Chapter 22
Microbial Enzymes and Their Role in Phytoremediation

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Contents

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1 Introduction

Due to the dramatic increase in toxic products from various human activities, it has become an important challenge to control environmental pollution. Among them, the major increase in recent years has been soil pollution which might harm human health, crop quality, agriculture, and the climate (Conesa et al. 2012). One of the prominent reasons for soil pollution is due to human activities. The common strategies to remove toxic pollutants from contaminated soils and groundwater are often expensive, labor exhaustive, and not cost-efficient. There are several strategies to remove toxic substances from soil and groundwater. Phytoremediation can be one of these strategies to remove toxic substances from our environment. The plant organism and related microbial networks can be viewed as a daylight-driven hotspot for the turnover of natural, synthetic substances. In such conditions, the destiny of a compound won't just rely upon its inborn auxiliary soundness toward biochemical responses and its bioavailability yet additionally on the practical viability and solidness of common microbial networks as fundamental drivers of characteristic weakening of synthetic concoctions. Late research exhibits that collaborations among plants and microorganisms are significant for the biotransformation of natural, synthetic concoctions, for different procedures influencing the bioavailability of such mixes, and for the dependability of the affected biological system. Persistent natural poisons (POPs) and overwhelming metals, are considered as the most significant compound families that result in soil contamination (Belden et al. 2004; Xia et al. 2009). Due to the usage of insecticides against pests and mosquitoes, DDT has been collected in soil and river sediments (Lunney et al. 2004). The most common heavy metal pollution in soils is cadmium which is toxic to organisms. Low amount of Cd and DDT may influence the thickness of bone and increase the danger of vertebral breakage (Rignell-Hydbom et al. 2009). Bioremediation can convert pollutants to nonhazardous components enzymatically. However, the contaminant detoxification cycle can only continue if the conditions are suitable for the microorganism's growth and movement. Several bacteria complicate the process of eliminating organic contaminants, which rely mainly on the intracellular and extracellular enzymes (Madadi and Abbas 2017). Agricultural drainage and industrial release can be managed by rhizofiltration (Yadav et al. 2011; Yan-de et al. 2007). There can be approximately 275 hazardous substances that cause a threat to human health (Bernard 2010). The top 10 most "priority substances" are presented in Table 22.1. To circumvent the harmful effect of these hazardous compounds, several methodologies have been proposed to lower them from the soil. These techniques mainly incorporate the expulsion of soil to landfill locales or mainly physical methods. Such methods are quick but not cost-effective and may pose a danger to physical, chemical, and biological properties of soil. Moreover, the elimination of toxic substances from the atmosphere may be classified by the various groups and forms of these chemicals. The soil can, for example, be polluted with metals, toxic inorganic compounds, or various organic compounds. Metals include cadmium, cobalt, copper, chromium, lead, zinc, selenium, nickel, or mercury, among others. Other

Table 22.1 The top 10 most toxic metal components are mentioned below

Rank	Substance
1.	Arsenic
2.	Lead
3.	Mercury
4.	Vinyl chloride
5.	Polychlorinated biphenyls
6.	Benzene
7.	Cadmium
8.	Polycyclic aromatic hydrocarbons
9.	Benzo[a]pyrene
10.	Benzo[b]fluoranthene

inorganic mixtures could include nitrate, arsenic, sodium, alkali, or phosphate. Uranium, cesium, or strontium can be radioactive compounds. Chlorinated solvents such as trichloroethylene may form organic compounds: explosives like trinitrotoluene (TNT) and 1,3,5-trinitro-1,3,5-hexahydrotriazine (RDX). Certain constituents include numerous petroleum hydrocarbons such as benzene, toluene, and xylene (BTX), polycyclic aromatic hydrocarbons (PAHs), and pesticides such as atrazine and bentazone.

2 Importance of Phytoremediation

Phytoremediation, a system that utilizes plants to corrupt, balance out, and additionally expel soil pollutants, has been broadly explored. Rhizoremediation, a specific kind of phytoremediation which includes the plants and their related rhizosphere microorganisms, can happen normally/generally or can be impelled through intentionally presenting explicit organisms. In stress condition, such microbes can act as degraders and encourage plant growth (Gerhardt et al. 2009; Ahamd et al. 2019). Whereas certain natural compounds may be metabolized (*i.e.*, remediated) by bacteria that can be contained in or adjacent to the soil, without plants, this technique is usually moderate and incompetent due to the relatively limited number of decaying microorganisms throughout the soil (Brookes and McGrath 1984). In another way, the use of plants for the remediation of polluted soils, *i.e.*, phytoremediation, is a technically safe, effective, and moderately modest technology that is likely to be readily adopted by the applicable accessible. Soil microorganisms which are in close contact with plant roots may often promote metal phytoextraction (Shilev et al. 2001).

Phytoremediation has improved plant biotechnological approaches. The transgenic plants have more potential for productivity and are perfect and modest with economic bioremediation innovations which are highly encouraging; with few difficulties remain. Phytoremediation is a promising innovation that utilizes plants to debase, absorb, use, or detoxify metals, hydrocarbons, pesticides, and chlorinated solvents.

3 Merits and Demerits

The various merits of bioremediation are enlisted below:

1. It is conceivable as well as freely acknowledged (Marmiroli and McCutcheon 2004; Watt 2007).
2. Can be moderated by solar energy (Ali et al. 2013).
3. It can work together with organic compounds (Cofield et al. 2007).
4. Not expensive (Cornish et al. 1995).
5. On the plantation side, it reduces soil erosion by wind and water (Cunningham et al. 1995).
6. The metal-rich plant residue is reusable.
7. Water and airborne secondary diseases can be eliminated (Lili and Hui 2007).

Although some demerits are listed here below:

1. Due to the short root system of plants, only sub-surface contaminants can be cleaned up (Padmavathiamma and Li 2007).
2. Trees with longer root system can tidy up somewhat more profound pollution than plants, regularly 10–15 ft., yet fail to clean up intense springs moving forward without any more structure work.
3. These plants which have absorbed toxic pollutants can be a threat to the food chain (Arthur et al. 2000).
4. It requires large space and intense care.
5. Some volatile compound from groundwater can be a problem for air pollution too (Sakakibara et al. 2010).
6. Plants used in the remedy become inedible (Mejáre and Bülow 2001).
7. It takes a lot of time to clean up a small space (Stomp et al. 1994).

4 Mechanism of Phytoremediation

Rhizoremediation is a kind of phytoremediation which helps clean up pollutants from the low to moderate pollution level suitable mainly for both small and large sites (Zhuang et al. 2007) (Fig. 22.1).

The rhizosphere is identified with the root system and encompassing the surface and sub-surface soil. The three zones of rhizosphere are as follows:

1. *Endorhizosphere*: Some root tissue part (endodermis and cortical layers).
2. *Rhizoplane*: The root surface area where microorganisms associate with soil. It consists of three layers (epidermis, cortex core, and layer of polysaccharides).
3. *Ectorhizosphere*: Zone in which the roots adjoin the soil surface.
4. For expulsion of corruption forms, plants are engaged with several instruments to evacuate both natural and chemical toxic materials from contaminated situations (Rao et al. 2010).

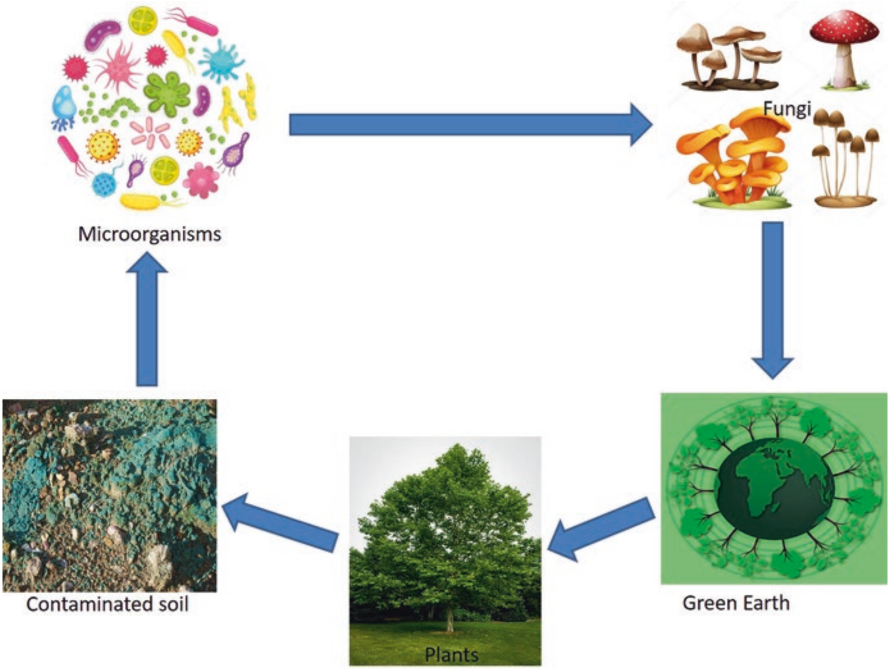

Fig. 22.1 A simple diagrammatic presentation of phytoremediation

Heavy metals pose a grave danger to human and animal health. Heavy metal accumulation in bodies of plants and animals happens after it enters the food chain (Haris et al. 2021; Dhankar et al. 2020; Hussain et al. 2021). They pose a threat because of the mutagenic ability of some heavy metals as it damages the DNA (Mohamed 2011; Mohamed et al. 2016; Akladious and Mohamed 2017). That is why the removal of these heavy metals for soil and several in situ and ex situ technologies that are used for this purpose is required. Phytoremediation is an environmentally sustainable technique, cost-effective for cleaning metal-polluted soils. In their growth, plants embrace various processes to lower the metal in soils without any antagonistic impacts (Table 22.2).

Phytostabilization, phytoextraction, and phytovolatilization are the main mechanisms, but here we are giving a brief explanation of phytovolatilization.

4.1 Phytovolatilization

Changing of toxic heavy metals such as Hg, Se, and As into less dangerous, unforeseeable structures released into the atmosphere by plants is called phytovolatilization (Malik and Biswas 2012). The reasonable utilization of phytovolatilization is

Table 22.2 Various plants used as phytoremediation

Plant	Metal	Reference(s)
Sedum alfredii H.	Pb, Cd	Anjum et al. (2012)
Pteris vittata	As	Datta et al. (2017)
Thlaspi goesingense	Ni	Puschenreiter et al. (2003)
Sedum alfredii	Zn	Yang et al. (2006)
Arabidopsis thaliana	Cd	Kiyono et al. (2012)
Pistia stratiotes	Cd, Pb, Zn	Vesely et al. (2012)
Eichhornia crassipes	As	Theeta et al. (2018)
Pistia stratiotes L.	Cd, Zn	Vidal et al. (2019)
Alyssum species, *Brassica juncea*	Ni	Kerkeb and Krämer (2003)
Oryza longistaminata, *Sorghum arundinaceum*, *Tithonia diversifolia*, and *Hyparrhenia rufa*	Hydrocarbon-contaminated soils	Ruley et al. (2020)
Athyrium wardii	Cd, Pb	Zhang et al. (2012); Zou et al. (2011)
Brassica juncea	Cd	Seth et al. (2008)

addressed because of the arrival of harmful unstable mixes to the environment with a hazard evaluation ought to be finished (Marques et al. 2009). Although some reported that these volatile compounds pose no threat to the environment, they mostly become diluted and dispersed (Meagher et al. 2000). Arsenic effectively volatilized into a mixture of arsenic mixes, arsenite, and arsenate (Sakakibara et al. 2010).

4.2 *Phytoextraction*

This is the mechanism in which foliage plants remove heavy metals from soil. The heavy metals in the soils are absorbed, transported, and accumulated in the plant's parts above the ground. These plant parts are then collected and safely handled to either dispose of the heavy metals or recycle them. These plants must have the capability of both metal tolerance and fast-growing to produce high biomass (Fig. 22.2).

5 Role of Microbial Enzyme in Phytoremediation

Table 22.3 shows the role of the plant and microbial enzymes in the biodegradation of organic compounds. Microbial sources are identified as (B) the bacterium or (F) the fungus.

Microbial enzymes play an essential role in the removal of environmentally toxic substances that are dispersed in the environment due to human activities. Various catalysts, e.g., oxygenases, are significant chemicals as they are fundamentally associated with the underlying procedure of corruption and reduce and debase the

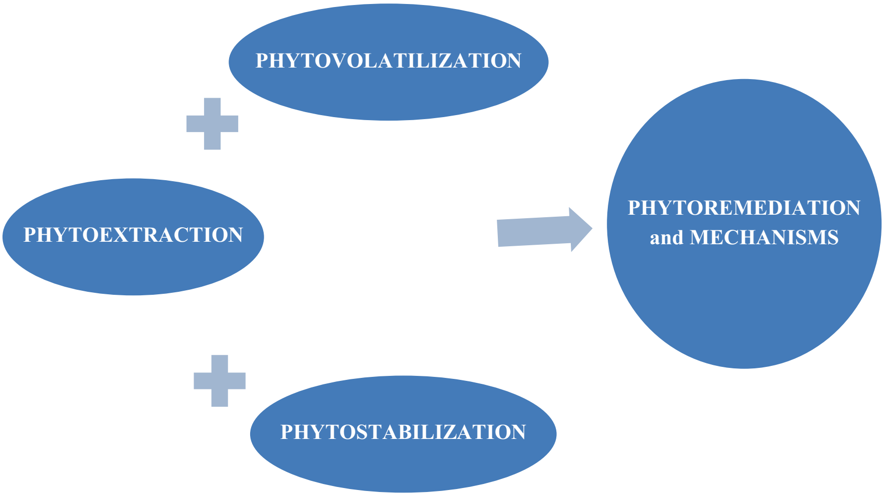

Fig. 22.2 Phytoremediation and its mechanisms

Table 22.3 List of different plant and microbial enzymes which function in organic compound biodegradation

Enzyme family	Examples of known source(s)	References
Various plant enzymes for uptake, transport, sequestration, and degradation	All plants	Pilon-Smits (2005)
Dehalogenase	*Xanthobacter autotrophicus* (B) Hybrid poplar (*Populus* spp.) *Sphingobium chlorophenolicum* (B)	Mena-Benitez et al. (2008) Susarla et al. (2002) Cai and Xun (2002)
Laccase	Alfalfa (*Medicago sativa*) *Trametes versicolor* (F)	Gramss et al. (2013) Novotny et al. (1997)
Dioxygenase	*Pseudomonas* sp. (B) *Mycobacterium* sp. (B)	Pieper et al. (2004) Pieper et al. (2004)
Peroxidase	Horseradish (*Armoracia rusticana*)	Susarla et al. (2002)
Nitrilase	Willow (*Salix* spp.) *Aspergillus niger* (F)	Susarla et al. (2002) Kaplan et al. (2006)
Nitroreductase	*Comamonas* ssp. (B) *Pseudomonas putida* (B) Hybrid poplar (*Populus* spp.)	Liu et al. (2007) Caballero et al. (2005) Susarla et al. (2002)
Phosphatase	Giant duckweed (*Spirodela polyrhiza*)	Susarla et al. (2002)
Cytochrome P450 monooxygenase	Most aerobic bacteria, all fungi, and all plants	McLean et al. (2005)
Oxidoreductases	*Flavobacterium* sp., *Phanerochaete chrysosporium*	Fierer (2017)
Oxygenases	*Bacillus subtilis* (B)	Muthukamalam et al. (2017)
Esterase	*Bacillus subtilis* (B)	Gangola et al. (2018)
Oxidoreductase	Fungi	Barber et al. (2020)

fragrant mixes. They reduce the toxic substances into the substrates. Two major oxygenases are monooxygenases (add one molecule of oxygen) and dioxygenases (add two molecules of oxygen) (Arora et al. 2010; Karigar and Rao 2011).

5.1 *Microbial Oxidoreductases*

Oxidoreductases used to remove the harmful effect of organic compounds by various bacteria, fungi, and plants (Husain 2006; Karigar and Rao 2011) by oxidative association. Microbes derive energy using biochemical reactions mediated by these enzymes in order to cleave chemical bonds and assist in electron transfer from a reduced organic (donor) substrate to another chemical (acceptor) compound. The pollutants are gradually oxidized to harmless compounds during these oxidation-reduction reactions (Karigar and Rao 2011). Oxidoreductases are involved in humidifying various phenolic substances which are formed in a soil environment from the decomposition of lignin. In the same way, oxidoreductases can also detoxify toxic xenobiotics by polymerization, such as phenolic or anilinic compounds, copolymerization, or binding of humic substances with certain substrates (Park et al. 2006). Microbial enzymes were used to decolorate and degrade azo dyes (Husain 2006). In the energy production process, bacteria consume electrons from organic compounds and use radioactive metal as the final electron acceptor. Eventually, the precipitant can be the product of bacterial redox reactions that reduce metals (Leung 2004).

The most common recalcitrant waste are chlorinated phenolic compounds that are present in the paper and pulp-processed effluents. Such compounds are formed during the process of pulp bleaching upon partial degradation of lignin. Most fungal organisms are considered appropriate for the removal from polluted habitats of chlorinated phenolic compounds. The filamentous fungal mycelia produce extracellular oxidoreductase enzymes which are released into the natural environment and are more effective in penetration of soil pollution than bacteria (Rubilar et al. 2008). Plants can decontaminate water polluted with phenolic compounds using enzymes which are produced and released from their roots. Phytoremediation of chemical contaminants has generally concentrated on three groups of compounds: chlorinated solvents, explosives, and hydrocarbons for petroleum (Duran and Esposito 2000).

5.1.1 Microbial Oxygenases

Oxygenases are a member of the enzyme class called oxidoreductase, FAD/NADH/NADPH used as cosubstrate to transfer oxygen from O_2. Oxygenases are classified into two classes, depending on the number of oxygen atoms used for oxygenation: monooxygenases and dioxygenases. They play a vital position in the chemical process of an organic compound by increasing their reactivity or water solubility or by causing cleavage of the aromatic ring. O_2 atoms are normally incorporated by oxygenase into the organic molecule, leading to cleavage of the aromatic ring (Arora et al. 2009).

5.1.2 Microbial Monooxygenases

The addition of a singlet oxygen molecule is achieved in the substrate by using monooxygenase enzyme. The cofactors used can be divided into two subgroups: (1) monooxygenases based on flavin and (2) monooxygenases P450 (*Bacillus megaterium*). The first subgroup prothetic group is flavin that is activated by using the coenzymes (NADP or NADPH), and the second subgroup includes heme. Monooxygenases are initiated and increase the rate of a chemical reaction activity in the phytoremediation. The other enzymes are cofactor-autonomous that play out their action with the subatomic oxygen as it were. Numerous procedures including desulfurization, denitrification, nitrification, ammonization, dehalogenation, shift, hydroxylation, and fragrant and aliphatic biodegradation are regulated by catalyst monooxygenases (Lock et al. 2017; Sirajuddin and Rosenzweig 2017; Syed et al. 2013).

5.1.3 Microbial Dioxygenases

Those are farraginous systems of enzymes which add molecular oxygen into the substrate. They degenerate the aromatic complex which raises a serious damage to the environment. This can be divided into two subclasses, depending on the enzyme's mode of activity: hydroxylation and cleavage dioxygenases. The hydroxylation enzyme catalyzes the expansion into the substrate of two oxygen atoms, while the cleavage enzyme catalyzes an aromatic ring usually carrying at least two or more groups of hydroxyls. The dioxygenase cleavage is further divided into two groups: intradiol and an extradiol. Such enzymes are concerned with environmental degradation of aromatic molecules. They are soil bacteria that are involved in the transformation process by converting aromatic precursors into aliphatic products (Al-Hawash et al. 2018; Fulekar 2017; Muthukamalam et al. 2017; Xenia and Refugio 2016).

5.2 *Microbial Peroxidases*

Peroxidases (EC 1.11.1.7) are disseminated widely in the environment. Plants and microorganisms are different sources that produce peroxidase enzymes. These microbial enzymes include degradation of pollution, raw materials, food and paper industries, degradation of textile dyes, lignin degradation paper/pulp industry, decoloration of the dye, sewage treatment, and animal feedstock and as biosensors.

For plants, they help in the production of lignin, the formation of cell walls, auxin metabolism, cell elongation, and channel protection. Also, they are subdivided into both heme and nonheme proteins. Furthermore, heme peroxidases in the prokaryotes and the eukaryotes are classified into three groups based on contrast (Bansal and Kanwar 2013; Falade et al. 2016).

5.2.1 Microbial Lignin Peroxidases (Lip)

During secondary metabolism, the white-rot fungus produces lignin peroxidases. Having the existence of H_2O_2 and mediator like veratryl alcohol LiP, lignin and other phenolic compounds are depleted. During the reaction, H_2O_2 is reduced to H_2O by obtaining electron from LiP (which is oxidized by itself) (Ten Have and Teunissen 2001). Lignin peroxidase (LiP) plays an essential function in the biodegradation of plant cell walls' lignin constituents (Piontek et al. 2011).

5.2.2 Microbial Manganese Peroxidases (MnP)

MnP is produced from basidiomycete fungus that caused lignin-degrading and oxidation of different phenolic compounds (Ten Have and Teunissen 2001), in which a multistep reaction oxidizes Mn^{2+} to the oxidant Mn^{3+}. Mn^{2+} stirs up the output of MnP and plays an important role as a substrate for MnP.

5.2.3 Microbial Versatile Peroxidases (VP)

VP enzymes are capable of oxidizing Mn^{2+} and phenolic aromatic substrates (Ruiz-Duenas et al. 2007). In the absence of manganese, VP has an unusually high specificity of substrates and a tendency to oxidize substrates compared to other peroxidases and plays important role in the bioremediation (Tsukihara et al. 2006).

5.3 *Microbial Laccases*

Laccases belong to multicopper oxidase family that are produced by certain plants and microorganisms which cause oxidation of phenolic and aromatic compounds while at the same time convert the molecular oxygen to water (Nigam 2013). Most microorganisms contain intracellular and extracellular laccases capable of catalyzing the oxidation of polyphenols, polyamines, and lignins (Rodrıguez Couto and Toca Herrera 2006) and repolymerization to humic materials (Viswanath et al. 2014). The production of laccase is depending on the concentrations of nitrogen in the fungi. Typically, the high concentrations of nitrogen are required to obtain large quantities of laccase (Viswanath et al. 2014).

5.4 *Microbial Lipases*

Lipase breaks down lipids which are produced by a wide array of microorganisms, bacteria, actinomycetes, and plants. Recent research has found that lipase is strongly related to the soil's organic pollutants. These microbial lipases are more flexible due to their active industrial use. Lipase enzymes can catalyze different reactions, including hydrolysis, interesterification, esterification, alcoholysis, and aminolysis (Prasad and Manjunath 2011). The lipase activity controlled the dramatic reduction of the total hydrocarbons of polluted soils and plays an important role as bioremediation of oil spills (Riffaldi et al. 2006; Sharma et al. 2011; Okino-Delgado et al., 2017). Lipases cause hydrolysis of triacylglycerol into glycerol and free fatty acids. Lipases were categorized into two groups based on criteria such as (a) enhanced enzyme activity once the triglycerides form an emulsion and (b) protein (lid)-looped lipases that cover the active site (Sharma et al. 2011).

5.5 *Microbial Cellulases*

Cellulases now provide the ability to turn cellulose waste materials into foods to overcome the increase in the population (Bennet et al. 2002). Some organisms formed a bound cell, associated cell envelope, and some extracellular cellulases. Some bacteria and fungi have shown that extracellular cellulases, hemicellulases, and pectinases are expressed constitutively at very low levels (Adriano-Anaya et al. 2005). Cellulose is broken down by cellulases during enzymatic hydrolysis to reduce the amount of sugar that can be fermented to ethanol by yeasts or bacteria (Sun and Cheng 2002). Cellulases extract microfibrils of cellulose that form during washing and the use of cotton-based clothes. This is often known in the textile industry as the brightening of colors and softening of fabrics. *Bacillus* strains produced alkaline cellulases, and *Trichoderma* and *Humicola* fungi produced neutral and acidic cellulases (Leisola et al. 2006).

5.6 *Microbial Proteases*

Proteases cause protein material degradation entering the atmosphere like animal mortality and a by-product in other industries such as livestock, fishing, and clothing, as a result of shedding and molting appendages (Beena and Geevarghese 2010). A varied and unique protease is used in the pharmaceutical industry to grow effective medicinal agents. Clostridial collagenase or subtilisin is used for the treatment of burns and wounds in conjunction with wide-spectrum antibiotics (Beena and Geevarghese 2010; Bhunia and Basak 2014).

5.7 Microbial Pullulanase

Several microorganisms such as *Klebsiella* spp., *Bacillus* spp., and *Geobacillus stearothermophilus* are used to produce pullulanases. It is very common in industrial uses due to its specific enzymatic action on pullulan, particularly in the specific connections (α-1,6 linkages), and starch is very essential as bioprocessor for its action (Karigar and Rao 2011; Lee et al. 2017).

5.8 Microbial Amylases

Alpha-amylases are extracellular enzyme that breaks in starch molecules, the α-1,4-glycosidic bond, and produce oligosaccharides, β-amylase, which also breaks the second maltose α-1,4-glycosidic bond and is synthesized in plants and bacteria. Amylases are important enzymes for their specific application in the process of conversion of industrial starch. Such enzymes are especially active on disaccharides (sucrose) and polysaccharides (starch) and are grouped into the glycoside hydrolase community (Singh et al. 2016; Gopinath et al. 2017).

6 Role of Plant Growth-Promoting Rhizobacteria (PGPR) Under Stress

PGPR is used to improve the execution of plants through different components, such as the production of precious hormones, the upgrading of plant nutrition status, and the decrease of the harm associated with the environment. The association among plants and PGPR happens to specific enthusiasm for situations that are described by imperfect developing conditions like high or low temperatures, dry spell, soil saltiness, and supplement shortage (plant development under stress) (Hussain et al. 2020a–c; Mandal et al. 2021). Primary expects to discuss the fundamental mechanisms of interaction between PGPR and plants and will focus on how PGPR can reduce abiotic stress damage in plants, which are essential crops for human diet (Hussain et al. 2020).

Abiotic stress thusly influences numerous plants like vegetables. In any case, vegetables, which are plants developed for their vegetative parts, are gradually affected by abiotic stress when compared with the family of grasses. The abiotic stress reduces the climate for the vegetable ranch and thus results in reduced crop yields. PGPR are beneficial to soil microscopic organisms suitable for stimulating plant physical substance and natural changes (Mohamed and Gomaa 2012).

Wholesome status, physical and biological properties of the soil, continuously changing environment, and other abiotic stresses are important drivers for reduced output in agriculture (Gopalakrishnan et al. 2015). Abiotic stresses are the fundamental reason for losses in crop yields and hiking food prices in the world with an increasing population. Attempts are being made to create stress-tolerant vegetables through traditional breeding or transgenic approaches, as multiple genes and metabolic procedures are stress-resilient (Ashraf and Akram 2009). The use of useful has recently become a possible new approach for protecting crops from damage caused by abiotic stress (Palaniyandi et al. 2014; Fatnassi et al. 2015; Wang et al. 2016; Hussain et al. 2020a–c).

6.1 Plant Growth-Promoting Bacteria (Subheading)

Natural exudates discharged through the roots are correlated with PGPR into plants and colonize the root surface and soil in direct contact with the root. The rhizosphere is the region of soil in the vicinity of plant roots in which chemistry and microbiology are influenced by their growth, respiration, and nutrient exchange which is illustrated in Fig. 22.3 (Smalla et al. 2006; Martino 2019), whereas the extracellular root surface has called been the rhizoplane (Foster 1986). Exudates discharged from plant roots pull microorganisms in the soil that can colonize rhizosphere or potentially plant tissue. Here, they offer the plant various helpful mixes in the supplement trade, primarily photosynthesis (Kawasaki et al. 2016).

Remarkably, through alternating environmental factors, plants may indirectly influence rhizosphere colonization. For example, increases in pH levels are through the absorption of ions and reduction of O_2 and H_2O levels caused by root respiration and water supply (Philippot et al. 2013). Two different studies (Bouffaud et al. 2012; Peiffer et al. 2013) showed how various genotypes of related plant species can be linked with different bacterial communities of the rhizosphere. Exudates differ in the different parts of the roots, the formative phases of the plant, and the conditions for growth (Zahar Haichar et al. 2008). This implies that after some time and space, a similar plant will link with a large number of different soil bacterial strains (Compant et al. 2010). Several bacterial species can spread from the endodermis of roots, enter, and colonize other stem organs (Compant et al. 2005; Dimkpa et al. 2009).

6.2 Plant Growth Promotion is driven by Rhizobacteria (Subheading)

Interactions with PGPR can lead to increased plant productivity, mineral contents, and plant growth. A portion of the primary benefits obtained by plants due to treatment with PGPB are increased root development, offering better protection against temperature and osmotic pressure, soil poisons, vermin, and pathogens (Lugtenberg and Kamilova 2009).

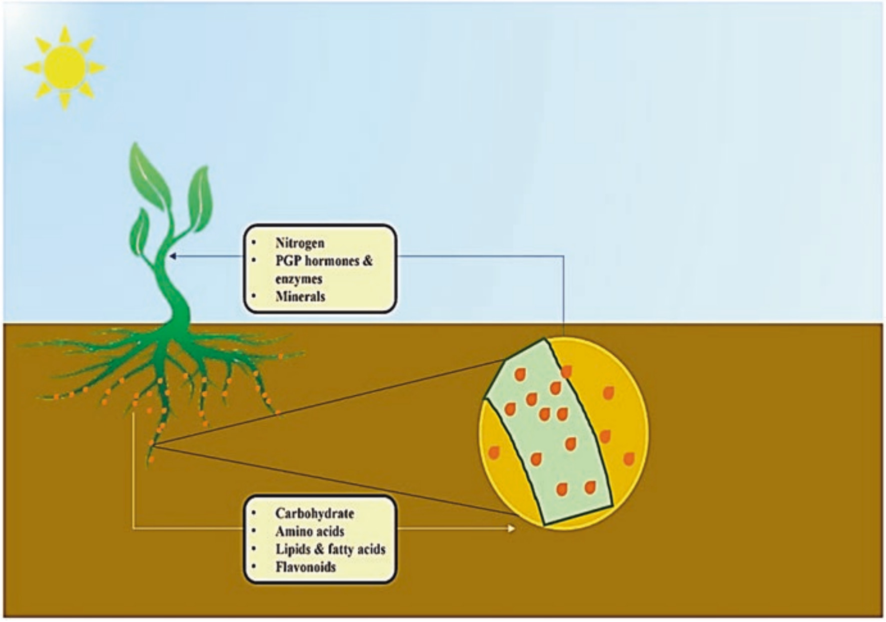

Fig. 22.3 A diagrammatic representation of plants and PGPR

6.3 Hormone-Related Mechanisms (Subheading)

PGPB produced indole-3-acetic acid (IAA) which caused enhancement of plant growth, cell elongation and differentiation, and stimulating lateral root growth (Dimkpa et al. 2009). IAA will roundly boost the plant's dietary status by extending root progression (explicitly sidelong roots), allowing the plant to reach a higher soil substratum, a main feature of nutrients with low mobility such as phosphorus (Wittenmayer and Merbach 2005). Gibberellins (GAs) are considered to play an important role in the promotion of plant development and produced by PGPR (Bastian et al. 1998). These diterpene hormones are present in plants, directing key procedures, for example, germination of the seed, elongation of the stem, expansion of the leaves, root growth, and fullness of root hair (Bottini et al. 2004; Yamaguchi 2008). The function of gibberellins in the reaction of grains to stresses fluctuates relying upon the stress type (Iqbal et al. 2011). The ethylene biosynthetic precursor is ACC, a hormone that is usually found in plants and increased under environmental stress. Ethylene is required for critical procedures such as tissue differentiation, root growth, flowering, grain production, senescence, and abscission; but it may suppress plant performance in case of overproduction (Saleem et al. 2007; Hays et al. 2007). Abscisic acid (ABA) is a plant hormone and increased under abiotic stress (Fahad et al. 2015). ABA is naturally engaged with seeds and bud's torpidity, and ABA imparts the primary biosynthetic strides to cytokinins, a phytohormone class that regularly assumes an adversarial role to ABA. Under salt stress condition, the plant biosynthesis of ABA which moved to leaves and caused stomatal closure, reduced transpiration and water loss (Xing et al. 2004), and reduced photosynthesis due to the CO_2 emission into the leaves (Yang et al. 2009; Barnawal et al. 2017; Shahzad et al. 2017).

6.4 Role of PGPB in Nutrient Stress (Subheading)

Comparatively, the use of PGPB as a biofertilizer has been found to improve plant nutrient usage and promote plant production (Calvo et al. 2015; Çakmakçi 2016). Once added, these inoculants improve plant growth and development or protect plants against pests and diseases (Ramjegathesh et al. 2013). Several microbial inoculants have been used as biofertilizers in this consideration which supply plants with nutrients such as N, P, K, S, and Fe. The more widely used genera as biocontrol agents are *Pseudomonas* (Tewari and Arora 2015), *Bacillus* (Alavo et al. 2015; Hussain and Khan 2020a, b), *Burkholderia* (Pinedo et al. 2015), *Agrobacterium* (Bazzi et al. 2015), and *Streptomyces* (Viaene et al. 2016). By production of antibiotics (Prasannakumar et al. 2015) and siderophores (Patel et al. 2016), by induction of systemic resistance (Zebelo et al. 2016), or any other mechanism, these organisms reduced plant disease.

7 Role of Biotechnology in Phytoremediation

Heavy metal pollution poses a global threat. Pollution from heavy metals remains a global threat. Contamination of heavy metals is an effect on the quality of soil and water as well as to human and animal health since they will pile up in the food chain (El-Beltagi et al. 2020; Moustafa-Farag et al. 2020; Sofy et al. 2020). Phytoremediation is a particular method of bioremediation. It is a characteristic natural procedure of corruption of xenobiotic and stubborn mixes liable for ecological contamination. In this, genetically engineered plants are used which directly uptake the pollutants from the soil (Macek et al. 2000). The word phyto means "plant"; that's why the remediation is mediated by the plant system (Sonali 2011). Phytoremediation includes numerous procedures which are done by the plant during their development on the sullied site. Thus, the pollutants are treated by plants utilizing of these responses like phytoextraction, phytostabilization, phytotransformation, phytostimulation, and phytovolatilization (Sonali 2011). Various contaminations have various destinies in plant-substrate frameworks, so they have diverse rate-restricting variables for phytoremediation that may focus on utilizing hereditary designing. Biotechnology shows us the chance to move hyper-aggregator phenotypes into quickly developing large biomass plants that can be exceptionally successful in phytoremediation (Rupali and Dibyengi 2004; Maurya et al. 2020).

A perfect phytoremediator characterizes more resistance for contamination, the capacity to either debase or assemble the impurities at an elevated amount in the biomass, broad root frameworks, the ability to assimilate a lot of water from the soil, and also quick development rates and significant levels of biomass (Cherian and Oliveira 2005). Albeit a few species can endure and develop in some defiled destinations, these species regularly become gradual, produce extremely low degrees of biomass, and are adjusted to quite certain natural conditions. What's more, trees which have broad root frameworks, high biomass, and low horticultural sources of info necessities endure poisons ineffectively and don't gather them. Traditional plants neglect the requirements for fortunate phytoremediators (Gratão and Braz 2005). The healing limit of plants can be essentially improved by hereditary manipulation and plant transformation technologies (Kraomer 2005). Presentation of novel qualities for the take-up and aggregation of contaminations into high biomass plants is demonstrating a fruitful procedure for the advancement of improved phytoremediators (Martanez et al. 2006). This reviews a portion of the exploration endeavors in this field and highlights future difficulties.

8 Phytoremediation Mechanism of Cd Adopted by Soil Plants

Remediation of Cd-sullied soil is a considerable issue far and wide, and it turned out to be progressively huge because of the exchange of Cd in higher trophic degrees in a natural way of life. Cd hyperaccumulators are exceptionally compelling a direct result of their capacity to endure and take up noteworthy measures of overwhelming metal from soils. Plants of various species have various capacities to hyperaccumulate Cd. Cd has low affinities with soil ligands due to its versatile nature and henceforth is effortlessly extricated by attaches and further shipped to other flying bits of the plant. The factors responsible for plant-based remediation of Cd are pH, temperature, media concentration, and concentration of other than Cd components (Mahajan and Kausha 2018; Dhankar et al. 2020). The phytoremediation process for extracting Cd in soil plants is shown in Fig. 22.4.

9 Conclusion and Future Prospectus

Metal pollution of soils is a common issue in various regions across the globe with varying intensities and magnitudes. Several remediation techniques for each bearing a broad variety of benefits and demerits have already been explored in depth elsewhere. Phytoremediation across all types of remediation is considered environmentally friendly and low cost. Around the same time, the introduction of commercial-scale phytoremediation technology requires careful consideration of the costly

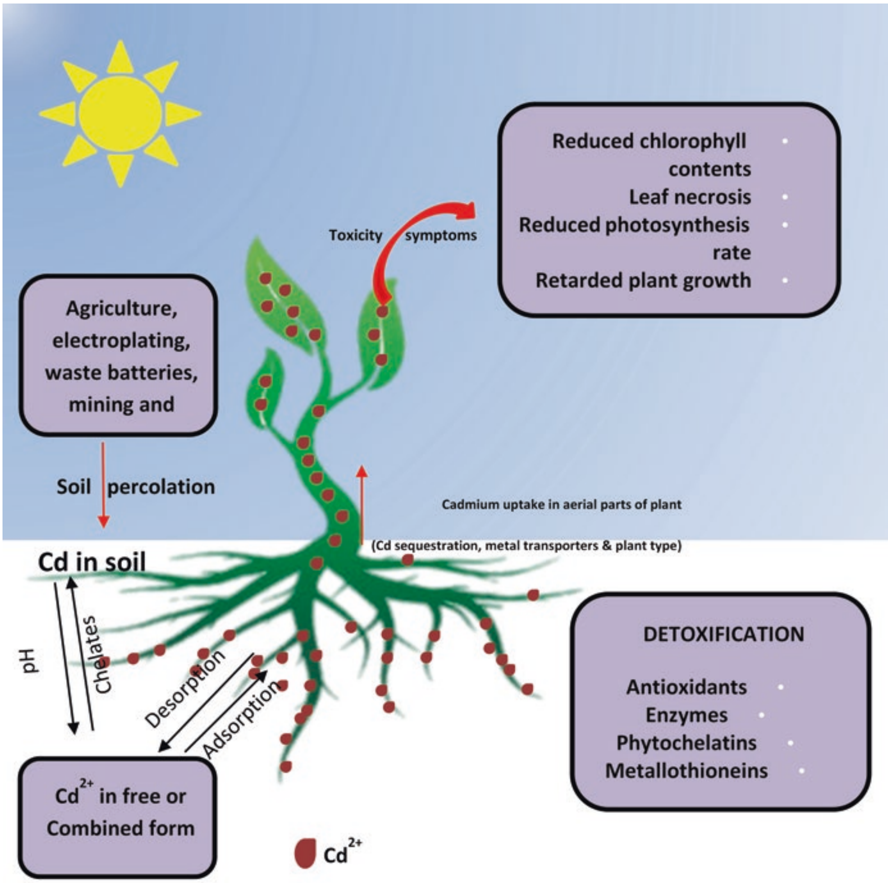

Fig. 22.4 A mechanism for phytoremediation of Cd accepted by soil plants

and time-consuming problems and the fate of the plants being used. It has been recognized that a variety of plants are prepared to accumulate high metal centralizations in their ethereal parts, keep the metals in roots or balance the metals in soils, eventually restrict their translocation to the shoots, and remove the metals from the dirt by amalgamating volatile mixtures. Growing of the above technologies includes different mechanisms that are already discussed in depth. The decision to use innovation in phytoremediation to remediate metal-defiled premises is based on soil type, metal content, degree of tainting, and natural upsetting effect. An understanding of the different processes involved will enhance decision-making when implementing a specific technology. Phytoextraction is commonly used by various advancements in phytoremediation, and a wide variety of hyperaccumulator plants fit for gathering high metal centralizations have been described. Distinguishing evidence and accepting qualities responsible for hyperaccumulation in hyperaccumulator plants into those plants fit for metal accumulation, and high biomass production may disturb the progress in phytoremediation. It requires a deeper understanding of the molecular basis of the pathways involved in pollutant degradation. Further analysis and disclosure of qualities appropriate for phytoremediation are important. Innovation in phytoremediation is still at an early stage of development, and field trials of transgenic plants for phytoremediation are unusually limited. Biosafety concerns should be properly answered, and protocols should be developed to avoid quality streams becoming wild species. Innovations in phytoremediation are currently accessible for only a limited subset of pollutants, and several destinations are being debased with a few synthetic substances. In this way, phytoremediators with various stacked qualities should be designed to satisfy the prerequisites of specific destinations.

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