organophosphates	Parathion, malathion, acephate, phorate, chlorpyrifos	Moderate	High
Carbamates	Carbaryl, methomyl, aldicarb, carbofuran	Low	High to moderate
Pyrethroids	Permethrin, bifenthrin, esfenvalerate, decamethrin	Low	Low

10.2.3 Persistence of Pesticides

Understanding the properties and the behavior of agrochemicals is important in the environment. These properties are linked to the products' mobility in the soil, dissociation in water, bioaccumulation, and durability in the environment (Pereira et al. 2016). The extended half-life, the more the persistent pesticide. Pesticides show considerable variations in their persistence in soils (Fig. 10.4). Persistence is affected by chemical, microbial, and photodegradation processes in the breakdown of a single pesticide (Schaafsma et al. 2016). The rate of pesticides degradation depends on its chemistry, soil environment, and microbial activities (Tiryaki and Temur 2010).

The persistent nature of pesticides in the soil is determined by their continuous applications and classifies as non-persistent, moderately persistent, or persistent

(Kerle et al. 2007; Tiryaki and Temur 2010). Less than 1% of the pesticides applied to crops attain the target pest species while an excess of them moves throughout the environment and enters marine ecosystems and keeps them there sufficiently long (Carvalho et al. 1997).

Toxicity is also another important characteristic of pesticides and it can vary depending on the target organism taken into consideration Table 10.1 (Madigan and Martinko 2006).

10.2.4 Health Effects of Pesticides

Although pesticides bring indiscriminate use resulted in serious health, they considerably improve crops production and productivity (Tudi et al. 2021). There are many routes for the entrance of pesticide residues into the food chain and can be carcinogenic or cytotoxic. This in turn causes different disorders, infertility to the affected organisms (Audrey et al. 2012). There are multiple uses of pesticides to destroy weeds, insects, fungi, and rodents (Kumar et al. 2012). Each year, 3 million insecticide poisoning, 220,000 deaths, and 2.2 million people are exposed in developing countries (Hicks 2013). The damage of pesticides to living organisms including plants is enormous (Rasheed et al. 2019). For instance, photosynthesis is impaired in susceptible plants (Tandon 2018). The author further remarked that cardiovascular, retinal, and muscle degeneration occur in humans via herbicides exposure.

Recently, pesticide poisoning caused greater than 17 million deaths from 1960 to 2019 (Karunarathne et al. 2020). Globally, the accumulation of organochlorine in the food chain distresses nearly one billion people due to hypertension (Karunarathne et al. 2020). A study in New York reported the presence of 100% and 47–78% levels of organophosphate (OP) and organochlorine pesticides (OCPs), respectively in pregnant women (Whyatt et al. 2002).

10.2.5 Environmental Outcome of Pesticides

Microbial consortia degrade and transform different pesticides and still, the resistant ones stay in the environment and food chains (García-Reyes et al. 2007). There are different modes of distribution of pesticides from target to non-targeted organisms in the environment (Tiryaki and Temur 2010). Many things happen to pesticides including the leaching of some herbicides into the root zone that can give better weed control.

The methods of pesticides application cause intoxication to the victimized individuals (Carvalho 2017). Globally, 355,000 people died each year with excessive exposure and inappropriate use of toxic chemicals (Alavanja and Bonner 2012). Pesticides may attribute to the soil, plants, move with eroded soil, dissolve in water,

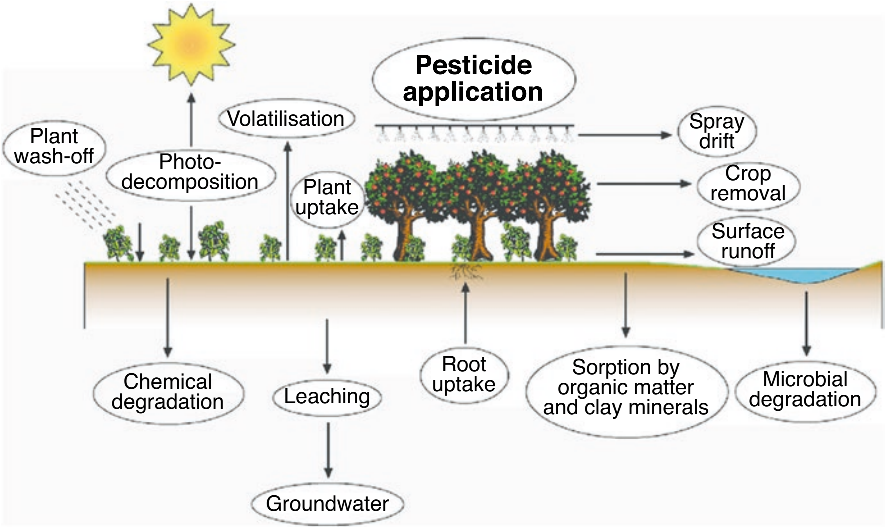

Fig. 10.5 The environmental outcome of pesticides. (Adapted from Sarmah et al. 2004)

leach, volatilize, and become airborne (Kerle et al. 2007; Tiryaki and Temur 2010). The environment is affected by pesticides via bidirectional sources, i.e., point-source and nonpoint-source pollution (Viman et al. 2010). The former is contamination that comes from a specific and identifiable place, while the latter is the contamination that comes from a wide area (Toth and Buhler 2009). Once the pesticides are disposed to the environment, they enter into physical, biological, and chemical processes which in turn affect their behavior, efficiency, and persistence (Fig. 10.5; Briggs 2018; Sarmah et al. 2004).

10.3 Removal Strategies of Pesticides

The prominent stability and water solubility of pesticide residues determine their persistence in the ecosystem. The physical, chemical, or biological technologies are used to reduce, eliminate, or stabilize pesticides in the soil (Marican and Durán-Lara 2018; Saleh et al. 2020). Each treatment technique has its limitations in operational costs, efficiency, operability, reliability, and toxic byproducts (Khalid et al. 2017; Saleh et al. 2020). The generations of many emerging contaminants that led to the development of eco-friendly treatment techniques are presented in (Fig. 10.6). Site characteristics, concentration, and type of pesticides should be considered during designing pesticides removal strategies (Morillo and Villaverde 2017).

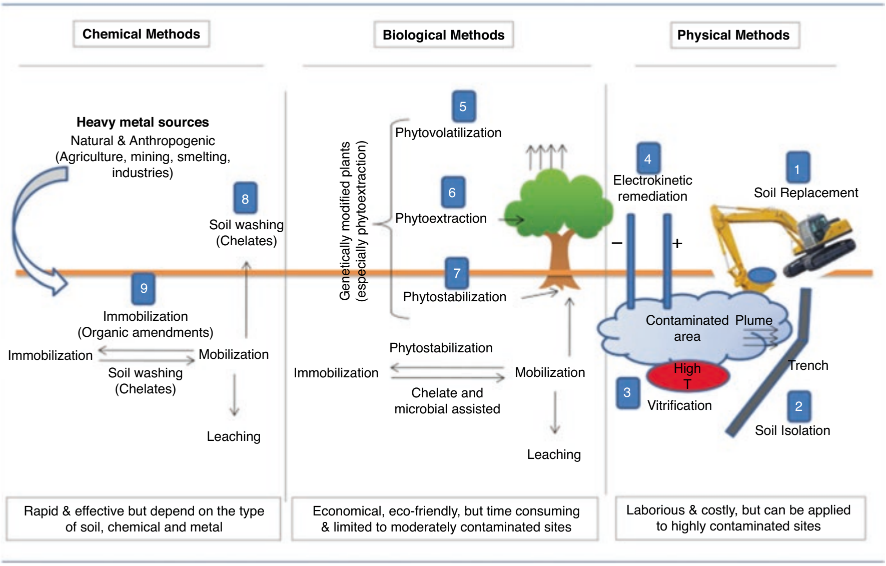

Fig. 10.6 Different soil treatment approaches. (Amended from Khalid et al. 2017)

10.3.1 Physical and Chemical Methods

One way of pesticides treatment option is by using physical and chemical methods. The majority of them are costly, destructive (which may implicate some level of hazard), and time-consuming (Khalid et al. 2017; Monteiro et al. 2012). Activated carbon and oxidation systems are energy-demanding, expensive, and increase local water prices by 10–40% (Ågerstrand et al. 2015). Physical, chemical, and physico-chemical degradation have resulted in further environmental deterioration (Huang et al. 2008). This necessitates the application of economical and eco-friendly pollutants removal options (Monteiro et al. 2012).

10.3.2 Biological (Bioremediation) Processes of Remediation

Bioremediation is a process in which bacteria, algae, plants, fungi, and other biota are involved in the process of contaminant removal (Garcia-Rodríguez et al. 2014). During this process, contaminants are degraded, altered, immobilized, or detoxified. The biological method is an attractive and greener technology that completely

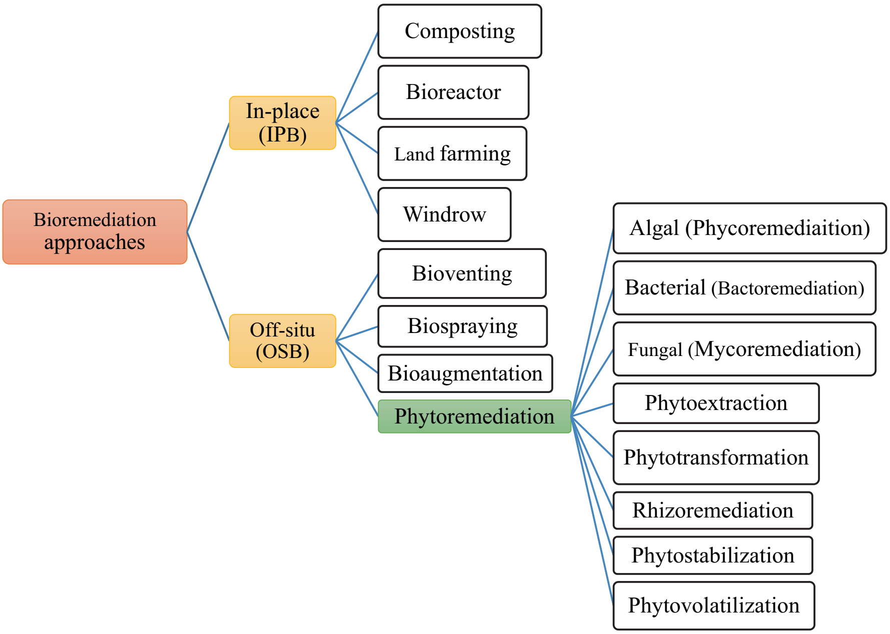

Fig. 10.7 The different types of contaminants and their bioremediation techniques

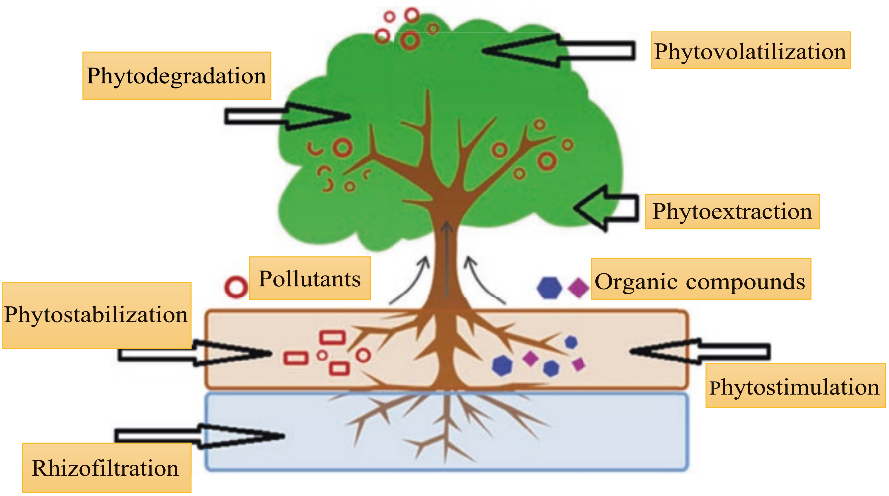

Fig. 10.8 Different types of phytoremediation practices. (Adapted and modified from Schnoor 1997)

converts neutralized contaminants and minimize their harmful effect (Nwankwegu and Onwosi 2017; Sinha et al. 2009).

Ex situ and in situ are the two major types of bioremediation techniques based on application sites (Azubuike et al. 2016). During the in situ bioremediation method, pollutants are treated on the place of contamination (natural site) but contaminants are transported from natural place during ex situ bioremediation (Caliman et al. 2011). Composting, phytoremediation, and bioaugmentation are the main bioremediation methods by involving a diverse group of organisms (Fig. 10.7). Many bacterial genera of *Alcaligenes*, *Flavobacterium*, *Pseudomonas*, and *Rhodococcus* are involved in pesticide degradation (Boricha and Fulekar 2009; Richins et al. 1997). There are various factors for the choice of the most appropriate and feasible in situ or ex situ bioremediation techniques (da Silva et al. 2020).

Phytoremediation uses plants as the main tool to remove different contaminants from the environment by involving diverse mechanisms (Fig. 10.8; Schnoor 1997).

10.3.2.1 Off-Site Bioremediation Approaches (OSB)

Off-site biotreatment (OSB) is the removal of contamination out of their natural site (Pandey et al. 2009). During OSB, contaminated soil is transported to another location for treatment and this approach makes OSB more expensive since it incurs the cost of transportation (Azubuike et al. 2016).

Contaminated Soil Treatment

Contaminated soil treatment is a land farming off-site bioremediation (OSB) technology in which contaminants are mixed with amendments in the upper soil horizon (Castelo-Grande et al. 2010). This process is a proven soil remediation technology that reduces the concentration of contaminants found in the soil (Parween et al. 2018). Soil contains microbes (fungi, algae, and bacteria) that can metabolize pesticides to enhance the remediation process. Land farming is a cost-efficient and eco-friendly approach to implement (Morillo and Villaverde 2017). The periodic turning of contaminated soil helps to increase aeration, moisture, nutrients affect pollutants biodegradation process by stimulating the activities of autochthonous microorganisms (Sharma 2020). Bhadbhade et al. (2002) have also described 83–93% of the degradation of the organophosphorus pesticide by soil bacteria. In another study, a 96% reduction in isoxathion using bacteria (Ohshiro et al. 1996). Furthermore, Tang and You (2012) have verified that bacteria were capable of degrading 33.1–95.8% of triazophos pesticides in soil indicating the efficiency of land farming in the removal of toxicants.

Composting

It is an aerobic process of degrading organic wastes into humus-like fertilizer by the involvement of microorganisms. The breakdown of contaminants is accelerated due to the heat produced during degradation (Niti et al. 2013). Microorganisms present during composting of wastes with pesticides play a significant role in bioremediation (Castelo-Grande et al. 2010; Yañez-Ocampo et al. 2016). The incorporation of different leftover wastes brings beneficial microorganisms with pesticide degradation potential (Briceño et al. 2007). Three successions of microbes occur during composting, i.e., psychrophilic, mesophilic, and thermophilic (Pavel and Gavrilescu 2008). Petruska et al. (1985) have indicated that diazinon 22% and chlordane 50% are lost during cow manure and sawdust composting due to volatilization. Singh (2008) has also identified 96.03% endosulfan degradation efficiency as a result of composting.

10.3.2.2 In-Place Bioremediation (IPB)

In-place bioremediation (IPB) remains a technology that removes contaminants under the natural environment without the need for excavation (Pandey et al. 2009). Strobel et al. (2011) have found that the effectiveness of IPB can be enhanced by improving the chemotactic behavior of the degrading microbes. White-rot fungi can be used in pesticide bioremediation due to the lignin-degrading potential of their enzyme complex (Magan et al. 2010).

Bioaugmentation

Bioaugmentation is on-site treatment practice done with the addition of cultured microorganisms to the surface of the soil for contaminant degradation (Cycoń et al. 2014). It is considered a green technology because of its eco-friendly approach to contaminant removal (Cycoń et al. 2017). The presence of a complete catabolic pathway would ensure the complete mineralization of the target pesticides (Isaac et al. 2017). Castro-Gutiérrez et al. (2019) have indicated atrazine (68.4%), carbendazim (96.7%), carbofuran (98.7%), and metalaxyl (96.7%) removal with a biomixture of the active core of bio-purification systems complemented with *Trametes versicolor*. A pesticide carbofuran is effectively removed from the contaminated site by *T. versicolor* inoculation (Madrigal-Zúñiga et al. 2016). Moreover, 85–90% atrazine reduction was achieved using *T. versicolor* (Bastos and Magan 2009). A novel bacterium (*Achromobacter xylosoxidans* PY4) had a 50% potential in metabolizing aromatic carbon rings (Nzila et al. 2018).

Phytoremediation

One of the promising cost-effective and eco-friendly strategies is phytoremediation or plant-assisted bioremediation and employed for over 300 years (Trapp and Karlson 2001; Zavoda et al. 2001). Phytoremediation is a solar power-driven technique that used pollutant scavenging potential plant species (Mir et al. 2017). In this process, contaminated sites are treated as the pesticides are take-up by plants and converted to less toxic ones (Singh and Singh 2017). Plants eliminate pollutants via phytoextraction, phytodegradation, phytovolatilization, and rhizodegradation (Truu et al. 2015). Plants deliver a promising microenvironment that facilitates contaminants degradation using both rhizospheric and endophytic bacteria (Niti et al. 2013).

Successful toxic herbicide residues reduction by bacterial endophytes in plants was investigated earlier (Germaine et al. 2006). In the contaminated soil, improved atrazine, metolachlor, and trifluralin reduction observed in the place where *Kochia* sp. was planted (Coats and Anderson 1997). Herbicides isoproturon and glyphosate are eliminated from contaminated water by planting *Lemna minor* (Dosnon-Olette et al. 2011). Genetic engineering of both microbes and plants provides a promising bioremediation approach (McGuinness and Dowling 2009). A growing body of evidence shows that transgenic plants are produced to avoid different pesticides from contaminated places (Kawahigashi 2009). Fifteen different persistent organochlorine pesticides were successfully reduced by *Ricinus communis* after 66 days of evaluation (Rissato et al. 2015).

Mycoremediation

It is the involvement of fungi in pollutant removal (Kulshreshtha et al. 2014). Toxicants/pollutants are accumulated inside fungal structures and are also used as a carbon source upon enzymatic degradation (Adenipekun and Lawal 2012). Accordingly, these transformation and detoxification processes can efficiently remove pesticides from the ecosystem (Tortella et al. 2005). The presence of an extended hyphal network and uniqueness preferred fungi in pesticide remediation (Chen et al. 2012).

Ligninolytic fungi secrete several extracellular enzymes to transform recalcitrant pollutants (Anastasi et al. 2013; Harms et al. 2017). Saprotrophic fungi produce many enzymes for pesticide degradation (Wu et al. 2015). There are many white-rot fungal strains reported as lindane, diuron, and other pesticides degraders (Sagar and Singh 2011; Singh et al. 2020).

Bactoremediation

Pesticides bioremediation uses beneficial bacterial strains as an alternative option (Gavrilescu 2005). The surging need for green technology forces in searching potential bacteria strains (Jay et al. 2011). There are many bacterial genera with a

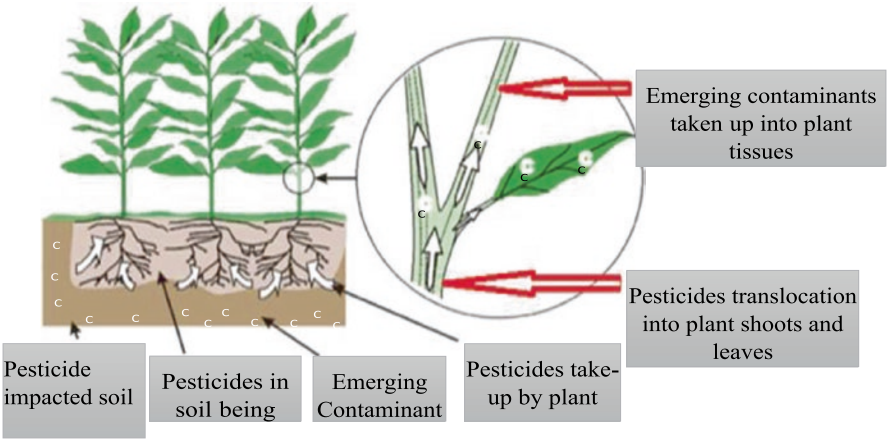

Fig. 10.9 Phytoaccumulation of organic contaminants. (Adapted and modified from Technology and Council 2009)

promising pesticides removal efficiency (Ortiz-Hernández et al. 2013). Bacterial species are known to hydrolyze bonds responsible for the enhancement of organophosphorus pesticide degradation (Singh and Walker 2006). Many bacterial species are effective in pollutant degradation (Huang et al. 2008). A 100% diazinon and organophosphate removal is seen in *Stenotrophomonas* sp. (Deng et al. 2015). *Arthrobacter*, *sulfonivorans*, *Variovorax soli*, and *Advenella* sp. bring 22–69% diuron mineralization (Morillo and Villaverde 2017). The process of degradation depends on bacterial type due to the release of different enzymes including oxygenase, hydroxylase, hydrolase, and isomerase (Karigar and Rao 2011).

Phycoremediation

Phycoremediation is one of the green technologies used to remove toxic substances via the application of microalgae or macroalgae (Rao et al. 2019). The fast growth nature, utilization of light and organic carbon offer microalgae a better pollution degradation (Dębowski et al. 2020). Internal defense mechanisms of microalgal species help to survive in contaminated sites (Torres et al. 2017). Many pollutants and different heavy metals are eliminated from the contaminated sites using microalgae (Danouche et al. 2021). During 11 days of treatment, the removal and reduction of atrazine herbicides and lindane by green algae *Selenastrum capricornutum* have been confirmed in the earlier investigation (Friesen-Pankratz et al. 2003). Moreover, chlorophenol is transformed and stored in the cells of *Chlorella* VT-1 by reducing its toxicity level (Scragg et al. 2003).

Phytoextraction/Phytoaccumulation

Phytoextraction is the ability of plants or algae to eliminate contaminants from their site via storage in their parts. The contaminants are phytoextracted in the aboveground plant parts (Singh and Singh 2017). Shoots and leaves are the plant parts where the pollutants accumulated (Abdel-Shafy and Mansour 2018). Hyperaccumulators and chelators are the main processes in phytoextraction (Utmazian and Wenzel 2006). Mukherjee and Kumar (2012) have confirmed that 47.2% and 34.5% organochlorine pesticide (endosulfan) removal using mustard (*Brassica campestris*) and maize (*Zea mays*) respectively. Transport protein inhibitors prevent the entrance of pollutants into the plant but help to be sequestered into the vacuoles of root cells (Fig. 10.9; Technology and Council 2009).

Phytodegradation (Phytotransformation)

Phytodegradation/phytotransformation is a process of pollutant degradation using microorganisms within plant tissues (Abdel-Shafy and Mansour 2018). Detoxification, transformation, and mineralization are important features involved in contaminant metabolism (Singh and Singh 2017). In this process, contaminants are degraded using microbial/plant enzymes. There is no complete breakdown (H_2O, CO_2, etc.) for complex and recalcitrant compounds by plants (Newman and Reynolds 2004). By and large, different pesticides are transformed in plants that release different enzymes (Kurasvili et al. 2014). For instance, enzyme glucosyltransferases detoxify organochlorine in *Phragmites australis* plants (San Miguel et al. 2013).

Rhizoremediation

Rhizoremediation is the process of pollutant degradation using catalytic microorganisms in association with plants around the plant rhizosphere (Khan et al. 2013; McCutcheon and Schnoor 2004). In this method, pesticides are degraded by naturally occurring rhizosphere due to the release of nutrients (Niti et al. 2013). Plant root exudates act as a carbohydrate source for microbial growth and are used as chemotactic signals for microbes (Dzantor 2007). The interaction of mycorrhizal fungi and ryegrass rhizosphere in bioremediation of chlorpyrifos is found effective (Korade and Fulekar 2009). The microbial populations near the rhizosphere of plants are stimulated by organics released from roots (Miya and Firestone 2001; Shaw and Burns 2007). The bacterial species *Klebsiella*, *Pseudoarthrobacter*, and *Pseudomonas* are known to transform lindane from 10% to 15% (Nagpal and Paknikar 2006).

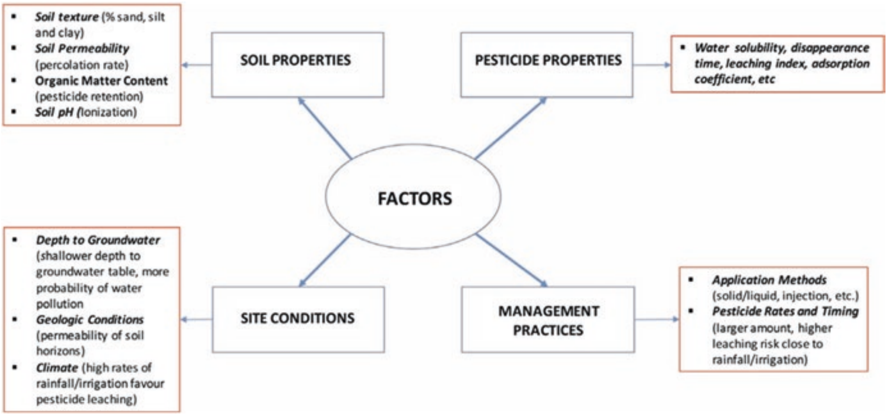

Fig. 10.10 Aspects of pesticides bioremediation in the soil. (Adapted from Gavrilescu 2005)

10.4 Detrimental Factors for Emerging Pesticides Bioremediation in Soil

The final fate of pollutant bioremediation is determined by the chemical nature and concentration of pollutants, characteristics of the environment, and microorganisms present in the soil (El Fantroussi and Agathos 2005). Soil type, temperature, pH, presence of oxygen, and nutrients are some of the factors that remarkably influence microbial pesticides degradation (Rani and Dhania 2014). Higher pollutant degradation is realized near the sub-surface soil due to higher nutrient levels (Lauber et al. 2009). Several factors potentially limit pesticides treatment strategies (Gavrilescu 2005). Soil is the ultimate sink of the pesticides applied in agriculture and acts as a storehouse of various kinds of microbes (Fig. 10.10).

Water (moisture content) is required for the biodegradation process (Riser-Roberts 1998). Generally, the optimum moisture level of 25–85% water holding capacity is needed for soil bioremediation (Niti et al. 2013). Evidence is accumulating that fluroxypyr degradation is slow under low water holding capacity (Tao and Yang 2011). Pesticides degradation is also limited if the nutrient availability and oxygen concentration are minimal. Hence, microbial augmentation can enhance nutrient availability for better pollution removal (Eskander and Saleh 2017). The pH of the soil affects the availability of nutrients and microbial activity and thus reduces the bioremediation process (Odukkathil and Vasudevan 2013). For instance, some strains of bacteria can degrade over 70% of petroleum at pH 7 and 9 (Xu 2012).

Temperature is the other influential factor affecting the rate of pesticide biodegradation by governing the speed of enzymatic reactions within microorganisms. Soil temperature less than 20 °C is not conducive for atrazine and lindane removal and causes leaching from the contaminated site (Paraíba et al. 2003). On the other hand, better oxyfluorfen biodegradation was seen at 40 °C (55.2–78.3%) than at 28 °C (17.5–36.6%) (El Hussein et al. 2012). Thus, the optimum temperature for biodegradation of pesticides may depend on the chemical nature of a pollutant and a microbe involved in the process of removal.

10.5 Merits and Demerits of Biodegradation of Pesticides

Appropriate methods, suitable environments with the right microorganism are needed for a successful bioremediation process (Cycoń et al. 2017). Residues from the treatment are usually harmless products (H_2O, CO_2, and cell biomass) (Rani and Dhania 2014; Singh 2008). In situ bioremediation is an appropriate bioremediation or phytoremediation technique and would be self-maintained through all the year. Bioremediation has also its limitations. Few bioremediations have been found for each pesticide. One important issue is the time required for remediation because biological processes are slow compared to conventional physical and chemical methods. However, bioremediation is superior to physical and chemical remediation methods since the latter is destructive, costly, and tedious.

10.6 Genetics for Pesticide Degradation

Many pollutants are recalcitrant and remain resistant to microbial attack. This condition necessitates an urgent need for microbial genetic manipulation. Correspondingly, genetic engineering is a better solution for microbial improvement for a better remediation process (Janssen and Stucki 2020). Soil contains metabolically versatile microbes but the search for new strains with potential pesticide degraders requires genetic modification of existing genetic material from metagenomic studies (Maheshwari et al. 2017). Thus, it is possible to develop bacterial strains that can adapt and immobilize pesticides with a high degradation rate (Saez et al. 2014). The modifications and manipulation of microbes to effectively remove contaminants from the site are a suitable and effective approach (Huang and Lu 2021; Ortiz-Hernández et al. 2013). Genetic alterations allow an alternative for better pesticide degradation (Zulfiqar and Yasmin 2020). Accordingly, herbicides 2,4-D and 2,4,5-T were mainly degraded by *Pseudomonas* sp. and *Alicaligenes* sp. (Huong et al. 2008).

10.7 Future Perspectives

The increased food demand to feed the global growing populations prompts the application of different pesticides to increase the production and productivity of crops by controlling plant diseases and pests. However, pesticides application brings serious harm to human and environmental health and demands eco-friendly solutions. Thus, bioremediation technologies are considered an eco-friendly strategy to overcome problems associated with synthetic agrochemicals. The understanding of the environmental fate and an integrated approach for pesticide remediation has a vital impact on the knowledge of pesticide science and biological applications. Furthermore, to avoid bioaugmentation, it is essential to find the most satisfactory bioremediation strategies.

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