Chapter 20
Soil Pollution by Industrial Effluents, Solid Wastes and Reclamation Strategies by Microorganisms

Sourav Singha and Sabyasachi Chatterjee

Abstract Soil receives enormous pollutants from industrial effluents, agricultural & municipal wastes at a higher rate every day and cause accumulation of toxic heavy metals (Cr, Hg, Cd, Pb, & As etc.), radioactive nuclei, halogenated compounds, aromatic hydrocarbons and phenolic compounds etc. At elevated concentration, these pollutants are proved to be having an adverse effect on soil health, resulting in to unnatural changes in soil physiology affecting all forms of life directly or indirectly. Therefore, it is imperative to mitigate soil pollution aiming to restore soil ecosystem. Several study suggested, bioremediation have been extensively explored to reclaim soil & showed favourable outcome. Especially, microbial based techniques used to remove, reduce or transform noxious pollutants & are considered as most efficient, reliable & eco-friendly approach. The decontamination of soil is confined to bioavailability of pollutants. However, it is induced by type, chemical characteristics & concentration of pollutants, considering soil physical conditions. Microbes, especially bacteria, fungi & algae adopted different of bioremediation strategies. This study provides a comprehensive insight on occurrence of organic & inorganic soil pollutants, their characteristics & impact on soil health. We also discuss about the in situ & ex situ remediation methods and their applications with special emphasis on advance techniques. Moreover, this review will give a definite idea of microbial processes that would aid in selection of a competent approach (s) combating soil contamination effectively.

Keywords Soil pollution · Bioremediation · Organic pollutant · Industrial effluent · Soil reclamation · Heavy metals

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S. Singha
Department of Microbiology, Bankura Sammilani College, Bankura, W.B, India

S. Chatterjee (✉)
Department of Botany (PG), Ramananda College, Bishnupur, Bankura, W.B, India
e-mail: schatterjeebiotech@gmail.com

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20.1 Introduction

Soil is a natural habitat of living organisms that contributes to basic needs like food and water. Soil accounts for sustaining the ecosystem & managing biodiversity to a great extent. It also acts as a vital resource that essentially contributes to the perseverance of life on Earth. Especially agricultural practices like food grain cultivation, horticulture & vegetation etc. solely dependent on the physicochemical properties of soil (Mishra et al. 2016). The inherent soil property has a direct influence on soil behaviour and nature; hence the comprehensive knowledge of soil properties, nature & behaviour becomes imperative managing environment in sustainable way (Sonwane et al. 2010).

Biotic & abiotic components of soil also have a role to play in soil health. Living components including plants, flora & fauna equally contribute to soil functioning. Soil acts as a major harbouring site for interactions where processes like decomposition, humification, solubilization & mineralization are taken place. These processes impact soil fertility by the reciprocal action of soil biota with humus materials, minerals and maintaining soil structure (Xue et al. 2021). Soil physicochemical characteristics such as pH, water content, availability of nutrients including the amount of carbon (C), nitrogen (N) and Potassium (K), etc. are very essential parameters. A slight imbalance causes a notable change in soil which directly or indirectly hinders its habitants. Therefore, soil quality necessarily has to maintain to confer its native functioning (Vincent et al. 2018).

In the last decade or so degradation of soil quality become a global issue of concern, where the soil is exceedingly contaminated by industrial effluents and solid wastes. Unplanned urbanization with booming industrialization, improper waste disposal, and anthropogenic activities had caused unsettling of soil composition & ended up with soil pollution. Industries without proper waste management systems are the biggest contributors to soil pollution (Lavanya et al. 2019; Kumar and Agrawal 2020). Industries like textiles, metallurgy, tannery, battery manufacturing industries, glass factories, microelectronics, paper processing plants, iron & steel plants, coal burning thermal plants, nuclear power stations, petroleum industries & plastics manufacturing etc. producing more pollutants which directly or indirectly released into the soil. The by-products of these industries are disposed of inappropriate manner as a form of effluent contains several organic and inorganic pollutants including toxic heavy metals and other non-biodegradable substances (Chhonkar et al. 2010; Zhan et al. 2015). The bioaccumulation of organic & inorganic waste materials & heavy metals in the environment exert toxicity & causing several health issues to the living world (Tchounwou et al. 2012; Jaishankar et al. 2014; Engwa et al. 2019; Zwolak et al. 2019). Especially heavy metals, pesticides & other xenobiotic compounds present in industrial effluents, are not biodegradable and have the tendency to persist in the environment, and their concentrations can be magnified significantly with time. These pollutants are not water-soluble thus they primarily accumulate on top layer of soil (Mishra et al. 2016). An elevated concentration of these could cause severe damage to the living cells by showing extreme toxicity due to inhibition of metabolic reactions

(Vongdala et al. 2018). Plants' lifecycles are shortened when they are exposed to such high contamination due to the inability to adapt that abrupt change in soil chemistry. Even the plant-associated microorganisms found in soil (Fungi and bacteria) begin to decline; their natural interactions disrupted which creates additional problems to the soil. It slowly hampers fertility and converts land unsuitable for agriculture and any vegetation to survive.

Urban & rural household waste materials also cause problems as they are been discharged in the environment in an uncontrolled manner. Sewages & garbages from domestic as well as commercial waste sources primarily consists of plastics, papers, discarded food, clothes, metallic cans, sludge, glasses, fibers, bottles, rubbers, etc. Among these, a few are biodegradable and are recycled by composting, while non-biodegradable materials are disposed of in landfills. Landfills are common in practice and economical but uncontrolled disposal of solid wastes gives rise to major consequences related to soil sustainability. It creates nuisance and has considerable environmental impacts by unsettling the soil ecosystem. These kinds of open landfills produce sanitary problems and act as a harbour of insect vectors & major sources of vector-borne pathogens. These waste dumps also produce several organic acids that percolate into the soil and cause underground water contamination (Chadar and Chadar 2017). Several reports suggested that the production of acids resulting in an acidic environment may inhibit biodegradation of waste materials by inherent microbial communities. In due course those soil ecosystems destroyed fully and are converted to the barren and unfertile land, unable to support any life on it.

Recent studies revealed that the presence of radioactive nuclei impacted soil degradation greatly, which is one of the pivotal factors of soil pollution generates both naturally and in a technogenic way. Emission of radioactive elements like ^{3}C, ^{60}Co, ^{90}Sr, ^{137}Cs, ^{226}Ra, ^{232}Th, ^{238}U and ^{239}Pu, etc. from nuclear power plants contaminate soil and accumulated in the vegetables and crops grown on that contaminated soil (Aleksakhin 2009; Ali et al. 2019).

Several bodies are formed in many countries in order to regulate and minimize the pollution level. Environmental Protection Agency (EPA) is one such organization working on the restoration of the environment by making a perfect balance of sustainability, economy & Society (report.epa.gov 2016). Published literature suggested that potential biological remediation strategies can be employed to retrieve soil native nature. Biological operations like microbial remediation or phytoremediation are effectively used for the removal of soil contaminants to a great extent. Especially microbial cells exert various processes including oxidative reduction, precipitation, mineralization, biosorption, complexation and enzymatic transformation by which hazardous pollutants are removed from soil efficiently (Ojuederie and Babalola 2017; Igiri et al. 2018).

The prime focus of this study is to recount the profuse sources & nature of soil contamination through industrial effluent and solid wastes & plausible soil restoration strategies (Fig. 20.1).

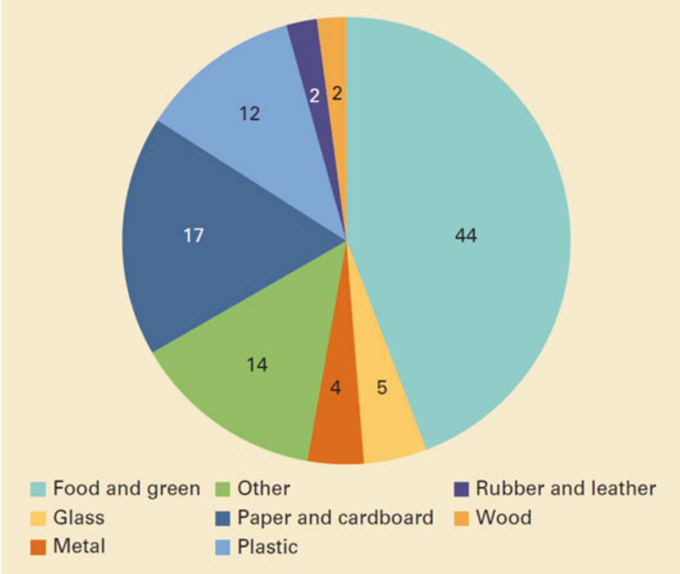

Fig. 20.1 Composition of Solid waste as per USEPA 2016

20.2 Nature, Composition & Characteristics of Industrial Effluent

Industries generally discharge wastewater in untreated form into the environment. Including India, worldwide wastewater generation from industries and production plants is common in practice. It has been reported by several researchers that, due to the shortage of requisite space or lack of proper disposal management system, a huge amount of toxic liquid is produced and enters into the open environment. Most industries disposed of their raw effluents in nearby water channels, drains or open soil (Ahmed et al. 2016). According to the published data of CPCB in the year 2010, 13,500 million litre industrial wastewater produced per day in India. These effluents typically consist of organic & inorganic materials which exert high toxicity (Table 20.1). Organic pollutants mainly includes phenolic compounds, hydrocarbons, pesticides, azo dyes, esters, etc. (Bhargava & Saxena 2020). Heavy metals are major constituent of inorganic pollutants. Commonly found heavy metals in industrial effluents are arsenic (As), nickel (Ni), chromium (Cr), lead (Pb), mercury (Hg), and cadmium (Cd), etc. Certain free living electrolytes (K^+, Ag^{2+}, Na^{2+}, Mg^{2+}, Ca^{2+}, Cl^-, CO^{3-}, HCO^{3-}, Cl^-) are also likely to be found in the form of inorganic pollutants (Subramani et al. 2014; Ahmed et al. 2016; Tejaswi et al. 2017) (Table 20.2).

The composition & chemical nature of the effluents varies according to the industries it released. Generally, industries like paper mills & Zn smelter release acidic (pH 3 to 5) drain water while the textile wastewater is alkaline in nature. On the other

Table 20.1 Different types of industrial effluent and their characteristics

Different sources of industrial waste water	Composition & chemical properties
Petrochemical industry waste water	Primarily hydrocarbon compounds, BTEX (benzene, toluene, ethylbenzene, xylenes) & dioxins, presence of phenolic compounds with metals. High in sulphides High COD with alkaline pH
Paper & pulp industry wastewater	Ligno-cellulose components, phytosterols phenol and chlorophenols compounds with resin acids & fatty acids. Highly toxic chlorinated compounds (dioxins & furan). Elevated BOD & COD with alkaline pH
Steel Industry waste water	Iron (Fe) & chromium (Cr) are the main components. bag filter dust (BFD)
Textile and fabric industry wastewater	Principal pollutants are harmful residual chlorinated dyes (Azo, diazo & anthraquinone), several carcinogenic metal complexes (As, Hg, Ni, and Cr etc.) High TDS & BOD
Tannery or leather industry wastewater	High concentration of toxic metals (Cr, Cu, Pb and As) & organic compounds (phosphate, bicarbonate and chloride) with salts (sodium, chloride, and sulphide), high in BOD, COD TDS and TSS, presence of hazardous phenolic compounds & phthalates (cause neuro toxicity)
Distillation process waste water (stilage)	Dark brown coloured effluent contains several organic compounds in higher concentration like polysaccharides, protein residues, polyphenols, waxes & melanoidins (condensation of sugar & amino acids). high in BOD, COD & TDS
Wine industry wastewater	Acidic effluent contains high amount of sugars, ethanol polyphenols, tannin and lignin & short chain fatty acids, presence of Na, K & phenolic compounds elevates COD and TSS level. Presence of several toxic heavy metals including Co, Pb, Cd, Ni & Cr etc.
Pharmaceutical Industry wastewater	Containing hazardous organic solvents like petroleum ether, ethanol, benzene, chloroform, with several organic compounds such as steroids, antibiotics, analgesics, drug residues and pharma-metabolites along with significant amount of metalloids like mercury, chromium, copper etc.
Paint manufacturing industry wastewater	Presence of high amount of dyes, colorant, adhesives, trace of oils (hydrocarbons) & grease, organic solvents (toluene and methyl ethyl ketone).toxic heavy metals (chromium and lead) and dissolved solids
Abattoir (slaughterhouse) wastewater	High concentration of suspended organic materials contributed to high COD & BOD, excessive nutrients promote the growth of pathogenic and non-pathogenic microorganisms, presence of toxic heavy metals and other materials like fats, oil, and grease (FOG)
Landfill drainage water	Ample amount of organic compounds comprising proteins, carbohydrate, aromatic hydrocarbons, contains toxic metals, low molecular acids & gases (CO_2 & H_2), Volatile fatty acids (VFA) etc. high in total suspended solids leads to increased COD & BOD

(continued)

Table 20.1 (continued)

Different sources of industrial waste water	Composition & chemical properties
Mining industry drainage (acid mine)	Dark colour, acidic (pH below 2) effluent contains high concentrations of toxic metals such as Iron, Cadmium, Lead, Nickel & Copper, Cobalt etc. Presence of hydrated sulphates (SO_4^{2-}) is characteristics of the effluent

Adapted from Ahmed et al. (2016), Bhargava & Saxena (2020)

Table 20.2 Different organic contaminants in industrial waste water with their sources & functions

Type of organic pollutants	Sources and characteristics
Phenol & Chlorinated phenols	Major sources are pesticides, pharmaceuticals wastes, petroleum refineries, distilleries, pulp and paper mills, wood preservation plants & coal excavation sites It causes various skin related problems like dryness and burn even hamper central nervous system Chlorinated phenols are potent carcinogenic and mutagenic agents
Nitro-aromatic (Azo dyes)	Released from industries which uses different colorant materials frequently such as textile & fabric, pharmaceutical, cosmetics, paint, plastics, leather & paper industries etc., Non-biodegradable aromatic amines have severe health hazards in humans and animals such as neurotoxicity, digestive tract discomfort, nausea, vomiting etc., indiscriminate exposure of these may lead to liver and kidney dysfunction in human

hand, oil refineries, paper sugar mills, distillery and effluents possess much higher organic carbon. These effluents also contain xenobiotic compounds like aromatic hydrocarbons, metalloproteins and phenol compounds (Ahmed et al. 2016).

BOD and COD are the crucial parameters used to determine the wastewater characteristics. Several reports suggested that the abnormalities in BOD & COD values (Chhonkar et al. 2010) of untreated industrial effluents are very high contributed by various organic acids (Table 20.3).

20.3 Sources, Composition & Nature of Solid Wastes

Generation of waste material is an unavoidable phenomenon where a huge amount of waste is produced through industrial processes, from manufacturing units, or in the form of municipal and urban garbage. But the problem arises when these toxic & hazardous solid wastes are disposed of in an open environment without any proper treatments (Agarwal 2016; Kumar and Agrawal (2020)). These untreated solid wastes cause several complications. Generally, developing countries do have problems with

Table 20.3 Types of inorganic contaminants in industrial effluent with their sources & functions

Type of inorganic pollutants	Environmental pollution and toxicity profile
Cadmium (Cd)	Emission of Cd is greatly contributed by fuel combustion & waste incinerations along with steel industries, phosphate fertilizer manufacturing unit & paint sludge. Accumulation of Cd can cause severe problems like muscle cramp, stomach pain with vomit tendency, psychological disorders & damage of neuro system etc.
Chromium (Cr)	Major sources are glass factories, wood preservation plants, paint manufacturing units, tanneries, steel & alloy industries & mining. Inhalation of Cr can have lethal effect like respiratory distress, perforation in lungs, significant dysfunction of several organs e.g. renal failure, cardiovascular damage etc.
Arsenic (As)	Majority of As contamination occurs from fuel combustion, coal burning power plants, mining & metal extraction processes It cause systematic disruption of internal body parts like lungs, liver, spleen etc. High exposure of As leads to anaemia, cardiovascular malfunction, disruption in neuro transmission, gastrointestinal lesions and even death of individual
Lead (Pb)	Pb mostly released from battery wastes, ceramic industry, pesticides industry, fuel combustion, smelting operations, thermal power plants etc. Hypertensions, renal dysfunctions, abdominal discomfort, encephalopathy, hearing loss, reduced consciousness, CNS dysfunction & difficulties with concentration etc. are the major Pb associated problems arose upon exposure
Mercury (Hg)	Contamination Hg of rises from several industries like chemical processing, pharmaceuticals, coal based power stations, chemical metal extraction processes, electronic wastes, agricultural wastes, & hospital waste etc. Mercury has drastic impact on human heath like development of odd metal taste, frequent vomiting, breathing problems including neurological disorder which leads to loss of vision & hearing with speech slurring

Adapted from Tchounwou et al. (2012), Ahmed et al. (2016), Tarekegn et al. (2020)

waste management where solid waste materials are dumped in a specific site or they can be used as landfill materials. Lack of space near-source stations is a major reason for that (Lavanya et al. 2019). Preferably waste materials are transported to outskirts areas of cities where landfills or dumpsites are located. According to Shankar and Shikha, in India, it is only about 40% of total municipal solid wastes are collected and dumped in specified sites in daily basis. Insufficient infrastructure adding up more problems and ended up with Piling up of hazardous materials (abdel-Shafy and Mona Mansour 2018; Ferronato and Torretta 2019) (Table 20.4).

A massive amount of waste materials emancipate openly from industries can be categorized as hazardous and non-hazardous. Waste materials like papers, plastics, wood, cardboard, packaging materials are relatively less harmful and can be utilized further or recycled. However trashes of heavy industries like coal ash from thermal power plants, steel melting slag, scrap metal & blast furnace slag from the steel manufacturing unit, lime from pulp and paper industries, gypsum from allied industries, red mud and tailings other than Iron (e.g. aluminium, zinc and copper) from

Table 20.4 Type of solid wastes and their characteristics

Solid waste material	Characteristics
Steel and Blast furnace slug	Scrap materials produced during Iron & steel making, rich in minerals (mainly silicate, iron, aluminium, calcium & magnesium)
Brine sludge mud	Organic rich semi solid waste from Chlorine-alkali & Caustic soda industry, major component soda ash
Copper slag	By product of various metallurgical processes present As, Fe, Cu etc.
Fly ash	By product of Coal-combustion contains ample Pb & Al
Lime sludge waste	Prime component is Calcium carbonate ($CaCO_3$) released generally from different industries like pesticide, sugar, soda ash & paper
Mica mine scrape	Mining of Mica produce silica, aluminium, oxides of potassium and Iron
Phospho-gypsum	Known as calcium sulphate, produced during processing of phosphate & phosphoric acid, contains radioactive elements
Bauxite mining waste (Red mud)	Metallic waste (contains-iron, silica, titanium & alumina) produced from bauxite ore
Coal dust	Mining of coal produce fine particles
Iron ore tailing	Solid by product of iron ore processing, typically posses alumina & iron oxide

Adapted from Basu et al. Brifa et al. (2020) & Tarekegn et al. (2020)

metal industries are really creates environmental problems (Agarwal 2016; Lavanya et al. 2019).

20.4 Impact of Industrial Effluent & Solid Waste on Soil Health

The solid & liquid industrial waste are rich in chemicals, which are non-biodegradable and exert toxicity. At elevated concentrations of these ingredients of wastes exert an adverse impact on soil health. The components present in effluents tend to change the chemical makeup of the soil. Overabundance may influence soil stability by altering composition and physical factors like pH, salinity, etc. Deposition of organic and inorganic materials into the soil also amend the microenvironment of soil which indeed very essential for crop production. Several instances proved that the precipitation of fly ash on topsoil nearby industrial belts result in the loss of fertility. The immediate consequence of that is the production of barren lands (Bhat 2015).

It is evident that bioaccumulation of heavy metals have shown phytotoxicity (Hiroki 1992; Ahmed et al. 2016). Many researchers have highlighted the lethal effect of heavy metals on biological systems. The physiology of cell interior (organelles) markedly affected by these toxic ions (Jayashankar et al. 2014; Brifa et al. 2020; Tarekegn et al. 2020). In general, metals are indispensable for plant growth. Physiological & biological processes are highly dependent on metal concentration with in the cell. Depending upon the dose and exposure these chemicals started affecting plant health & disintegrate soil natural microbiota functioning. The presence of contaminants like inorganic metals affect adversely & causes various plant diseases such as high concentration of Cd result chlorosis, excess Cu produces oxidative stress etc. (Ahmed et al. 2016).

Man made organic chemicals such as halogenated organic pollutants (HOPs), polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), BTEX (benzene, toluene, ethylbenzene, and xylenes), nitro-aromatic compounds and organophosphorus compounds are found in soil in large quantity. Their high molecular weight and poor water solubility makes biologically unavailable and therefore, tend to persist in the environment. These organic chemicals are potentially mutagenic and carcinogenic, often accumulates in vegetables & fruits and cause a major threat to humans (Perelo 2010; Ali et al. 2019).

20.5 Reclamation of Soil by Microbial Remediation of Industrial Effluent & Solid Waste Contaminants

Microbial remediation is considered as effective techniques for removing soil pollutants. One of the key attribute of microorganism is the capacity to transform soil pollutants into harmless entity by exploring their wide metabolic range. Especially, fungi and bacteria able to produce variety of extracellular enzymes and low molecular weight organic acids that can somehow modify organic pollutants. (Rajendran et al. 2003). Therefore, *in-situ* & *ex-situ* treatment of pollutants proven as a cost-effective, eco-friendly & sustainable approach (Megharaj et al. 2011).

20.5.1 Microbial Remediation of Heavy Metals

Heavy metal pollutants can be partially or completely removed from soil by utilizing the metabolic activity of microbes. It is an entirely sustainable process i.e. no harm to the environment compare to other physical or chemical processes. Microbes are employed to remove, reduce, transform or completely remove the heavy metals from the soil. Several genes either present in the genome or plasmid are responsible for these physiochemical activities (Rajendran et al. 2003).

Efficient microorganisms including *Bacillus* sp., *Arthrobactor* sp. *Pseudomonas* sp., *Staphylococcus* sp. *Streptomyces* sp., *Aspergillus* sp., *Rhizopus s*p., *Sacharomyces* sp. *Penicillium* sp. etc. are widely distributed in soil and effectively remediate soil under natural conditions (Table 20.5).

Table 20.5 Microorganisms & respective metals they remediate

Microorganisms	Remediating heavy metals
1. Bacteria	
Pseudomonas aeruginosa	Hg(II)
Pseudomonas sp.	Pb(II)
Bacillus sp.	Pb(II)
Arthrobacter viscosus	Cr(VI)
Staphylococcus epidermidis	Cr(VI)
Eichhornia sp.	Cu(II)
Brevibacterium sp.	Zn(II)
Rhodobacter capsulatus	Zn(II)
Pseudomonas aeruginosa	Cd(II)
Bacillus cereus	Cd(II)
Ochrobactrum sp.	Cd(II)
Sporosarcina ginsengisoli	As (III)
Bacillus cereus	Cr (VI)
Kocuria flava	Cu(II)
Pseudomonas veronii	Cd (II), Zn, Cu
Actinomycetes sp	Cd (II)
Stenotrophomonas maltophilia	Pb (II)
Enterobacter cloacae	Cr (VI)
Rhodopseudomonas sp	Co
Bacillus subtilis	Cr (VI)
Cupriavidus metallidurans	Se (VI)
Bacillus megaterium	Cr (VI)
Pseudomonas aeruginosa	Cr (VI)
2. Fungi	
Aspergillus versicolor	Ni, Cu
Aspergillus niger	Cr (VI)
Aspergillus foetidus	Cr (VI), Pb (II)
Aspergillus fumigatus	Pb
Drechslera rostrata	Cr (VI)
Gloeophyllum sepiarium	Cr (VI)
Rhizopus oryzae	Cr (VI)
Penicillium canescens	Hg
Sacharomyces cerevisiae	Pb, Cd
Rhizopus stolonifer	Cd, Pb, Zn
Rhizopus arrhizus	Hg, Pb, Cd

(continued)

Table 20.5 (continued)

Microorganisms	Remediating heavy metals
3. Algae	
Spirogyra sp.	Cd, Hg, Pb
Cladophora glomerata	Cu, Pb, Cd
Spirullina sp.	Pb, Cr, Cu, Fe, Zn
Hydrodictylon sp.	As
Rhizoclonium sp	As
Oedogonium rivulare	Cu, Pb, Cd, As

Adapted from: Dwivedi (2012), Snehalata et al. Rodriguez et al. Igiri et al. (2018)

Tabak et al. (2005) described different mechanisms of bioremediation by which soil microbes can minimize the effect of heavy metals including bioaccumulation, bioprecipatation, biosorption, transformation, immobilization & cometabolism etc. Under an intuitive environment, microbes adopt one of these techniques and make toxic metals biologically unavailable.

20.5.1.1 Biosorption

Biosorption or bioabsorption refers to the physical attachment of metals on the cell exterior by extra cellular polymeric substances (Tabak et al. 2005; Tarekegn et al. 2020). Biosorption is strictly dependent on physicochemical properties of the host cell. The ion absorbing efficacy is greatly vary upon composition of cell wall, temperature & pH of the surroundings, surface area for contact and metal gradient, exposure time, ionic strength as well as the chemical nature of the metal ions, etc. (Shamim 2018). Biosorption is a very common technique employed by many fungal, algal or bacterial species to defend themselves against cadmium, silver, lead, or nickel etc. (Tabak et al. 2005; Tarekegn et al. 2020). According to Shamim (2018), the accumulation of metal ions is not ATP dependent process rather the concentration of metals in the exterior, i.e. chemo osmotic pressure greatly influences the uptake capacity. The ionic nature of the membrane along with the gradient created on either side helps in specific and nonspecific metal sorption. Especially the presence of peptide chain linked repeated unit of NAG (N-acetyl glucosamine) & NAM (1,4-N-acetylmuramic acid) make bacteria more negative charge which attracts positively charged metallic ions (Shamim 2018) (Fig. 20.2).

20.5.1.2 Bioaccumulation

Microorganisms can retain toxic heavy metals within their biomass in a physical manner. It is evident that microbial cells are able to uptake metals through the cell

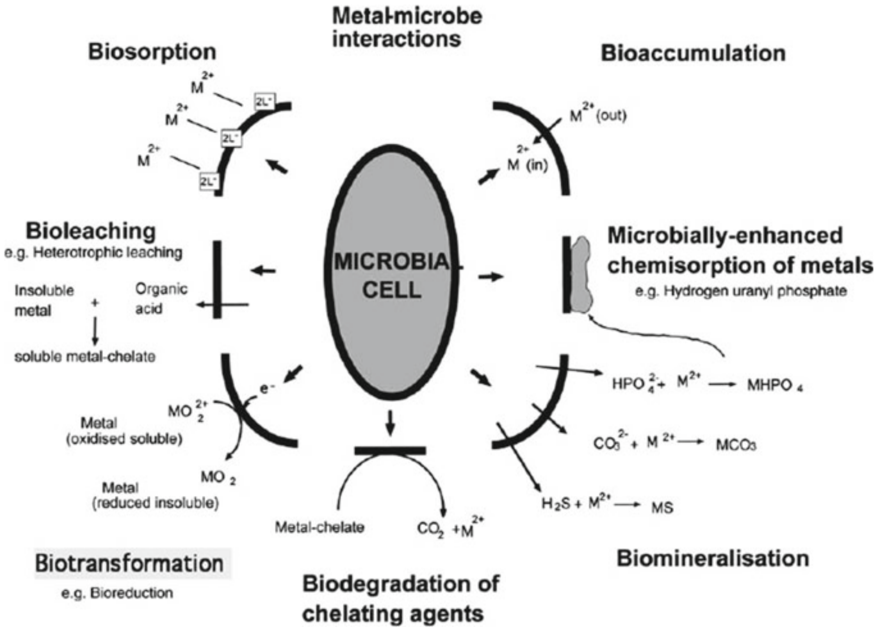

Fig. 20.2 Interactions of metals and microbes affecting Bioremediation. *Source* Tabak et al. (2005)

membrane due to several compounds released by the cell (Tabak et al. 2005; Banerjee et al. 2015). Several indigenous soil bacterial genera accumulates toxic metals such as *Escherichia hermannii* and *Enterobacter cloacae* showed resistance against Cd and Ni, *Bacillus cereus & Citrobacter* sp. uptake Pb and Cd, *Thiobacillus ferrooxidans* & *Bacillus subtilis* absorb Ag & Cr respectively. Similarly, *Pseudomonas aeruginosa* (U) & *Micrococcus luteus* (Sr) are also reported to show bioaccumulation. Certain fungal species efficiently deal with metals e.g. *Saccharomyces cerevisiae* act on U (Urenium), *Rhizopus arrhizus* act on Hg and *Aspergillus niger* on Th (Thorium) etc. (Juwarkar 2010).

20.5.1.3 Biotransformation

Microbiological transformations deals with the conversion of notorious pollutants (heavy metals) which can participate in the metabolic process. This technique is very useful to detoxify hazardous metals by reducing them enzymatically. Microorganisms takes up metals ions and then undergo various reactions such as oxidation, reduction, alkylation or methylation (Tabak et al. 2005). For example, *Corynebacterium* sp. shows biotransformation & reduce Chromium from its toxic form (Cr^{6+}) to less toxic form(Cr^{3+}) (Zhao et al. 2021). Similarly, *Bacillus licheniformis* cells can reduce of Pb^{2+} to Pb^0 enzymatically (Jin et al. 2018).

20.5.1.4 Bioprecipitation

Various microbial activity may result in the precipitation or crystallization of metallic compounds which facilitate transformation of noxious metals into comparatively harmless one (Tarekegn et al. 2020). Eltarahony et al. (2020) reported that growing microbial cells secrete carbonate compounds which trap heavy metals causing precipitation. Such depositions of metals are greatly elevated when microorganisms tend to produce secondary metabolites. Previous researchers have shown that bio precipitation of Pb in a compound form ($PbHP_O{}^4$) that precipitates on the cell surface of by *Citrobacter* sp. & *Bacillus* sp (Peens et al. 2018).

20.5.1.5 Bioleaching of Metals

Bioleaching or biomining is the extraction of specific metal from mineral-rich natural compounds (ore) through microbial transformation. Bacteria like A*cidophilus ferrooxidans* & *Thiobacillus* sp. are capable to extract Cu, As, Hg, Pb, Fe, Ni etc. efficiently from mineral ore (Jerez 2017). Biomining widely used as a replacement of conventional chemical mining proved to be cost-effective & hazard-free. Several reports suggested that the microorganisms which are associated with bioleaching tend to have tolerance towards heavy metals. Since, this process produce certain organic acids like citric acid, gluconic acid & oxalic acid etc. which aids the mineralization of insoluble metal sulfides into soluble one.

20.5.1.6 Biomineralization

Biomineralization is the transformation process by which metallic compounds turns into crystalline precipitates. Microbial induced mineralization mainly based on cellular metabolism where metals are subjected to modify chemically and partially precipitates on the cell surface.

20.5.1.7 Cometabolism

Cometabolism is the process where degradation of one compound dependent on another compound (Hazen and Terry 2015). Usually, it is referred to as the simultaneous degradation of two compounds where the first substrate is fortuitously degraded by an enzyme which is the metabolic product of another compound (the secondary substrate). Typically, the microorganisms involved in it having no direct benefit from each other. Such co-metabolism strategies explored to cope with complex pollutants (Daniel et al. 2019; Zhao et al. 2021).

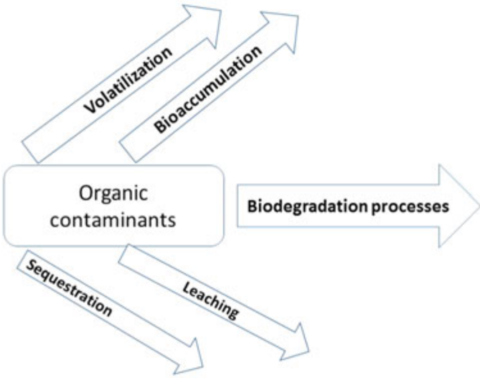

Fig. 20.3 Scheme of Microbial biodegradation of organic pollutants. Adapted from Tabek et al. (2005)

20.5.2 Remediation of Organic Pollutants

The major contaminants like Poly aromatic hydrocarbons (PAHs) and Polychlorinated biphenyls (PCBs) popularly known as Persistent Organic Pollutants (POPs) are found frequently and are considered as recalcitrant due to their high molecular weight & low water solubility (Mir and Gulfishan 2020). However, certain indigenous microorganisms have shown the potential to degrade these materials partially without hampering the native ecosystem and make these carcinogenic biologically unavailable (Perelo 2010; Megharaj et al. 2011; Mir and Gulfishan 2020) (Fig. 20.3).

Microbes mediated biodegradation of organic pollutants primarily occurs by anaerobic or aerobic metabolism and are mainly based on various processes including Monitored natural recovery (MNR), biostimulation & bioaugmentation & addition of compost material etc. (Kang 2014). Under controlled physical conditions microorganisms utilizing catabolic enzymes like oxygenase or dioxygenase to transform pollutants and ultimately the products of the microbial activity incorporated in the metabolic pathway (Perelo 2010). Bacterial species like *Pseudomonas sp., Burkholderia sp., Methococcus sp., Bacillus sp.* etc. were studied for their biodegradation capacity of PAHs, & PCBs (Kang 2014) (Fig. 20.4).

20.5.2.1 Monitored Natural Recovery (MNR)

Monitored natural recovery (MNR) is a sustainable process of remediating polluted sediments (Perelo 2010). A combined approach (biological & chemical) is adopted to treat contaminated site for a time span under close monitoring. MNR often employed indigenous factors which minimize the ecological and human health related risk significantly.

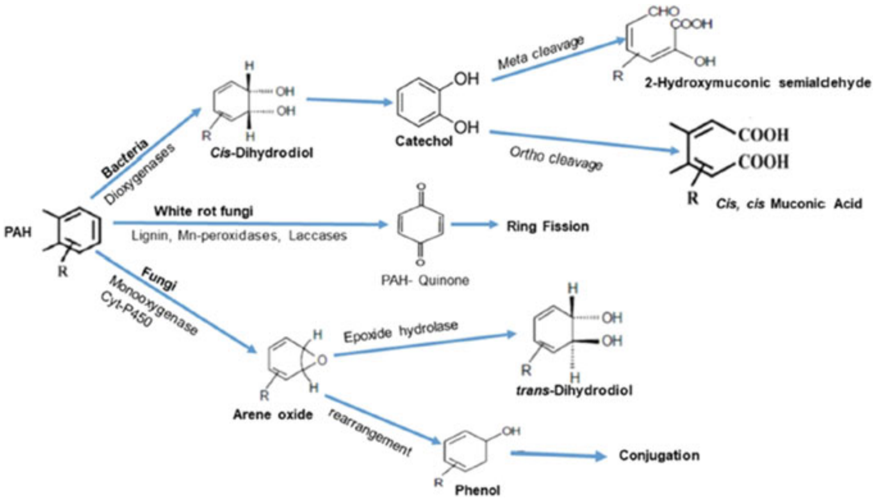

Fig. 20.4 Microbial Biodegradation Pathways of PAHs. Adapted from Sayara and Sanchez

20.5.2.2 Biostimulation

Biostimulation is the moderation of the growth parameters of microorganisms to enhance the rate of the bioremediation process in soil. Various nutrients such as phosphorus, nitrogen, oxygen, or carbon supplemented as stimulants for microorganisms (Ratnakar et al. 2016; Goswami et al. 2018). Preferably under controlled environment addition of the stimulants improves potential growth affecting biomass & accelerates bioremediation. (Igiri et al. 2018).

20.5.2.3 Addition of Compost

Many researchers have reported that the addition of inoculum in compost form in contaminated soil has shown a significant response in terms of bioremediation. (Kästner and Miltner 2016). Compost bioremediation has proven to be effective procedure for minimizing the toxicity of many types of contaminants, especially chlorinated and non-chlorinated hydrocarbons. This process works in a precise manner as it treats specific contaminants at specific sites therefore it is often called to as “tailored” or “designed” compost (Ratnakar et al. 2016).

20.5.2.4 Bioaugmentation

Bioaugmentation is the incorporation of exogenous microorganisms or genetically modified strains to contaminated sites to get rid of pollution. The idea behind this is to speed up the biotransformation of the hazardous elements into less toxic substances under optimized conditions (Kastner and Miltner 2016). These transformed substances can be further utilized by other microbes and be incorporated into metabolism (Smitha et al. 2017). This process is effectively used where other bioremediation processes failed to show satisfactory results due to the lack of sufficient microbial populations or efficacy (Megharaj et al. 2011).

20.6 Conclusion & Future Aspects

Rapid industrial development and unimpeded urbanization in an unplanned manner are producing enormous wastes and continuous uncontrolled dumping of these wastes affects soil physicochemical properties and productivity. There is no doubt about the need for industrialization at this progressive era but conservation of natural resources also indispensable & equally important. Thus, proper management and safe removal of wastes can be ensured to diminish soil pollution-related problems.

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