# 10 Bioremediation: Remedy for Emerging Environmental Pollutants

Arti Sharma and Sandeep Shukla

**Abstract**

Bioremediation is one of the approaches to recycle wastes into another form that can be utilized by other microbes. At present, the environment is suffering from numerous environmental pollution problems. Microbes are the key players to overcome these challenges. Microorganisms persist everywhere on the planet because their metabolic activity is astonishing; then come into presence in all over range of ecological conditions. The microorganism's nutritional capability is completely varied and that's why it is used as bioremediation of environmental pollutants. Bioremediation is involved in eradication, degradation, immobilization, and decontamination of different chemical wastes and physically harmful materials from the environment via the all-inclusive and achievement of microorganisms. The principle is altering pollutants such as oil, heavy metal, hydrocarbons, pesticides, dyes, and so on. It is done by enzymatic way via breaking down, so it has great involvement to solve numerous environmental difficulties. There are two kinds of factors these are biotic and abiotic circumstances are determined rate of degradation. Presently, dissimilar methods and strategies are applied in the area in different part of the biosphere. For example, biostimulation, bioventing, bioaugementation, biopiles, and bioattenuation are the common ones. All bioremediation methods have their own merits and demerits because they have their own specific uses.

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**Keywords**

Microbes · Pollutants · Bioremediation · Heavy metal · Pesticides

## 10.1 Introduction

Due to rapid industrialization and modern agricultural practices, the environment in the past few decades has been polluted severely, which has resulted in pollution of air, water, soil, and even the food consumed by animals and humans. This problem is worldwide and may cause a threat to both the environment and human health (Manisalidis et al. 2020). The use of pesticides and herbicides helps to increase agricultural productivity; however, using these chemicals causes a huge loss of biodiversity and contaminates agricultural land. Based on the half-life, pollutants remain in the environment for a long period. Some of them fade away by microbial transformation into non-toxic by-products, while some pollutants such as polychlorinated dibenzodioxyfurans (PCDDF), dichlorodiphenyltrichloroethane (DDT), hexachlorocyclohexane (HCH), dioxins, and chlordane may persist in the surroundings over different periods and enter the food web biomagnified (Guo et al. 2019). This uncontrolled release of lethal pollutants into environments is a serious concern. Conventional approaches such as pyrolysis, land-filling, and recycling for the removal of contaminants are not that efficient to end the production of toxic compounds (Ferronato and Torretta 2019; Rai et al. 2020). Thus, the use of microorganisms is more suitable than conventional methods for the remediation of toxic environmental pollutants. Bioremediation is an approach that causes restoration of the natural ecosystem by eliminating pollutants from the environment and also preventing further pollution. Bioremediation is more cost-effective than alternative methods of remediation, i.e., chemical as well as physical. Using bioremediation, the pollutants' toxicity can be reduced by applying the microorganisms that transform highly toxic pollutants into lesser non-toxic forms. Some of the xenobiotic compounds, e.g., nitrated aromatic compounds, highly halogenated, and a few pesticides are still not reported to be degraded by microorganisms (Arora 2020). Nevertheless, the efficiency of microbes depends on various factors, i.e., chemical nature of pollutants, concentration, availability and physiological features of the environment. Therefore, the components that affect the degradation potential of microbes are either concerned with nutritional necessities or ecological factors.

Further, based on the exclusion of toxic compounds and their transport methods, bioremediation is of the following two forms: in situ *and* ex situ. Moreover, recent methods incorporate the application of recombinant microorganisms for the effective degradation of pollutants. Under specific conditions for the remediation of different pollutants, recombinant microbes have been found to be successful as they have the genetic make-up to deal with pollutants. The elimination of numerous poisonous pollutants remains a problem for the environmental biotechnologists due to inefficient degradation by culturable microbes. The main hurdles for the use of recombinant microbes under field conditions are biological concerns and regulatory restrictions (Ferronato and Torretta 2019). Despite the high efficiency of bioremediation, there are limited uses of recombinant microbes in the ecosystem due to the uncontrolled propagation and gene transfer. The present study's goals are to provide widespread details of combined approaches that have been accomplished for efficient evaluation of bioremediation processes (Srivastava 2021).

## 10.2 Bioremediation

Bioremediation is an approach applied to remove ecological impurities from the ecosystem. It utilizes the living mechanisms inherent in microbes and plants to exclude hazardous pollutants and reconstruct the ecosystem to its original condition (Ancona et al. 2019). The basic concepts of bioremediation are to reduce the solubility of ecological impurities by redox reactions, changing pH, and adsorption of contaminants from the contaminated environment (Sharma 2020). Lot of work have been done on provoking pentachlorophenol biosorption by changing the pH levels in aqueous solutions. For the exclusion of pentachlorophenol from aqueous solution, the biosorption capabilities of *Aspergillus niger* (Gulzar et al. 2017) and *Mycobacterium chlorophenolicum* (Das et al. 2015) were pH-dependent. It also evaluated the effect of pH on adsorption of pentachlorophenol by *M. chlorophenolicum* and confirmed that pH values were a crucial parameter which affected pentachlorophenol adsorption. Several authors had performed many experiments, in which appropriate pH was used for best performance of microbes used in bioremediation. Bioremediation approaches are dependent on redox processes which focus on changing the microbiology and chemistry of water using selected reagents into contaminated water to enhance the degradation and eliminate numerous contaminants by in situ chemical oxidation reactions (Ojuederie and Babalola 2017). Redox reactions convert harmful contaminants into less toxic, mobile or inert stable compounds (Singh 2021). They play a crucial role in modifying toxic heavy metals such as As, Cr, Hg, and Se in soils and sediments into harmless forms (Ahemad 2019). A groundwater redox reaction is affected by the medium's physicochemical properties of the medium, but it can be improved using the addition of organic and inorganic alterations such as biochar and composts (Nejad et al. 2018). The use of compost in metal-mixed soils can cause modifications in the soil microbial population by altering pH, diminishing the solubility of heavy metals, and provoking microbial biomass and presented nutrients (Abedinzadeh et al. 2020). Biochar is a product of pyrolysis produced by manure crop residue as well as solid wastes. It can be utilized to enhance microbes for bioremediation to make the environment more suitable (Zahed et al. 2021). Several authors have explained that biochar is used as an actual agent in immobilization of organic pollutants and metals (Yaashikaa et al. 2020). Through biological pathway, Biochar has the capability to donate or accept electrons within their surroundings (Yaashikaa et al. 2020). Some scholars said that biochar may allow microbial electron shuttling processes (Pascual et al. 2020). The toxicity of heavy metals such as lead, arsenic, chromium, selenium, nickel, and copper rely on their oxidation

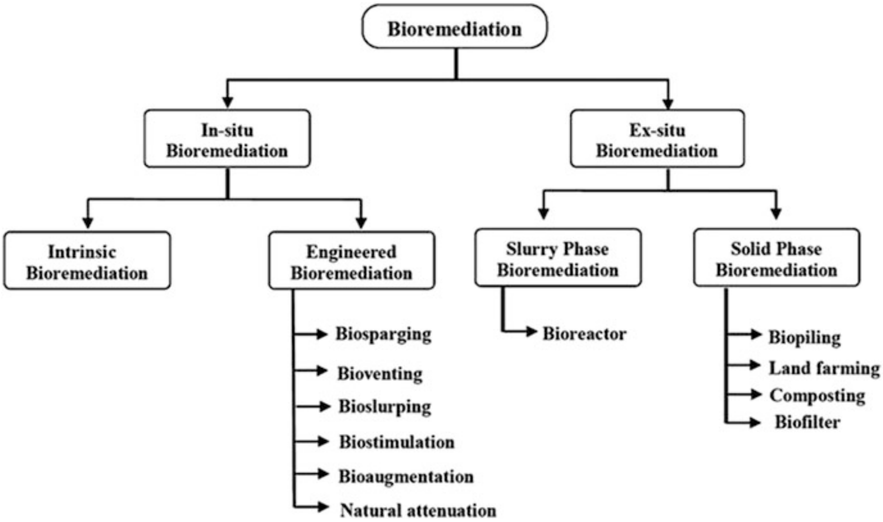


**Fig. 10.1** Bioremediation approaches for environmental clean-up (Sharma 2020)

states and is controlled by the redox reactions (He et al. 2019). Bioremediation depends on the prevailing environmental factors at the contaminated site and the nature of the organisms utilized as well as the degree of the pollutants in that environment (Ojuederie and Babalola 2017). Microbial bioremediation depends on the metabolic potential of the microbes to reduce ecological pollutants into modified innocuous forms via redox reactions (Ojuederie and Babalola 2017). Bioremediation can also be done through plants which remediate pollutants as well as contaminants from the environment. The bioremediation process carried out by plants is called phytoremediation. Heavy metals can be eliminated from the contaminated sites by plants (Nedjimi 2021). Bioremediation may be of two types, either in situ *or* ex situ. In situ bioremediation is the application of living treatment to clean up dangerous compounds present in the ecosystem and also to motivate microbes' capability to degrade contaminants or develop indigenous microbes to degrade contaminants present in environments using recombinant DNA technology (Goswami et al. 2018). Utilization of microorganisms for in situ bioremediation is affected using the non-availability of appropriate nutrient levels as well as environmental setting at the polluted site (Maulin 2014). Ex situ bioremediation is digging out the pollutant from its original location and transporting them to another site for treatment based on the pollutant type and depth of contamination, as well as geology of the contaminated site (Kumar et al. 2021). Figure 10.1 show the types of bioremediation and which have been explained one by one in the section below.

### 10.2.1 In Situ Bioremediation

There are two types of in situ bioremediation:

Intrinsic bioremediation and
Engineered bioremediation

#### 10.2.1.1 Intrinsic Bioremediation

A type of bioremediation in which inert capability of naturally found microbes to degrade pollutants or contaminants without taking any engineered step to provoke the process. It degrades organic pollutants employing in situ microorganisms via a natural process known as natural attenuation. Potential intrinsic bioremediation of tricholoroethylene (TCE) is being used, cholorobenzene as a primary substrate under aerobic and anaerobic conditions. Degradation of tricholoroethylene is being dependent on degradation of primary substrate cholorobenzene. Microbial enumeration is accomplished to recognize the occurrence of intrinsic bioremediation. The existence of daughter compounds is an indicator of effective remediation.

#### 10.2.1.2 Engineered Bioremediation

A type of bioremediation that enhance the growth and degradative activity of microbes by using recombinant DNA technology that transports electron acceptors and supply nutrients or other growth enhancing materials. It is divided into six types. These are as follows: biosparging, bioventing, bioslurping, biostimulation, bioaugementation, and natural attenuation. These are individually explained in the following sections.

**Biosparging**

Biosparging is the type of in situ bioremediation in which native microbes are used to degrade the organic constituents in the saturated zone. In Biosparging, nutrients are inserted into saturated zone to increase the biological activity to provoke the activity of native microbes. Biosparging can be used to reduce the concentration of petroleum ingredients that is dissolved in groundwater. It is the procedure in which pressurized air is pumped into a contaminated area to stimulate in situ aerobic biological activity. It targets chemical substances such as mineral oils, toluene, ethylbenzene, xylene, and naphthalene (BTEXN) that can be biodegraded in aerobic conditions (Soni et al. 2020; Verma et al. 2018; Yadav et al. 2020). It is used to treat soluble and residual contaminants in the saturated zone.

**Bioventing**

Bioventing was one of the first technologies that was applied in large scale in the 1990s. It is now mainly used in commercial applications. It is the type of bioremediation in which oxygen and nutrients are supplied into unsaturated zone. Oxygen is delivered into unsaturated zone via air movement through injection of air to enhance oxygen concentrations. This technique consumes the mandatory amount of oxygen that is essential for degradation. It also reduces the volatilization and liberation of contaminants into the atmosphere.

### Bioslurping

Bioslurping combines bioventing and vacuum-enhanced free-product recovery. Bioventing boosts the aerobic bioremediation of hydrocarbon-impacted soils. Vacuum-enhanced free-product recovery eliminates light non-aqueous phase liquid from the capillary fringe and the water table. Bioslurping is less effective in low-permeability soils. The main limitation to air permeability is extreme soil moisture. Optimum soil moisture is very soil-specific and too much moisture can decrease air permeability of the soil apart from also decreasing its oxygen transfer capability. Microbial activity is inhibited when soil moisture is less.

### Biostimulation

Biostimulation refers to the addition of phosphorus, nitrogen, and oxygen into severely polluted sites to stimulate the native microbes to degrade the toxic contaminates. It modifies the environment to enhance the bioremediation. It is highly efficient, eco-friendly, and cost-effective for ecosystem. Figure 10.2 shows the outlines of biostimulation.

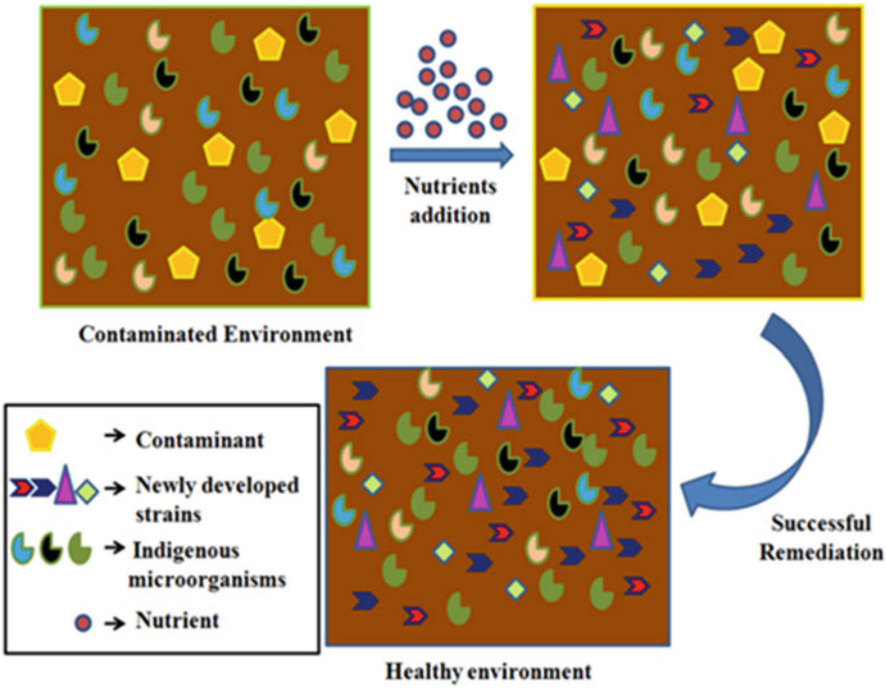


**Fig. 10.2** Depict the biostimulation bioremediation (Goswami et al. 2018)

**Bioaugmentation**

Bioaugmentation is the technique of insertion of a precise combination of naturally occurring or genetically engineered microbial strains having higher capabilities in polluted sites for augmenting the natural degradation process. It is used for remediating soil as well as groundwater contaminated with tetrachloroethylene and trichloroethylene. Bacteria *Acinetobacter and Comamonas testosteroni* biodegrade 4-fluoroaniline and 3-chloroaniline in wastewater, respectively. Figure 10.3 shows the mechanism of bioaugementation in which microorganisms convert contaminated environment into a contaminant-free environment.

**Natural Attenuation**

Natural attenuation is the process that naturally transforms contaminates into less toxic forms. It attenuates pollution from soil and groundwater.

### 10.2.2 Ex Situ Bioremediation

It includes removal of waste materials and their collection from the polluted site or place to assist microbial degradation. There are two types of ex situ bioremediation:

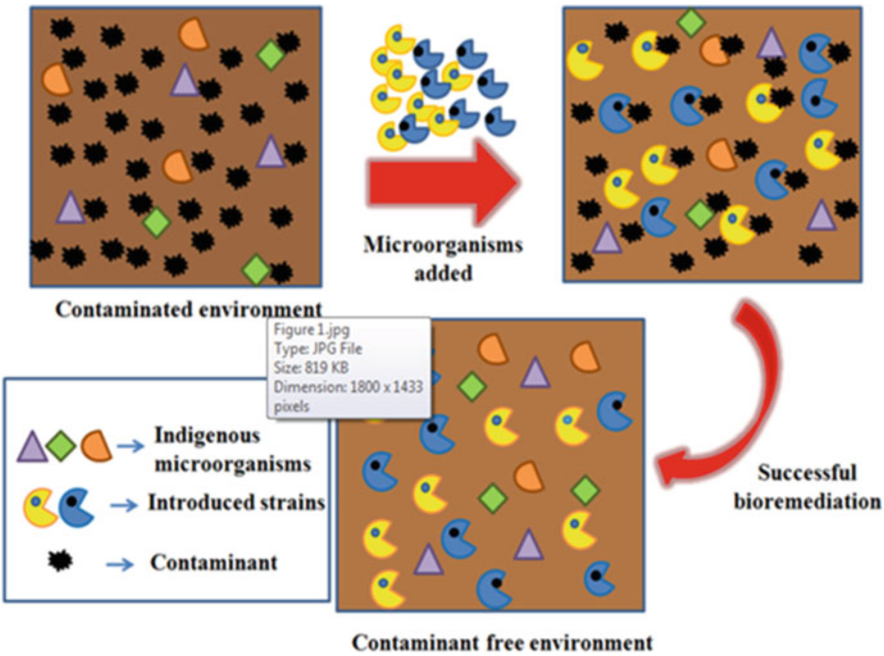


**Fig. 10.3** Depict the bioaugmentation bioremediation (Goswami et al. 2018)

1. Slurry phase bioremediation
2. Solid-phase bioremediation

#### 10.2.2.1 Slurry Phase Bioremediation

It involves the treatment of a mixture of water and excavated soil in a bioreactor. The excavated soil is treated to separate stones and debris. An aqueous slurry is created by combining the contaminated soil with water and nutrients amount depends on altering the concentration of bio-degradation to occur. This is then placed into a bio-reactor. The slurry is mixed to retain solids suspended and microbes in contact with the soil impurities. Upon achievement of the process, the slurry is dewatered and the treated soil can be reinstated to its original position. Merely the polluted fines and collected wastewater require further treatment.

#### 10.2.2.2 Solid Phase Bioremediation

Solid phase ex situ bioremediation contains organic wastes (e.g., agriculture wastes, leaves, and manures, etc.) and problematic wastes (e.g., industrial and domestic wastes, etc.). It involves treatment of different solid wastes such as animal manures, municipal solid wastes, leaves, and agriculture wastes. Solid phase bioremediation is divided into four types such as biopiling, land farming, compositing, and biofilter.

##### Biopiling

Biopiling is extensively used for remediating a wide range of petrochemical contaminates of soil. It involves the collecting of the soil into piles and provoking the biodegrading activity of microbial population by creating optimum growth conditions. It is used to treat non-halogenated volatile organic compounds and semi-volatile organic compounds. It is used recurrently to treat soils contaminated with petroleum hydrocarbons. Low weight petroleum products tend to vaporize from the pile owing to aeration, but the average and heavy petroleum hydrocarbons are degraded aerobically. Low levels of explosive residues, such as trinitrotoluene (TNT) and Royal Demolition Explosive (RDX) can also be treated, but less frequently. It is not used to treat inorganic contaminants and radionuclides.

##### Land Farming

Land farming is the treatment process that is accomplished in upper soil zone or in biotreatment cell. It has been proven most successful in treating petroleum hydrocarbons. Volatile hydrocarbons such as gasoline are treated very successfully. It has been used to treat surface soil contamination for hydrocarbons and pesticides. It enhances microbial degradation of hazardous compounds. As a rule of thumb, the higher the molecular weight, the slower the degradation rate. It means the more chlorinated or nitrated the compound, the harder it is to degrade.

##### Compositing

Compositing bioremediation remediates heavy metals, pesticides, and petroleum hydrocarbons from contaminated site. The benefits of compositing bioremediation are sequestering the precise contaminates, degrading the specific contaminates in water and soil, and providing additional benefits associated with compost use such as provoking plant establishment and health, but it is not effective on some contaminates.

**Biofilter**

Biofilter is the technology in which fuel hydrocarbon is passed through a soil bed where they sorb to the soil surfaces and are degraded by microbes in the soil. It is an important remediation method that can be useful in the removal of organic impurities from air and water. It also removes non-halogenated and is less effective for halogenated compounds. It is successfully used to control odors from compost piles. It is a highly effective air pollution control technology. It nearly changes all the contaminants to harmless products. Apart from that, it is a very low-cost technique.

## 10.3 Effects of Heavy Metals on the Environment

Heavy metals with their non-biodegradability nature makes it stable to remove them from polluted biological tissues and it is a primary concern for worldwide health because of their fatal nature. Iron (Fe), manganese (Mn), cobalt (Co), copper (Cu), and molybdenum (Mo) heavy metals are required in minor quantities for the existence of living organisms, but at higher concentrations, they could be detrimental. The heavy metals Cd, Se, Ag, Hg, Cr, As, Zn, Au, and Ni are lethal heavy metals that pollute the environment and affects the soil quality and public health as well as crop production (Kaur et al. 2019). These metals are primary sources of life-threatening diseases in human being such as Alzheimer's disease, atherosclerosis, cancer, Parkinson's disease, etc (Uttara et al. 2009). Each metal toxicity is evaluated by absorbed dosage by the organisms and the duration of exposure. Heavy metal toxicity typically affects plants' physiological activities and are harshly hampered. For example, photosynthesis, respiration, electron transport chain, and cell division are affected by elevated levels of heavy metals as expected by laboratory experiments. Furthermore, high metal toxicity affects cytoplasmic enzymes in plants' cell and cell structures due to oxidative stress, which consequently affects metabolism and plant growth. Humans' exposure to Pb heavy metal could cause lethal health issues such as paralysis and lack of coordination. Severe exposure to Cd affects internal organs of the body such as the liver, kidney, and cardiac tissues. Arsenic is the most common cause of severe heavy metal poisoning in humans and causes respiratory organ failure such as lung cancer. Exposure of humans to Hg causes respiratory organ failure and speech impairment, hearing, and muscles dystrophy. It collects in the cells of microorganisms where it gets transformed to methyl mercury and becomes detrimental for aquatic lives. Consumption of these fish and other aquatic animals by humans can cause the transmission of toxic methyl mercury to humans. Due to the negative effects of these heavy metals, intensive efforts need to be made to efficiently eradicate them from the atmosphere and stabilize the ecosystem (Jaishankar et al. 2014).

### 10.3.1 Mechanism of Heavy Metal Remediation

Heavy metals remove important components in biological molecules and hamper the functions of the molecules. These alter enzyme activity, protein or membrane transporter structure or function, thus becoming toxic to plants (Thakur et al. 2016). The major treatment used for heavy metal deprivation include methods such as chemical precipitation, coagulation, electrodialysis, floatation, flocculation, ion exchange, evaporative recovery, nanofiltration, reverse osmosis, and ultrafiltration. Physicochemical methods such as extraction, soil washing stabilization, and immobilization are being also used for removal of heavy metals. These methods, even if effective, are usually expensive as a result of chemical reagent and high energy requirements, apart from production of secondary noxious end-products. To remove toxic metal contaminants from the atmosphere and stabilizing the ecosystem is to make use of native microbes to degrade such heavy metals. Engineered microorganisms can be used to treat polluted environments by altering toxic heavy metals into non-hazardous forms (Srivastava 2021). However, the bioremediation method will only be successful when microbes that have the capability to remediate and endure heavy toxicity are utilized. Microbes are crucial to remediate heavy-metal-contaminated surroundings as they have a variety of ways to endure metal toxicity. Microbes that can change the oxidation state of several heavy metals have been broadly studied. Heavy metals bioremediation will be fruitful if a group of bacterial strains is employed rather than using a single strain culture. The synergistic effect of a group of bacteria on the mixture of Cd, Pb, and Cu heavy metal bioremediation from contaminated soils using the following strains of *Viridibacillus arenosi*, *Sporosarcina soli*, *Enterobacter* cloacae and *E. cloacae* were studied (Kashyap et al. 2019; Li et al. 2019). Bacterial mixtures had larger resistance for the remediation of heavy metals than using a single strain. Heavy metals are the key environmental pollutants and the assembly of these metals in soils are dangerous for agricultural manufacture owing to the toxic effects on crop development and food quality. Phytoremediation is an important and low-cost tool which is used for the remediation of metal-contaminated soils. *Solanum nigrum* is the best example which is widely used for the remediation of heavy metal-contaminated soils owing to its capability for metal uptake and endurance. *S. nigrum* can tolerate huge amounts of heavy metals by enhancing the activities of antioxidant enzymes and metal deposition in non-active parts of the plant. A summary of heavy metal uptake and tolerance in *S. nigrum* is given in Fig. 10.4. Both endophytic and soil microbes can play a role in augmenting metal tolerance in *S. nigrum*. Additionally, optimization of soil management practices and exogenous application of amendments can also be used to enhance metal uptake and tolerance in this plant (Muhammad et al. 2017).

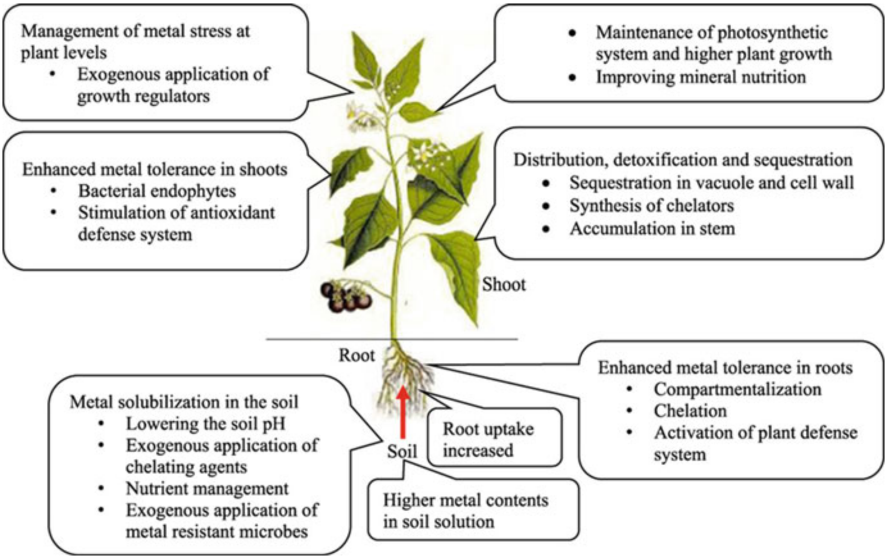


**Fig. 10.4** Mechanism of heavy metal remediation by *solanum nigrum* (ur Rehman et al. 2017)

## 10.4 Potential Hazards of Textile Wastewater

Textile wastewater containing hazardous dyes has adverse impacts on the human lifecycle and water resources. The textile dyes substantially affect the quality of water bodies, impair photosynthesis, inhibit plant growth, and provide recalcitrance and bioaccumulation. It increases Biological Oxygen demand (BOD) and Chemical Oxygen demand (COD) and may boost mutagenicity and carcinogenicity (Al-Tohamy et al. 2022). The presence of dyes in water has hostile environmental influences due to their carcinogenic nature. Dyes inhibit the dissemination of sunlight into the water. It changes the color of water and, apart from that, affects the photosynthetic reaction that damages aquatic life. The presence of chlorine and metals in textile wastewater could be injurious for certain forms of marine life. These dyes and pigments can damage water quality by eutrophication and disturb the ecological conditions of the aquatic flora and fauna. Dyes cause severe human health problems, and they can also cause a series of long-term harmful effects if they reach human organs via the food chain (Khan and Malik 2014).

### 10.4.1 Treatment of Dyes

Physicochemical and biological are two major techniques for the remediation of dyes. The physicochemical approach used for treating the textile effluents. These are oxidation, flocculation, coagulation, precipitation, bleaching, membrane filtration,

ion-exchange, and adsorption. The physicochemical techniques that are employed for dye remediation also have demerits such as high cost, high-energy requirement as well as generation of secondary waste. Besides these conventional methods, bioremediations have recently received considerable attention as a relatively low-priced and reasonably good treatment choice for textile effluents.

#### 10.4.1.1 Physicochemical Methods

Numerous physicochemical techniques have been used for the removal of dyes from wastewater. These contain adsorption, membrane separation, coagulation, flocculation, ion-exchange, photo degradation, and oxidation (Rajasulochana and Preethy 2016). However, these methods have economic and technical obstacles, such as high cost and generation of huge amounts of sludge and detrimental by-products as well as low viability on a commercial scale. Flocculation and coagulation approaches are effective for the decolorization of dye-containing wastewater. Coagulation approach employs ferrous sulfate and ferric chloride for the uptake of dyes from textile wastewater (Yaseen and Scholz 2019). Nevertheless, studies have also described the fruitful applications of other coagulants such as poly-aluminum chloride, magnesium chloride, and aluminum chloride (Gautam and Saini 2020) for the remediation of textile wastewater. However, coagulation has certain demerits such as high cost, low decolorization efficiency, and the generation of substantial amounts of sludge.

#### 10.4.1.2 Biological Methods

Besides the physicochemical methods, biological methods are an alternate choice because they have low operating cost. They also convert harmful and toxic materials into harmless as well as non-toxic products. Numerous bioremediation techniques for the elimination of textile dyes are discussed in the following sections. Bioremediation is an approach in which either organic wastes are degraded naturally into harmless compounds or their concentration is minimized to a standard range (Kumar et al. 2020; Uday et al. 2016). Microbes used in the bioremediation approach consume the environmental contaminants as food and break them down. Nutrients supply and other constituents are vital for the degradation of harmful substances. Enzymes are responsible to enhance the metabolic reactions. Different enzymes are responsible to degrade numerous dyes. The environmental conditions play a crucial role in the bioremediation approach because it affects the microbial growth that is crucial for the bioremediation. For an effective bioremediation process, the environmental circumstances can be improved to promote microbial growth, thereby enhancing the degradation productivity of the microbes (Kanissery and Sims 2011).

## 10.5 Degradation of Dyes by Bacterial Strains

Large amounts of sludge are produced due to using these high-cost physiochemical methods, using which result in a secondary level of air and water pollution. Due to that, there is an urgent need for cheap and eco-friendly removal techniques for polluting dyes. Biological processes is the potential alternative to conventional physiochemical method because they contain several microbes such as bacteria, fungi, yeast, and algae which are used to make the environment eco-friendly in nature. Bacteria can attain a higher degree of dye-degradation and process the complete mineralization of textile dyes under optimum conditions. Recently, the biological processing of textile effluent has been described as more cost-effective and eco-friendly than physiochemical techniques (Roy et al. 2020).

## 10.6 Mechanisms of Bacterial Dye Degradation

By using biosorption, desulfonation, deamination, and reduction of azo bond techniques, bacteria perform the decolorization process of dye. Electrons are produced during acetate, and sulfide oxidation results in azo bonds in the dye are fragmented. Azo reduction usually occurs by the degradation of aromatic amines (Ramalho et al. 2004). Biosorption is the technique to remove the dye or minimize the concentration of dye, heavy metals, and metalloids in a large amount of wastewater (Fig. 10.5).

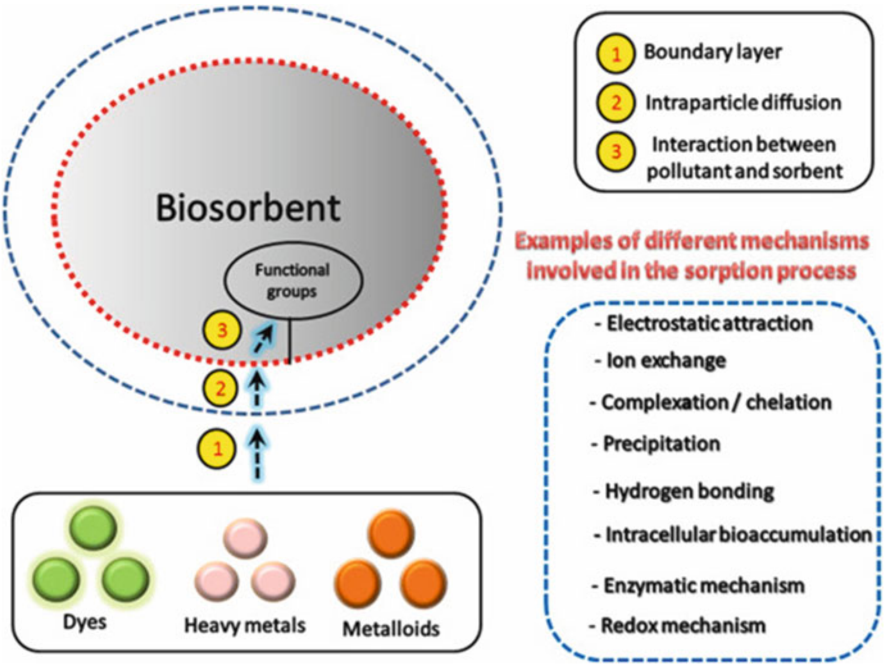


**Fig. 10.5** Mechanism involved in the biosorption process (Elgarahy et al. 2021)

## 10.7 Mechanisms of Fungal Dye Degradation

Enzymatic degradation as a dominant mechanism is used in fungal dye remediation. Enzymatic bioremediation is an ecological, economical, as well as innovative technique. This process explores the typical characteristics of microorganisms or genetically modified organisms of producing specific enzymes to metabolize the pollutant, transforming the toxic form into a nontoxic form, and sometimes into new products. The enzymes involved in bioremediation processes are laccases, dehalogenases, and hydrolases. Laccases are enzymes capable of catalyzing the oxidation of phenolic compounds, aromatic amines, and their compounds. Dehalogenases degrade a wide range of halogenated compounds by cleaving C–X bonds (X = halogen atom). Hydrolases break chemical bonds using water and convert larger molecules into smaller molecules, decreasing their toxicity. These enzymes facilitate the cleavage of C–C, C–N, S–N, S–P and C–P bonds. Other mechanisms are also involved; these are desulfonation, deamination, and hydroxylation as well as demethylation. Biosorption was the primary mechanism for the removal of Reactive Blue 19 (RB19), RB, AR57, and RBB by several fungal strains. The elimination of RB5, Acid Red 97 (AR97), Reactive Blue 49 (RB49), and Acid Violet 43 (AV43) by fungal strains using reduction of azo bond (Ihsanullah et al. 2020; Sabuda et al. 2020).

## 10.8 Mechanisms of Algal Dye Degradation

The crucial mechanism for algal remediation of textile dyes is biosorption. The adsorption of reactive dyes onto dried *Chlorella vulgaris* was principally a physical adsorption method, and it is exothermic in nature (Aksu and Tezer 2005). The degradation of Rhodamine B (RB) dye into $CO_2$ and $H_2O$ by *Coelastrella* spp. (Baldev et al. 2013). The removal of CR textile dye by *Haematococcus* spp. involves azo dye reduction and adsorption mechanism (Mahalakshmi et al. 2015).

## 10.9 Mechanisms of Dye Degradation by Yeast

Adsorption, asymmetric cleavage of the azo bond, and hydroxylation are the crucial mechanisms for the removal of dye by yeast. Azo-dye Acid Red B (ARB) dye is decolorized via yeast under aerobic conditions. The ARB dye was transformed into *ortho*-hydroxyl compounds upon further oxidation (Jamee and Siddique 2019).

## 10.10 Bioremediation Applications

Bioremediation must be considered as appropriate methods that can be applied to all states of matter in the environment such as, solids, liquids, gases, and saturated and vadose zones. The main methods of bioremediation are natural bioremediation and biostimulation. The biological community misused for bioremediation contain native soil microflora. Apart from that, higher plants can be manipulated to enhance toxicant removal called phytoremediation, especially for remediation of metal contaminates.

## 10.11 The Advantage of Bioremediation

There are many advantages of bioremediation (Tyagi and Kumar 2021), and these are as follows:

1. Bioremediation is a natural process and takes a little time to effect adequate waste-treatment process for contaminated material such as soil.
2. Microbes able to degrade the contaminant, the biodegradative populations, become reduced. The treatment products are commonly harmless, including cell biomass, water, and carbon dioxide. It needs very less effort and can be commonly carried out on-site regularly without disturbing normal microbial activities.
3. This also eradicates the transporting of amounts of waste off-site and the possible threats to human health and the environment. It is functional as a cost-effective process as compared to other conventional methods that are used for clean-up of toxic hazardous waste regularly for the treatment of oil-contaminated sites.
4. It supports complete degradation of the pollutants; many of the toxic hazardous compounds can be transformed to less harmful products and the disposal of contaminated material.

## 10.12 The Disadvantage of Bioremediation

It is restricted for biodegradable compounds since not all compounds are disposed by whole degradation process. There are new products of biodegradation that can be more toxic than the original compounds and persist in the atmosphere. Biological processes are ecofriendly and inexpensive. It includes the occurrence of metabolically active microbial populations, appropriate environmental growth circumstances, obtainability of nutrients and contaminants. It is demanding to encourage the process from preliminary study to largescale field operations. Pollutants might be existing in solids, liquids, and gases in all three states. It frequently takes larger than other treatment such as excavation and incineration. Study is required to develop and engineer bioremediation skills that are suitable for sites with complex mixtures of pollutants that are not uniformly dispersed in the atmosphere.

## 10.13 Conclusions

Biodegradation is ecofriendly and an attractive route to remediating, cleaning, and managing as well as improving method for resolving unhygienic atmosphere via microbial activity. The speed of undesirable waste substances degradation is determined in competition within microorganisms like bacterial, fungi, and algae's inadequate supply with nutrient, rough external abiotic circumstances, and low bioavailability. Bioremediation depends on several factors which hold, but are not restricted to, budget and concentration of pollutants. It may be used to treat a wider range of pollutants. In contrast, in situ techniques have no supplementary cost for excavation; but, on-site installation charge of equipment, committed with meritoriously and control the subsurface of polluted site can decrease some unproductive in situ bioremediation approaches. Geological features of contaminated sites, including soil and pollutant type as well as depth, human habitation, and performance of every bioremediation approach, should be incorporated in determining the most suitable and operative bioremediation technique for the successful treatment of polluted sites.

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