Causes, Effects and Sustainable Approaches to Remediate Contaminated Soil

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Abstract

Growing population, increase in urbanization and escalating standards of living have contributed to substantial increases in both quantity and quality of generated wastes (51%, mining and metallurgical; 32%, agricultural; 13%, domestic and municipal; 3%, urban infrastructure and transportation; and rest 1%). Soil is the major sink for a wide range of pollutants, carried by discarded wastes which ultimately affect the terrestrial ecosystems. This chapter aims to describe the toxicological impacts of organic and inorganic pollutants on plants, animals and human beings. Besides, the study encapsulates different strategies to manage generated solid wastes and bioremediation of contaminated sites. Major soil pollutants include persistent organic compounds, volatile organic carbons, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, pesticides, azo dyes, heavy metal(loid)s and non-metals. Pollutants in soil beyond their threshold levels may lead to adverse effects on plants such as alteration in plant community structure, crop yield loss, etc. Crop loss or nutritional loss in edible part of plants variably or invariably affects the countries' economy. Accumulation of contaminants in edible plant parts beyond FAO/WHO safe limits may lead to food chain contamination and affects the human health adversely. Several conventional technologies are available for remediation of contaminated sites, but phytoremediation (phytostabilization, phytofilteration, phytoextraction, phytodegradation and phytovolatilization) is the cost-effective and sustainable technique. Phytoremediation using naturally occurring hyperaccumulators, transgenic plants and organic/inorganic soil amendments and in conjugation with microbes have now been ascended as promising and highly efficient technologies in remediation of obstinate pollutants in soil. Thus, phytoremediation techniques

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R. Prasad (ed.), *Environmental Pollution and Remediation*, Environmental and Microbial Biotechnology, https://doi.org/10.1007/978-981-15-5499-5_16

need to be explored and require further advancement to expedite waste management at broader scale even under various environmental stress conditions.

Keywords

Environmental impacts · Organic/inorganic pollutants · Bioremediation · Soil · Sustainable management

16.1 Introduction

"Soil pollution" refers to the presence of chemicals in soil at a higher than normal concentration, is likely to cause adverse effects on non-targeted organisms and impedes the natural balance of the ecological system (The Food and Agriculture Organization (FAO) and Intergovernmental Technical Panel (ITPS) 2015). Although majority of the pollutants have anthropogenic origin, some occur naturally in the soil as minerals' components and can be toxic at high concentrations. Industrialization, urbanization, warfare activities, escalated standards of living and intensification of agriculture have left a legacy of polluted soils around the world (European Environment Agency (EEA) 2014; Bundschuh et al. 2012).

Accumulation of organic (persistent organic pollutants, POPs; volatile organic carbons, VOCs; polychlorinated biphenyls, PCBs; polycyclic aromatic hydrocarbons, PAHs; pesticides, etc.) and inorganic (metal(loid)s and non-metals) pollutants in soil is predominantly associated with the emissions from the rapidly expanding industries, disposal of metallic wastes, mine tailings, leaded paints and gasoline, agricultural application of pesticides and fertilizers (organic and inorganic), municipal waste generation, wastewater irrigation, coal combustion, spillage of petrochemicals and atmospheric depositions (Table 16.1). Contamination of soil is caused by either point or diffuse (non-point) sources:

16.1.1 Point-Source Pollution

Release of pollutants or contaminants to the soil by a specific or series of events within a particular area where one can easily identify the source and pollutants. Anthropogenic activities, viz. industries, mining sites, wastewater disposal, uncontrolled landfills, excessive application of agrochemicals, etc., are the main sources of point-source pollution.

16.1.2 Diffuse-Source Pollution

Spread of pollutants is over a wider area. Pollutants accumulate in soil by deposition and do not have a single or easily identified source. It occurs where emission,

Table 16.1 Major anthropogenic and natural sources of organic and inorganic pollutants in soil

No.	Types of pollutants	Major sources
Organic pollutants		
1.	Phenols	Distilleries, pulp and paper industries, coal mines, oil refineries, wood preservation, plants, pharmaceuticals, coke-oven batteries, herbicides, pesticides and their wastewaters
2.	Petroleum hydrocarbons	Refineries, industries and transportation
3.	Endocrine-disrupting chemicals	As plasticizers in industries, plastic resins' factories and polyurethane polymers manufacture
4.	Chlorinated phenols	Pulp and paper industries, tanneries, distilleries, dyes, paint manufacturing and pharmaceutical industries
5.	Pesticides	Industries, factories and agricultural applications
6.	Azo dyes	Textile, leather, paint, acrylic, cosmetics, plastics and pharmaceutical industries
7.	Melanoidins	Agro-based industries especially from cane molasses-based distilleries and fermentation industries
Inorganic pollutants		
1.	Aluminium	Mining and metallurgical industries and municipal, hospital and electronic wastes
2.	Iron	Metallurgical and mining, batteries, volcanic emissions and municipal and hospital wastes
3.	Zinc	Fertilizer, mining and metallurgical industries and municipal and hospital wastes
4.	Molybdenum	Combustion of fossil fuels and mining and metallurgical industries
5.	Magnesium	Mining, agriculture, fertilizers and municipal and hospital wastes
6.	Manganese	Municipal and agricultural wastes, combustion of fossil fuels and mining and mineral processings
7.	Cobalt	Wood preservatives and volcanic emissions
8.	Copper	Mining and metallurgical industries, municipal wastes incineration, carbon black production, electronics, wood preservatives and architecture
9.	Beryllium	Combustion of fossil fuels, electronics, municipal waste incineration, weathering of rocks, beryllium alloy and chemical industries
10.	Nickel	Metal electroplating and nickel mining industries, oil refineries, municipal wastes and combustion of fossil fuels
11.	Selenium	Incineration, coal, oil and mining, milling and metallurgical industries
12.	Lead	Mining and metallurgical industries, plastics, paints, pipes, batteries, gasoline and automobiles
13.	Cadmium	Fertilizers, plastics, pigments, oil refineries and mining and metallurgical industries
14.	Chromium	Tanneries, paints, pigments, fungicides and mining and metallurgical industries
15.	Mercury	Coal, vinyl chlorides, electrical batteries and thermometers

(continued)

Table 16.1 (continued)

No.	Types of pollutants	Major sources
16.	Barium	Dust control equipments and industrial controls
17.	Arsenic	Mines, smelters, oil refineries, pesticides, electrical waste, treated wood products, paints and herbicides
18.	Sodium, potassium and calcium	Municipal and agricultural wastes, fertilizers, volcanic emission, combustion of fossil fuels and weathering
19.	Nitrogen, sulphur and phosphorous	Fertilizers, volcanic emission, weathering, combustion of fossil fuels and municipal and agricultural wastes

Sources: Mishra et al. (2019), Yadav et al. (2017), Wuana and Felix (2011) and USEPA (2008)

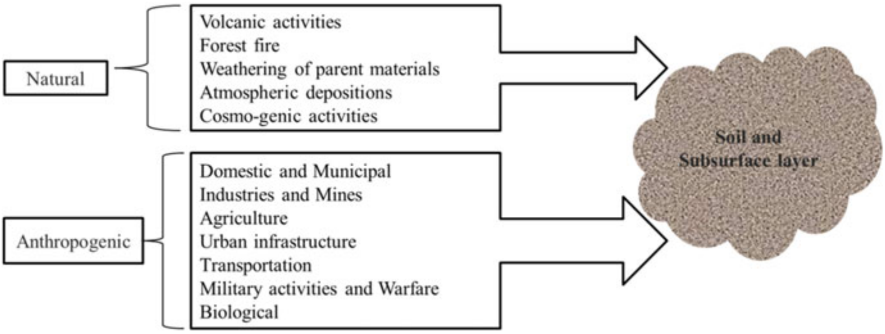

Fig. 16.1 Various natural and anthropogenic sources of soil pollution

transformation and dilution of pollutants takes place via air-soil-water systems before being transferred to soil (FAO and ITPS 2015).

16.2 Sources of Soil Pollution

16.2.1 Natural Sources

Events such as forest fires, volcanic eruptions and cosmogenic activities are the natural sources of soil pollution when many toxic elements are released into the environment (Fig. 16.1). These elements include metal(loid)s, dioxin-like compounds, PAHs and radionuclides (Deardorff et al. 2008). Dœlsch et al. (2006) reported high levels of PAHs and heavy metal(loid)s mainly mercury (Hg), copper (Cu), chromium (Cr), zinc (Zn) and nickel (Ni) in soil of Réunion, France, due to volcanic activity and weathering of the parent rocks. Arsenic (As) contamination is one of the global environmental issues where volcanic eruption (Ma et al. 2019) and weathering of minerals and ores (Mandaliev et al. 2013) occur. Li (2009) and Trendel et al. (1989) reported that PAHs in soil are of cosmogenic origin or due to diagenetic alteration of waxes in soil organic matter. Naturally occurring asbestos and radioactive gases in soil are mainly attributed to ultramafic rock specifically serpentine and amphibole (Bloise et al. 2016; Swartjes and Tromp 2008).

16.2.2 Anthropogenic Sources

Anthropogenic activities have been causing widespread environmental pollution to the land, air and water (Fig. 16.1). Amongst them mining and metallurgical industries followed by agriculture, municipal and urban infrastructure and transportation contribute significant proportions in wastes generation (Fig. 16.2).

16.2.2.1 Domestic and Municipal Wastes

According to the report by the World Bank, global municipal solid waste generation was estimated to be 1.3 billion tonnes (BT) per year (Hoornweg and Bhada-Tata 2012). Municipal wastes consist of many organic and inorganic pollutants such as heavy metal(loid)s, PAHs, VOCs, pharmaceutical compounds, personal care and their derivative products (Ghosh et al. 2014). Electronic waste contains valuable elements such as Cu, aluminium (Al), gold (Au) and many other hazardous substances (such as lead (Pb), Cd, Cr, brominated flame retardants and PCBs) (Fornalczyk et al. 2013). Use of pesticides such as dichlorodiphenyltrichloroethane (DDT), chlordane, etc. for the control of vector-borne diseases has led to soil pollution in urban and peri-urban areas (Mansouri et al. 2017). Table 16.1 shows various pollutants ensue from domestic and municipal sources. Biosolids from municipal wastewater treatment are the major sink for many organic and inorganic chemicals, and their land application can potentially introduce harmful contaminants into terrestrial environments (Haynes et al. 2009).

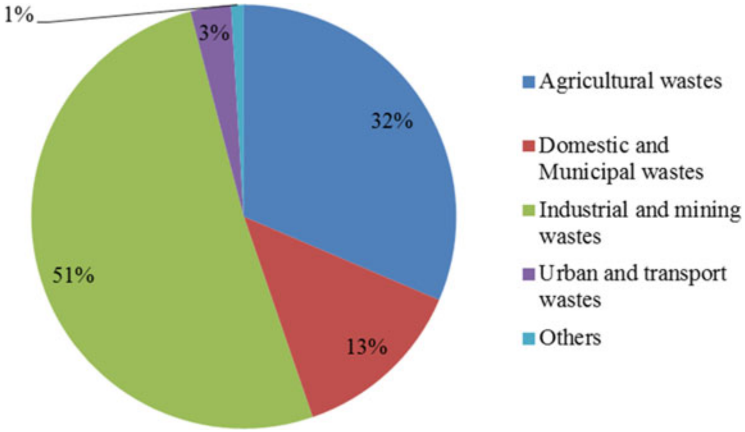

Fig. 16.2 Percentage contribution of various anthropogenic sectors in waste generations. (Source: Pappu et al. 2007)

16.2.2.2 Transportation and Urban Infrastructure

Widespread development of infrastructure such as housing, roads and railways has considerably contributed to environmental degradation by land consumption and soil sealing (Table 16.1). Transportation constitutes one of the main sources of soil pollution, perhaps not only because of the emissions from fuel combustion but also from petrol spills and the relevant activities as a whole (Mirsal 2008). Splashes generated by traffic during rainfall and run-off cause translocation of particles rich in heavy metals from the corrosion of vehicular parts and pavement abrasion (Venuti et al. 2016; Zhang et al. 2015a, b). Plastic, PAHs and rubber-derived compounds from urban infrastructure and transportation are also the sources of soil contamination (Kumar and Kothiyal 2016).

16.2.2.3 Industrial and Mining Wastes

According to the integrated pollution prevention and control (IPPC) directive, the European Union, potentially polluting activities associated with small- and large-scale industries can be grouped into the following six main categories (García-Pérez et al. 2007):

1. Energy industries
2. Production and processing of metal(loid)s
3. Mineral industry
4. Chemical industry
5. Waste management
6. Others (paper/board production, manufacture of fibres/textiles, tanneries, slaughterhouses, animal farm and manufacture of carbon or graphite)

Land in the vicinity of industries and factories are polluted by inappropriate storage of chemicals, spillages of raw materials, fuel ash, dusts, fires and refuses from the industrial activities (Alloway 2013). Small- and large-scale industries release huge amount of heavy metal(loid)s, gaseous pollutants, metal(loid)s, POPs, VOCs, radionuclides, etc., which in the environment persist for longer period of time even after the end of those activities (Table 16.1). These pollutants are dispersed by air and water to a larger distance, thereby contaminating residential and agricultural areas (Mileusnić et al. 2014). Salinization is another threat to soils mainly associated with the production of glass, rubber, pigment, ceramic, soap and detergent, processing of animal hide and metal(loid)s, leather tanning, chlor-alkali, textiles, oil/gas drilling and pharmaceuticals (Saha et al. 2017).

16.2.2.4 Agriculture

Sources of pollution in agricultural settings are accidental spills of hydrocarbons, utilization as fuels in machines, transportation, agricultural application of agrochemicals such as organic and inorganic fertilizers, animal manure, pesticides, weedicides and agricultural wastes (Table 16.1). Accidental spills of fuels and agrochemicals represent serious risks of soil pollution with POPs and heavy metal (loid)s (Osman et al. 2014). The fertilizers used for agriculture are rich sources of

Hg, Cd, Pb, Cu, Ni, Cu and natural radionuclides (^{238}U, ^{232}Th and ^{210}Po) (Kanter 2018; Stewart et al. 2005). Liu et al. (2015) and Cang (2004) found significant levels of heavy metal(loid)s in soil from livestock and poultry operations. In many countries, use of biomedical wastes as manure is also a chief source of soil pollution (Shankar and Shikha 2017).

16.2.2.5 Miscellaneous Sources

Nuclear testing laboratories and industries are the prime sources of radioactive substances (^{106}Rh, ^{131}I, ^{140}Ln, ^{144}Ce, ^{44}Ru, ^{106}Ru and ^{140}Ba) in the soil (Jadiyappa 2018). Long-term deposition of radionuclides in soil emits gamma radiation which is harmful for the health of soil living organisms (Jadiyappa 2018). The excreta of animals, birds and humans are also one of the contributory sources of soil pollution by biological agents (Clark 2014). In the developing countries, wastewater irrigation, wrong methods of agricultural practices and application of animal manures constitute serious soil pollution problems (Alloway 2013). Military and warfare activities accustom non-degradable weapons of destruction and chemicals (remains of ammunitions, landmines, leftover chemicals, radioactive and biological toxic agents) that persist in the affected soils for centuries after the end of the conflict (FAO and ITPS 2015).

16.3 Major Pollutants in Soil

Anthropogenic sources are the main drivers of wide range of organic as well as inorganic pollutants in the soil. Pollutants based on their chemical characteristics are categorized into organic and inorganic forms (Fig. 16.3).

16.3.1 Inorganic Pollutants

Small- and large-scale industries mainly associated with textiles, glass, rubber, chemicals, tanneries, pharmaceuticals, detergent and soap production are the major contributors of salts (mainly NaCl) produced in the world today (Fig. 16.3). Inorganic pollutants mainly include radionucleotides, non-metals, heavy metals and metalloids (Fig. 16.3). Heavy metal(loid)s refer to the group of metals and metalloids with high atomic density $> 4.5\ \mathrm{g\ cm^{-3}}$ (Hawkes et al. 1997). Heavy metal(loid)s are further categorized into two main groups: (1) elements such as molybdenum (Mo), Ni, Zn, Cu, iron (Fe) and magnesium (Mg), which are essential to life and ecosystems but are noxious to plants and animals when their concentrations exceed certain threshold levels (Buchmann 2008), and (2) elements such as As, Cd, Hg, Cr and Pb, which do not pose any significant role in any biochemical processes, but their presence alters the soil quality and normal metabolic functioning in living beings (Edelstein and Ben-Hur 2018; Patinha et al. 2018).

Radionuclides in soil occur in three different forms, viz. primordial, cosmogenic and man-made radionuclides (United States Environmental Protection Agency

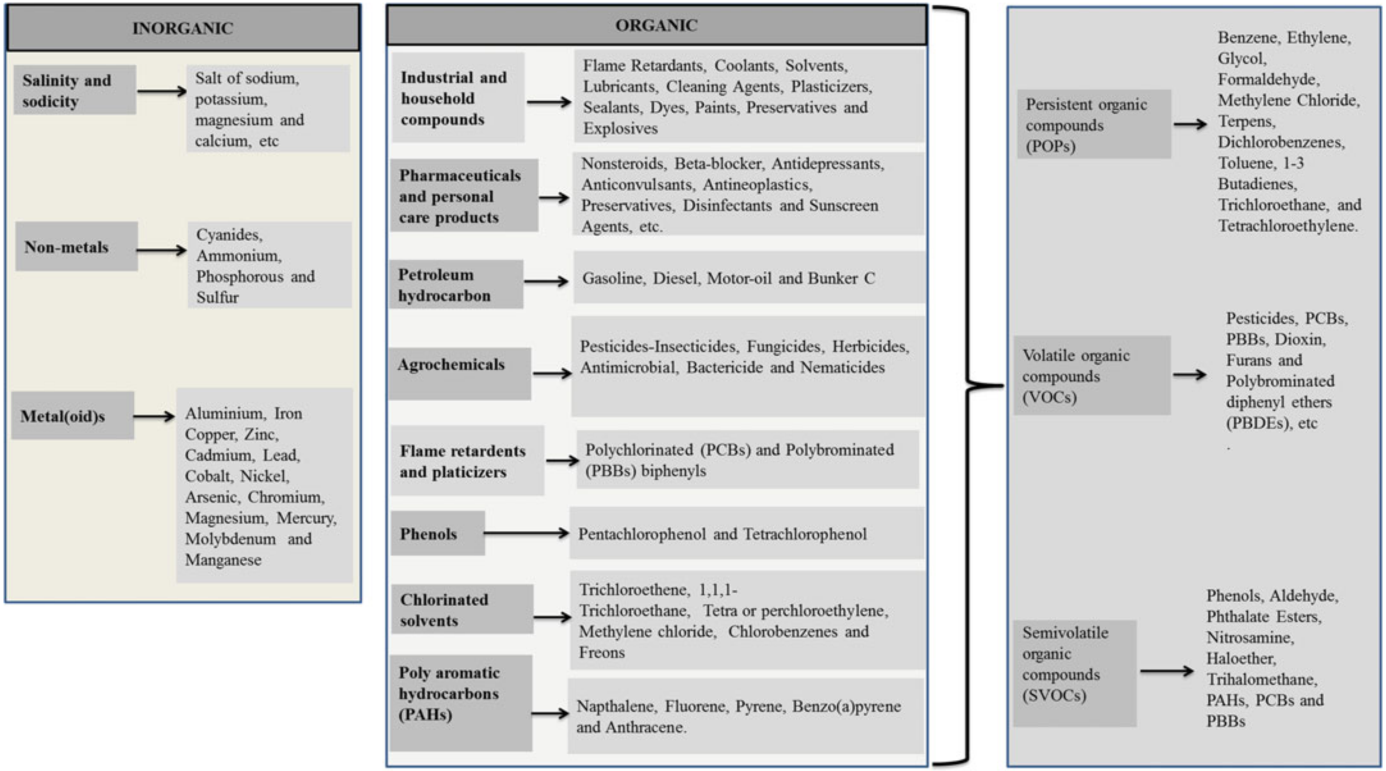

Fig. 16.3 Major organic and inorganic pollutants found in soil worldwide. (Sources: Rodríguez-Eugenio et al. 2018; Padmavathiamma et al. 2014)

(USEPA) 2006). Primordial radionuclides (^{235}U, ^{238}U, ^{232}Th and ^{40}K) are basically remain-over from the creation of the earth and have half-lives of hundreds millions of years. Primordial radionuclides end up in soil due to weathering of rocks. Cosmogenic radionuclides are produced by cosmic rays in the atmosphere and have long half-lives, while majority have shorter half-lives than the primordial radionuclides. Cosmogenic radionuclides include ^{14}C, ^{3}T and ^{7}Be. Anthropogenic activities such as nuclear testing and radiological events like the Chernobyl accident lead to deposition of radioactive particles in soil through air and water (Romanovskaia et al. 1998). Inappropriate disposal of radioactive substances also contributes to increasing contents of radionuclides in the soil (USEPA 2006).

16.3.2 Organic Pollutants

Organic pollutants include POPs, VOCs and semi-volatile (SVOCs) organic compounds (Fig. 16.3). POPs are recalcitrant towards degradation, highly toxic and are carcinogenic as well as mutagenic (Ashraf 2017). It includes pesticides, chlorinated solvents, industrial fluids and flame retardants (Bartrons et al. 2016). Short- and long-distance transportation of gaseous or particulate forms of POPs in the atmosphere is facilitated by air and water (Ashraf 2017). Besides, atmospheric dry and wet depositions constitute the main input of these compounds to the soil (Cousins et al. 1999). Indirect deposition of compounds in soil occurs through decomposition of litter fall from plants (Wania and Mclachlan 2001). Accumulation of POPs in soil horizons rich in organic matter may lead to their persistence for years (Masih and Taneja 2006). For an instance, it has been reported that 90% of United Kingdom's land are rich in POPs (Cousins and Jones 1998). There are about 7 key POPs, viz. PCBs, DDT, hexachlorocyclohexane (HCH), dieldrin, perfluorooctanesulfonate (PFOS), hexabromocyclododecane (HBCD) and endosulfan, which are restricted as per Stockholm Conference held in 2001 (Ashraf 2017). Organic pollutants such as gasoline and hydrocarbons as a result of fossil fuel burning and automobile exhaust are volatile in nature. World Wildlife Fund enlisted 67 different types of environmental hormones in 1997 that were considered harmful for the soil biota (Lyons 2005).

A myriad of organic pollutants such as biocides, pesticides, flame retardants, pharmaceuticals, surfactants, PAHs, PCBs, polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), etc. end up in the soil as a consequence of human activities (Rhind 2009). The most commonly found organic pollutants in soils are chlorinated compounds (e.g., PCDDs, PCBs and PCDFs), oil hydrocarbons (e.g., alkanes, alkenes and cycloalkanes), monomeric aromatic hydrocarbons (e.g., toluene, xylene, benzene and ethylbenzene), PAHs (e.g., chrysene, benzo(a)pyrene and fluoranthene), pesticides (e.g., alachlor, acetochlor, atrazine and bifenox), fungicides (e.g., penconazole, procymidone and metalaxyl), insecticides (e.g., endosulfan, heptachlor, captan, benomyl and endrin), pharmaceuticals (e.g., antibiotics, analgesics, nonsteroidal anti-inflammatories, antiparasitics and antimicrobials), hormones (e.g., oestrogens and androgens), sterols (e.g., dihydrocholesterol, cholesterol and coprostanol), flame retardants (e.g., polybrominated diethyl ethers, bisphenol-A and hexabromocyclododecanes), nitrosamines (e.g., nitrose dimethylamine, nitrose-di-n-propylamine, nitrose diethyl-amine and nitrosopyrrolidine) and their fate compounds (Fig. 16.3).

16.4 Factors Affecting Toxicity of Organic and Inorganic Pollutants in Soil

Even though wide range of pollutants is present, their reactivity and bioavailability in soil are controlled by many of their physico-chemical and biological properties (Kabata-Pendias and Pendias 2011; Kodešová et al. 2011).

16.4.1 Soil Texture and Mineralogy

Soil texture signifies the relative amounts of sand, silt and clay proportions in soil. High clay (particles size < 0.002 mm) fraction in soil has strong ability to bind positively charged ions due to their layered structure, large specific surface area, chemical and mechanical stability and high cation exchange capacity (Uddin 2017). On contrary, sandy soils have larger pore size and lower sorption capacity which lead to the movement of pollutants to ground and surface water (Uddin 2017). Thus, soils having higher amounts of clay and humus have high buffering and sorption capacity which, despite the increase in concentrations of contaminants, do not cause adverse biological effects (Różański et al. 2016). Presence of minerals such as layered silicates, oxides/hydroxides of Fe and Al, carbonates, sulphates, allophane and associated amorphous clays is inorganic, while humus is organic colloid, which has high cation adsorption capacity. Fijałkowski et al. (2012) showed the affinity of metal cations for clay minerals in a series $Cu^{2+}>Cd^{2+}>Fe^{2+}>Pb^{2+}> Ni^{2+}>Co^{2+}>Mn^{2+}>Zn^{2+}$.

16.4.2 The pH and Electrical Conductivity

16.4.2.1 Changes in Surface Charge

Change in pH and salinity of soil greatly influences the net negative charge on the charged colloids (clays, silicates, oxides/hydroxides of Fe and Al), their ion exchange capacities and the binding energies of their sorption sites (Proust 2015; Violante et al. 2010). Thus, increase in surface charge on inorganic and organic colloids lowers the availability of pollutants in soil.

16.4.2.2 Competition for Adsorption Sites

Under acidic condition of soil, more protons are available to the binding sites of clays, organic matter and oxides, thus enabling organic and inorganic species more available to biological organisms (Rampazzo et al. 2013). On the contrary, under high soil pH, the cations replace protons and get adsorbed to charged colloids so tightly that they are not readily bioavailable (Olaniran et al. 2013). Transition (Fe, Al, Zn, Cu, Cr, Ni, Mn, Pb and Co) as compared to alkaline earth cations has strong tendency to get adsorbed onto charge colloids and form inner-sphere complexes (Violante et al. 2010). Moreover, organic pollutants with low molecular weight behold less adsorption capacity onto silicates in soil (Lin et al. 2015).

16.4.2.3 Hydrolysis of Inorganic/Organic Species in Solution

Sorption capacity of soil increases with increasing soil pH and vice versa (Paulose et al. 2007). The lower the pH value, the more organic and inorganic elements can be found in solution. Soil pH catalyzes the hydrolysis reaction and subsequently influences degradation of pesticides, atrazine and inorganic salts (Zhang et al. 2013).

16.4.2.4 Dissolution of Inorganic/Organic Complexing Anions

High soil pH lowers high solubility of dissolve organic carbon and base cation concentrations, whereas low pH enhances their solubility in soil (Olaniran et al. 2013). Several studies have reported a positive correlation between pH and retention of Cd, Pb, Cu and Zn in soil (Deurer and Bottcher 2007).

16.4.3 Soil Organic Matter

Soil organic matter can reduce or increase the bioavailability of pollutants in soil through immobilization or mobilization by forming various insoluble or soluble complexes, respectively (Shrestha et al. 2019). A wide range of organic acids (formic, acetic, oxalic, succinic, malonic, maleic, citric, malic, lactic, fumaric acids and aconitic) acts as ligands for many cations in soil (Vranova et al. 2013; Fijałkowski et al. 2012). Generally, citric acid followed by malic>acetic>tartaric>oxalic acid is the most effective in terms of desorption of different metals (Zn, Cu, Hg, Pb, caesium (Cs) and Cd) in soil due to more carboxyl group to form stable ligand (Köchy et al. 2015).

16.4.4 Cation Exchange Capacity

Cation exchange capacity (CEC) of soils depends upon soil types, amounts and types of different colloids (Harter and Naidu 2001). Clayey soils have higher CEC value (30 cmol kg^{-1}) compared to sandy soils (< 5 cmol kg^{-1}). Similarly, humus has very high CEC value compared to the inorganic clays (i.e., kaolinite). Thus, the greater the CEC value, more is the exchange sites on soil minerals for organic and inorganic species.

16.4.5 Oxidation-Reduction Potential

Oxidized and reduced soils have redox potential in the range of 400–700 and 250–300 mV, respectively (Pezeshki and DeLaune 2000). Redox potential plays a significant role in the reactivity of some soil oxides (Fe and manganese (Mn)) with organic and inorganic pollutants in soil (Alamgir 2016). It controls the predominant chemical speciation and sorption of metal(loid)s (As, Cr and selenium (Se)) in soil (Landner and Reuther 2004). Generally reducing condition favours decline in mobility of positively charged ions in soil (Gonsior et al. 1997).

16.5 Effects on Environment and Socioeconomic Segment

16.5.1 Effects on Soil

Organic and inorganic pollutants may cause alteration in soil pH, CEC and salinity and dispersion and/or flocculation of clays and adversely affect soil aggregation, mechanical strength and stability of soil (Zong and Lu 2019; Salem et al. 2017). Extremely high levels of nitrogen, phosphorous and potassium (NPK) in soil significantly lower the total porosity, water retention capacity and macroaggregate content and increase soil bulk density, plasticity index, coefficient of linear extensibility and tensile strength (Zong and Lu 2019). Soil pollution enables prodigious quantity of nitrogen to escape into the atmosphere through volatilization and denitrification (Fungo et al. 2019). Moreover, organic matter decomposition in soil emits sulphur dioxide and other associated compounds, instigating acid rain (Bricker and Rice 1993). Toxic elements, i.e. Cr, Cd and As, exhibit antagonistic behaviour with essential micronutrients in soil such as Zn, Cu, Mn, Mg and Fe for active binding sites of roots (Gautam et al. 2017). Various organic and inorganic pollutants inhibit the nitrification process and cause salinization of soil due to their highly saline properties. Soil pollution also causes loss of nutrients present in it, hindering plants ability to thrive therein, which consequently may result in soil erosion and disturbances in the balance of soil flora and fauna.

Soil biological properties play pivotal roles in affecting soil fertility and primary production through organic matter decomposition, nutrient cycling and aggregate formation (Brevik and Sauer 2015). Soil microbial communities and enzymatic activities are very sensitive to changes in soil properties accredited to pollution and thus are considered as indicators of soil fertility (Xu et al. 2015). Pollutants in soil interact with microorganisms and affect their normal metabolic functioning, thereby affecting the soil fertility and production (Saxena et al. 2015; Behera and Prasad 2020). Bastida et al. (2017) found that frequent use of agrochemicals adversely affects the water storage capacity, structure and function of microbial communities in soil.

16.5.2 Harmful Effects of Pollutants on Plants

Pollutants, specifically degradable, undergo physico-chemical and biological alterations before and after being deposited onto terrestrial ecosystems (Karthikeyan et al. 2004). Both organic and inorganic pollutants are available to plants either from soil or air (Fig. 16.4). Plants take up organic pollutants (pesticides, herbicides, weedicides, fertilizers and growth-promoting chemicals) mainly through leaf surfaces, roots and fruits which are then distributed within the plant either from cell to cell or through the vascular system (Rana and Rana 2015; Burken et al. 2005). Uptake of organic pollutants through roots is mediated by two pathways to the various parts of the plant via xylem vessels, i.e. symplastic and apoplastic (Fig. 16.4) (Kvesitadze et al. 2015). In former case, the tissue system is surrounded by plasmalemma and interconnected by plasmodesmata where movement of molecules within the conductive tissue occurs by mass flow and diffusion. In apoplastic pathway, cell wall and xylary elements form a continuous water-permeable column for short- and long-distance transport of solute by mass flow and diffusion. Certain chemicals are restricted to either apoplastic or symplastic pathways, while some are ambimobile (can follow both the domains efficiently). Uptake of organic molecule depends upon the molecular size, lipophilicity and dissociation constant (Schroder and Collins 2002). Generally, less lipophilic molecules take the apoplastic pathway, while more lipophilic one follow symplastic route (Karthikeyan et al. 2004). Moreover, pollutants with small molecular size can easily invade the membrane and vascular tissues of plants and vice versa (Kvesitadze et al. 2015).

The accessibility of inorganic pollutants (metal(loid)s and non-metals) in soil is an active process mainly governed by physico-chemical, biological and other environmental factors (Hajar et al. 2014). Moreover, phyto-uptake and transportation of

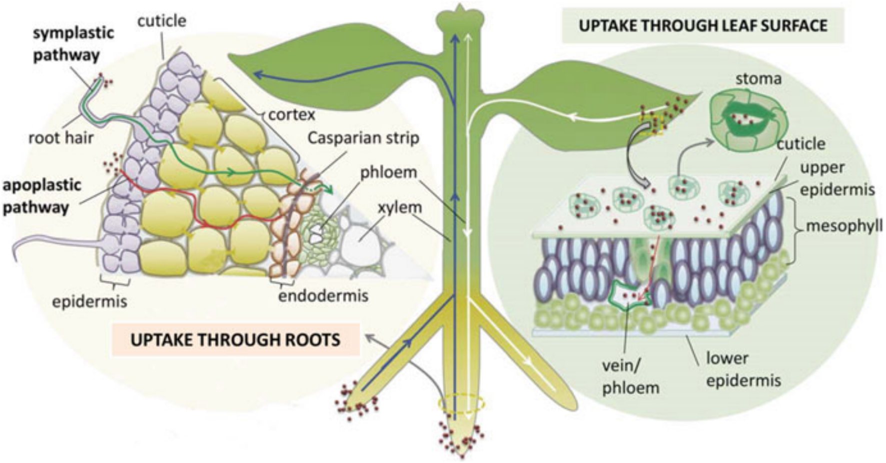

Fig. 16.4 Uptake of pollutants (brown dots) through leaves and roots over symplastic and apoplastic pathways (Source: Modified from Lv et al. 2019)

metal(loid)s and non-metals within the plant are principally reliant on the type of plant species, concentration of ions/molecules and their oxidation state (Tangahu et al. 2011). Intrinsic protein, proton pumps and transporters (IRT1, ZnT1, heavy metal ATPase-HMA2, and HMA4) facilitate the uptake and transportation of Zn, Cu, Cd, Pb, Ni and Fe to various parts of the plant (Martinoia 2018; Viehweger 2014). Contaminants translocate from roots to shoot by two regulatory mechanism, i.e. evaporation and transpiration (Tangahu et al. 2011). Plants are mainly of two types: accumulators and excluders. Accumulators continue to be present in spite of concerted pollutants in the shoots, whereas excluders confined pollutant phyto-uptake. Both accumulator and excluder manage to combat the high metal contents in their body parts through adapted defence strategies (Viehweger 2014).

Organic and inorganic pollutants in soil beyond National Oceanic and Atmospheric Administration (NOAA) soil quality guidelines may cause deleterious effects on plants (Buchmann 2008). They pose toxic effects on plant cell ultrastructure, biosynthesis, membrane stability and deoxyribonucleic acid (DNA) which consequently affect their metabolic, photosynthetic and reproductive processes. Organic and inorganic pollutants adversely affect the cellular ultrastructure such as distortion of the cell wall, leakage of the cytoplasm and alteration in the shape and size of chloroplasts from ovate to hexagonal (Xiong et al. 2017). Ramadass et al. (2015) found that organic pollutants, for example, bipyridylium and diphenylether, persuade cell membrane disruption and damage the plant tissues. Zhang et al. (2017) unravel the adverse effects of organic pollutants on the assemblage of micro-tubulins and associated proteins in the cell. Toxic effects of metal contents in plants may be direct and/or indirect. Some of the direct toxic effects associated with high metal contents include inhibition of cytoplasmic enzymes and damage to cell structures due to oxidative stress (Jadia and Fulekar 2009), whereas indirect toxic effect is composed of replacement of essential nutrients at cation exchange sites of plants (Taiz and Zeiger 2002).

Several studies have reported the impact of pollutants (toxic metal(loid)s, PCBs, antibiotics and herbicides) on plant cell biosynthesis, detrimental effects on photosynthesis and synthesis of proteins, amino acids, nucleic acids, lipids and hormones (Zhang et al. 2017; Asati et al. 2016). Photosynthesis is an essential process in plants, responsible for nutrient uptake, arbitrates growth as well as yield and provides potential resistance to plants under environmental stresses (Yang et al. 2010). Pollutants alter photosynthesis by hampering the formation of pigments causing leaves and stems to become translucent and white (Kaspary et al. 2014). It has been reported that ribonucleic acid (RNA), protein and lipid synthesis are significantly inhibited by prolonged exposure to hexazinone and chlorsulfuron treatments (Yang et al. 2010). Increase in malondialdehyde content is positively correlated with the inhibition of antioxidative enzyme activities in some plants under oxidative stress induced by organic and inorganic pollutants (Zhang et al. 2017; Gautam et al. 2016). Some studies have revealed that DNA damage can be caused by metals (Cd, Cr and Pb) and PAHs (Huang et al. 2013). A possible reason for this could be attributed to alteration in protein synthesis, enzyme activities and cell organelle dysfunction, which may result in inhibition of mitotic division in root tip cells (Van Dingenen

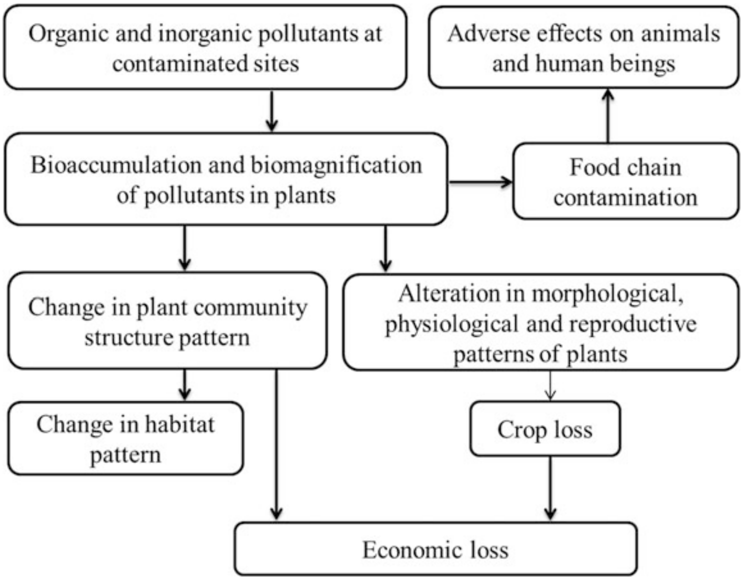

Fig. 16.5 A simplified diagram of the relationship between organic and inorganic pollutants in soil, change in plant community structure pattern, global climate change, crop loss, economic loss and health of animals and human beings

et al. 2016). Cell biosynthesis, membrane stability and synthesis of RNA, lipids, proteins and photosynthetic pigments, growth and yield are significantly affected in plants grown on contaminated sites (Zhang et al. 2017).

Habitat fragmentation or destruction, change in climatic condition, biogeochemical cycling and alteration in soil quality due to interference of wide range of persisting organic and inorganic pollutants (Fig. 16.5) are the major threat to plants diversity in an ecosystem (Krebs and Bach 2018; Bellard et al. 2012). Poorly developed soil structure, less available nutrients, readily available toxic constituents, poor soil biota and water-restricted conditions driven by soil pollution alter vegetation succession (Gautam et al. 2016). A number of studies have been reported on alteration in plant community structure due to accretion of pollutants in soil from various anthropogenic activities.

16.5.2.1 Changes in Plant Community Structure Pattern: Case Studies

Plant community structure study at abandoned red mud dumps of HINDALCO, Renukoot, showed less number of herbaceous, shrub and woody species when compared to forest site (Gautam et al. 2018). Relatively less number of species at red mud dumps was mainly attributed to high bulk density, salinity, alkalinity, exchangeable sodium percentage and toxic metal(loid)s (Cd, Cr, As and Pb) contents coupled with low porosity, moisture content, biological properties and available nutrients (Gautam et al. 2018). Species richness and Shannon-Wiener diversity index for all plant types were high at forest site compared to red mud dumps. The important value index (IVI) of sensitive species was low while that of tolerant species was higher and was accredited to altered soil properties.

According to Pandey et al. (2014), total number of plant species at Jharia coalfield (polluted site) was less when compared to the Central Institute of Mining and Fuel Research (reference site). At Jharia coalfield, total number of woody species was less than total number of herbaceous species. Multivariate analysis showed that number of woody species at study site was mainly governed by less sulphate and phosphorous contents in soil, whereas contaminated site with low total nitrogen and organic carbon contents were the prime factors governing the richness and IVI of herbaceous species.

A study by Vijayan (2011) showed that long-term spraying of endosulfan at eleven different panchayats in Kasargod district of Kerala reduced the plant biodiversity by 40–70% when compared to the site without endosulfan treatment. Besides, native species of the area such as *Hopea ponga, Cinnamomum malabatrum, Ixora polyantha, Premna serratifolia, Syzygium caryophyllatum* and *Embelia cheriyan-kottan* disappeared due to the adverse effects of organic pollutant on soil properties (Vijayan 2011).

Ensuing the rapid increase in global population, an estimate of 87% more food crops such as rice, wheat, soya bean, maize, etc. will be required to meet their demand for food by 2050 (Kromdijk and Long 2016). However, several restraints including abiotic and biotic stresses are likely to disrupt food security in near future, following the fact that increasing natural and anthropogenic activities are the major threats to food demand and security due to increasing severity of soil pollution on global scale (Riaz et al. 2019). Agricultural dependence on wastewater irrigation, chemical fertilizers, pesticides, fungicides, weedicides and rapid development of industries have increased the amount of toxic metal(loid)s and organic pollutants in cultivable land resulting in detrimental effects on soil-plant environment system (Bansiwal and Maheshvari 2018). In fact, persisting pollutants causes loss of soil productivity and also reduces crop yield. This challenge is adversely affecting the social and economic conditions of the world.

16.5.2.2 Crop Loss Due to Soil Pollution

Crop losses are the major threat to the wellbeing of rural families, economy of traders and governments as well as to food security worldwide (Avelino et al. 2015; Savary and Willocquet 2014). For instance, poor soil quality due to pollution-caused yield loss of annual crops such as rice ranged from 24 to 41% in Asia (Savary et al. 2000), potatoes from 5 to 96% in France (Rakotonindraina et al. 2012) and cotton up to 100% in Thailand (Castella et al. 2005). Yield loss of perennial crops such as apple and other stone fruits reached up to 5% in the Netherlands (Van Leeuwen et al. 2000), and for coffee, it ranged from 13 to 45% in Brazil (Barbosa et al. 2004). Crop losses due to pest attack, diseases, soil infertility and climate change for major food and cash crops (wheat, rice, maize, barley, soybeans, potatoes, coffee and cotton) were estimated between 20 and 40% at both country and regional levels in different continents (Oerke 2006; Cooke 2006). The phrase "losses between 20 and 40%" inadequately reflects the true costs of crop losses to farmers, fabrics, economic, environments, societies, public health and consumers (Savary et al. 2012). Crop losses owing to above-mentioned factors are direct and indirect:

Direct Losses

- Primary losses: Yield, quality, cost of control over losses, extra cost of harvesting, grading and replanting
- Secondary losses: Contamination of sowing and planting material, soil-borne diseases and weakening by premature defoliation of trees and perennials

Indirect Losses Agricultural farm, rural community, exporters, traders, wholesale retailers, consumers, government and environment.

Crop losses ultimately affect the financial structure of growers, distributors, wholesalers, transporters, retailers, food processors and others (Fig. 16.5). Economic loss basically is the reduction in economic benefits due to crop damage, the costs of labour, materials and inputs for the control of pests and diseases (Cerda 2017). An estimate of $1391 million has been incurred on the loss of crops and trees accredited to the use of pesticides (Pimentel and Burgess 2014).

16.5.3 Effects on Animals and Human Beings

Accumulation of organic and inorganic pollutants in edible or non-edible parts of crops and commercially important plants grown in contaminated soil may induce clinical disorders in biological systems (of animals and human beings) through food chain contamination (Li et al. 2018). Biological systems have no specific mechanism for the elimination of such pollutants from body parts; however, such xenobiotic after entering the body undergoes bioaccumulation and biomagnification (Tangahu et al. 2011). Organic and inorganic pollutants beyond their threshold levels for living beings (FAO/WHO 2001) are linked to a wide range of ailments (Table 16.2).

16.6 Advanced Technologies and Cost Incurred in Management of Wastes

According to the World Bank (2018), an estimate of 2.01 BT of total solid waste generation has been found in 2016 with a footprint of 0.74 kg per capita per day. Whereas in India, it ranged from 0.2 to 0.6 kg per capita per day with about 42 million tonnes (MT) of total solid wastes produced every year and likely to cross 260 MT in 2047 (World Bank 2018). Proper waste management has a lot of benefits such as reducing global warming and emission of noxious gases (methane, CH_4; carbon dioxide, CO_2; oxides of nitrogen, NO_x, and sulphur, SO_x; hydrogen peroxide, H_2O_2 and ammonia, NH_3), saving carbon footprint and maintaining the environment clean as well as pollution-free (Daniel and Perinaz 2012; Hoornweg and Bhada-Tata 2012). To manage the waste generated from agricultural, municipal, industrial and other sectors, several conventional and integrated advanced

Table 16.2 Harmful effects of excessive organic and inorganic pollutants in soil on human beings and animals

Types of pollutants	Harmful effects on human beings and animals	References
Organic pollutants		
Azo dyes	Skin irritation, nausea, vomiting, irritation in digestive tract and liver and kidney damage	Küçük and Liman (2018), Tadesse et al. (2017)
Phenols and chlorinated phenols	*Acute exposure*: Dryness of the mouth and throat, nausea, vomiting and diarrhoea *Inhalation and dermal contact*: Skin blisters and cardiovascular diseases *Chronic exposure*: Inhibit oxidative phosphorylation, damage mitochondrial structure, inhibition of circulatory system, methemoglobinemia, haemolytic anaemia, hypothermia, pulmonary oedema, arrhythmia, tachycardia, hypotension, central nervous system disorders, respiratory disease and heart failure *Ingestion*: Gastrointestinal damage, muscle tremors and death	Bharagava et al. (2020), Tadesse et al. (2017)
Endocrine-disrupting chemicals	Skin irritation, conjunctiva, mucous membranes of oral and nasal cavities, cryptorchidism, testicular lesions, prolongation of the oestrous cycle, hypospadia, obesity and anovulation	Bharagava et al. (2020), Sifakis et al. (2017)
Melanoidins	Severe toxic effects on fishes and other aquatic organisms	Bharagava et al. (2020)
Persistent organic pollutants	Allergies, hypersensitivity, damage to the central and peripheral nervous systems, neurobehavioural disorder, learning disabilities, endocrine system disorder, reproductive disorder, disruption of the immune system, mutagenicity and carcinogenicity	Ahmed et al. (2019), Bharagava et al. (2020), Alharbi et al. (2018)
Pesticides	Immune suppression, diminished intelligence, hormonal problems, reproductive abnormalities and cancer	Wang and Han (2019), Bharagava et al. (2020)
Petroleum hydrocarbons	*Dermal exposure*: Dermatitis, defatting injury and chemical burns *Inhalation*: Weakness, dementia, morbidity, mortality, central nervous system disorder, development of criminal/violent behaviour, memory and other cognitive deficits, cerebellar dysfunction, encephalopathy, metabolic acidosis and arrhythmia *Oral exposure*: Abdominal pain, irritation, vomiting and diarrhoea *Aspiration*: Fatal pneumonitis, coughing, wheezing, respiratory distress and hypoxia *Acute exposure*: Acidosis, dermatitis, pneumonitis, arrhythmia and encephalopathy	Bharagava et al. (2020), Varjani et al. (2018)

(continued)

Table 16.2 (continued)

Types of pollutants	Harmful effects on human beings and animals	References
Inorganic pollutants		
Aluminium	Aluminosis (pneumoconiosis followed by pulmonary fibrosis), neurotoxicity, Alzheimer's disease and breast cancer	Klotz et al. (2017)
Iron	Nausea, abdominal pain, seizure, cardiomyopathy, hepatic fibrosis, impotency, arthropathy, hereditary hemochromatosis, thalassemia, bone marrow failure and myelodysplastic syndrome	Zhang et al. (2015a, b)
Magnesium	Low blood pressure, nausea, diarrhoea, abdominal cramping and calcium deficiency	Institute of Medicine, Washington (1997)
Manganese	Low blood pressure, violent behaviour, hallucinations, schizophrenia, insomnia, muscle tremors, loss of appetite, apathy, dystonia, hypokinesia, lung disease, pneumonitis, impaired pulmonary and vascular function, improper foetus development and brain damage	Aschner et al. (2005)
Zinc	Dizziness, muscular cramps, vomiting, fatigue and renal damage	Yadav et al. (2017)
Copper	Stomach and intestine irritation, liver cirrhosis, brain and kidney damage and chronic anaemia	Yadav et al. (2017)
Cobalt	Diarrhoea, low blood pressure and paralysis	Yadav et al. (2017)
Nickel	Allergies; immunotoxic, neurotoxic, teratogenic, carcinogenic, genotoxic and mutagenic; lung cancer, infertility and hair loss	Yadav et al. (2017)
Barium	Muscle twitching, high blood pressure, respiratory failure, gastrointestinal dysfunction and cardiac arrhythmias	Yadav et al. (2017)
Cadmium	*Acute exposure*: Abdominal pain, gastrointestinal tract erosion, burning sensation, nausea, vomiting, salivation, muscle cramps, itai-itai disease, vertigo, shock, loss of consciousness, hepatic injury and coma *Chronic exposure*: Depression, DNA damage and cell death	Bharagava et al. (2020), Hassaan et al. (2016)
Chromium	Skin and nasal irritations, ulceration, eardrum perforation and lung cancer	Bharagava et al. (2020), Hassaan et al. (2016)
Arsenic	Melanosis, black foot disease, polyneuropathy, encephalopathy, disorder of cardiovascular and central nervous system, hemolysis, hepatomegaly, bone marrow depression and death	Jomova et al. (2011)
Lead	Headache, loss of memory, confusion, reduced consciousness, irritation, encephalopathy, acute psychosis and malfunctioning of kidneys, liver,	Bharagava et al. (2020), Hassaan et al. (2016)

(continued)

Table 16.2 (continued)

Types of pollutants	Harmful effects on human beings and animals	References
	endocrine and reproductive and central nervous systems	
Mercury	Loss of hearing, mental retardation, abnormal muscle tone, blindness, neurological deficits, dysarthria and developmental defects	Bhaargava et al. (2020)
Phosphorous	Chronic kidney disease, bone-related disorders, cardiovascular system disorder, cell damage, increased mortality, atherosclerosis and left ventricular hypertrophy	Komaba and Fukagawa (2016), Calvo et al. (2014)
Calcium	Irritability, headache, memory loss, lethargy, hypercalcemia, hypercalciuria, osteochondrosis, kidney stone, renal failure, coma and death	Whiting and Wood (1997)
Sodium	High blood pressure, hypertension and renal and cardiovascular diseases	Di Nicolantonio et al. (2017)
Potassium	Hypertension and cardiovascular disease	Adrogué and Madias (2014)
Sulphur	Eye irritation, chest pain, asthma and heart disease	Prasad (2014), Grimble (2006)
Nitrogen	Asthma, hyperthyroidism, methemoglobinemia, birth defects, insulin-dependent diabetes, central nervous system disorder, colon cancer, neural tube defects and digestive and respiratory failures	Davidson et al. (2012)

technologies are available on the basic principles of solid waste management (Agarwal et al. 2015):

1. 4Rs (refuse, reduce, reuse and recycle):
   - Refusal of buying anything which actually does not require
   - Reduction in the generation of garbage
   - Reutilizing the things to its maximum
   - Recycling the waste materials into useful forms wherever possible
2. Segregation of organic/biodegradable and inorganic/non-biodegradable wastes in separate container
3. Inculcation of different treatment techniques for different types of wastes to its nearest possible points

16.6.1 Conventional and Advanced Management Techniques

Composting It is simple and economically viable technique to manage agricultural and domestic (biodegradable) wastes using microorganisms and earthworm (Banerjee et al. 2019). Composts are very much rich in nutrients and are widely used as fertilizer in agriculture field and in horticulture. It maintains the soil health through increasing moisture-holding capacity and recycling nutrients into soil. However, composting of field emits methane and foul odour (Banerjee et al. 2019). Also, it may cause contamination of soil with toxic materials (organic and inorganic).

Anaerobic Digestion Composting of organic waste led to generation of biofuel (comprising 50–60% of methane) using anaerobes (Banerjee et al. 2019). The technique offers stabilization and disinfection of wastes like industrial sludge, farmland residue and animal slurries. The value-added part of the process is that the residue which is rich in nutrients and moisture can be used as fertilizer. Besides, energy and efficiency recovery of anaerobic digestion are better than composting.

Incineration Wastes are converted into ash under high temperature (980–2000 °C) with the emission of gaseous products (Banerjee et al. 2019). It is a stepwise process which leads to destruction of toxic material with recovery of energy from the wastes. Incineration reduces the volume of combustible waste to 80–90%, thereby facilitating the less requirement of land for its disposal (Banerjee et al. 2019). Additionally, the process is odourless, noise-free and environmentally safe.

Pyrolysis In pyrolysis, wastes are thermally degraded in absence of oxygen under the temperature ranged between 300 and 850 °C. Synthetic gas (CH_4, CO and H_2) and char (carbon and non-combustible materials) are the by-products of pyrolysis of waste material (Banerjee et al., 2019). Gases are further utilized for fuel, wax and tar production.

Gasification The process costs incentive and requires high power source. Gasification is a partial oxidation of wastes under insufficient oxygen condition under temperature >650 °C (Banerjee et al. 2019). In plasma gasification technology, high temperature (electric arc) is applied to the waste, thereby converting it into an inert residue (ash). Before thermal application, wastes are required to be dried and then segregated. During the process, gases produced as by-product comprise of H_2, CO and CH_4, which can be used as fuel. Unlike incineration, gasification does not emit any toxic gases like SOx and NOx because of insufficient oxygen. Non-combustible residual parts are disposed following proper handling.

Refuse-Derived Fuel (RDF) Alike gasification, RDF is obtained from partial oxidation of mixed municipal solid waste. Utilization of the fuel in combination with coal and other type of conventional fuel in industries could be a great input in minimizing the requirement of natural/synthetic fuel.

Landfilling This is the most common and ultimate way to manage all types of wastes (organic and inorganic) which do not require skilled employees and is a low-cost process. However, landfilling of wastes without proper pretreatment ranked lowest amongst all management techniques. Landfills are major source of greenhouse gas emissions and contamination of land and water with organic and inorganic pollutants.

Others Technologies Wastes from industrial and mining sectors are widely used through advanced engineered techniques in making construction materials, chemicals and other utilities (Gautam et al. 2016). Mining wastes such as Fe, Cu, Zn and Al tailings, coal washeries and overburden wastes are used as raw materials in the recovery of expensive minerals and manufacture of construction materials for embankments of roadways, railways, rivers, dams, bricks, concrete beams, tiles, lightweight aggregates, glasses, ceramics and fuel (Gayana and Chandar 2018; Indian Bureau of Mines 2002). Metallurgical wastes such as slags, red mud, fly ash and galvanizing residues are used in making cement, concretes, bricks, tiles, ceramics, blocks, polymers, composites, wood substitute products, paints, boards and in metal recovery (Matinde et al. 2018).

16.6.2 Bioremediation of Contaminated Sites

The engineered techniques in management of wastes from various sectors are although advanced and highly efficient but are still at their initial stages of development. Particularly in developing countries like India, these technologies do not offer a cost-effective option at present. The cost incurred in cleaning of contaminated sites in the USA alone is $6–8 billion per year, with global costs in the range of $25–50 billion (Tsao 2003). Conventional, mechanical or physico-chemical treatment techniques to manage polluted sites by excavation, soil washing, solidification/stabilization, electrokinetic remediation and soil incineration also suffer from limitations like cost ineffectiveness, intensive labour requirement and irreversible soil disturbances (Yeung 2010). Therefore, management of solid waste dumps and contaminated sites through biotechnological approaches is the only sustainable, cost-effective and environmentally benign options to safeguard the environment (Gautam et al. 2017; Meagher 2000). Proper management policies, suitable remedial strategies and sustainable utilization of resources without altering the natural ecosystem should be the prime aim of all researchers and decision-making bodies in order to combat soil pollution problems in a holistic way. The cost-effectiveness of bioremediation was reported by Blaylock et al. (1997), who were able to save 50–65% of cost, when bioremediation was used for the treatment of one acre of Pb-polluted soil compared with the use of conventional methods such as excavation and landfills.

Bioremediation is the use of biological agents (bacteria, fungi, plants and earthworm) to remove or neutralize harmful toxic substances by converting them to either less or non-toxic form in an eco-friendly manner for environmental safety (Mishra et al. 2019). Bioremediation is an effective means of mitigating both organic (hydrocarbons, halogenated organic compounds, pesticides, herbicides and other compounds) and inorganic (non-metals, metal(loid)s and radionuclides)

Table 16.3 Various techniques for remediation of organic and inorganic pollutants in soil

Types of contaminants	In situ	Ex situ
Organic pollutants		
Aromatic hydrocarbons and polycyclic aromatic hydrocarbons	Bioventing Microbial bioremediation Phytoremediation Thermal treatment	Biopiles Composting Land farming Bioreactors Thermal desorption Incineration
Petroleum	Microbial bioremediation Biosparging Slurping	Bioremediation Soil washing Thermal desorption
Chlorinated aliphatic hydrocarbons	Bioventing Microbial bioremediation Phytoremediation Slurping Thermal treatment	Biopiles Bioreactor Thermal desorption Incineration
Chlorinated and non-chlorinated phenols	Bioventing Microbial bioremediation Phytoremediation Slurping	Biopiles Composting Land farming Bioreactors Thermal desorption Incineration
Dioxins and furans	Thermal treatment Phytoremediation Microbial bioremediation	Soil stabilization and solidification
Inorganic pollutants		
Metal(loid)s and non-metals	Natural attenuation Phytoremediation Soil stabilization Thermal treatment (electrokinetics)	Chemical extraction and oxidation Soil washing, stabilization and solidification Solvent extraction
Hazardous chemicals	Microbial bioremediation Phytoremediation	Microbial bioremediation Soil washing Solvent extraction Thermal desorption

Sources: Lacatusu et al. (2017), Azubuike (2016), Petruzzeli et al. (2015), Agarry and Oghenejoboh (2015)

contaminants in soil by both in situ and ex situ remediation techniques (Wadgaonkar et al. 2019; Mosca Angelucci and Tomei 2016; Prasad 2017, 2018) (Table 16.3).

16.6.2.1 In Situ Bioremediation

In-situ bioremediation is accompanied by minimal interference to the environment at the contamination site. Besides, it incurs less cost when compared to conventional soil remediation techniques (ex situ bioremediation). In situ bioremediation techniques are further categorized into:

Intrinsic Bioremediation/Natural Attenuation Bioremediation relies on the natural environmental conditions and behaviour of soil microorganisms and plants that are indigenous. It occurs without human intervention other than monitoring. The techniques are widely used to treat hydrocarbons, dyes, chlorinated solvents and metal(loid)s at polluted sites (Roy et al. 2015; Frascari et al. 2015).

Enhanced In Situ Bioremediation Intrinsic bioremediation is enhanced by some additive agents for effective remediation of polluted sites. This includes bioventing, bioslurping, biosparging and phytoremediation (Azubuike et al. 2016).

a. *Bioventing*: It involves controlled stimulation of airflow by supplying oxygen to unsaturated zone (vadose) in order to increase microbial activities. Besides, soil amendments are used to supply moisture and nutrients for enhanced bioremediation of pollutants rendering them into a harmless form (Philp and Atlas 2005).
b. *Slurping*: The technique is the combination of vacuum-enhanced pumping, extraction of soil vapour and bioventing for indirect provision of oxygen for contaminant biodegradation (Gidarakos and Aivalioti 2007). It is effectively used in remediation of volatile and semi-volatile organic pollutants in soil (Table 16.3). The technique is not suitable for soil with low permeability.
c. *Biosparging*: Unlike bioventing, air is injected into the saturated zone of soil subsurface which causes skyward movement of VOCs into the unsaturated zone to stimulate bioremediation process. The effectiveness of the technique proportionally depends upon soil permeability and pollutant biodegradability (Philp and Atlas 2005).
d. *Phytoremediation*: The technique relies on the use of plants' interaction with physical, chemical and biological factors at polluted sites to mitigate the toxic effects of pollutants (Azubuike et al. 2016; Sarma et al. 2021).

16.6.2.2 Ex Situ Bioremediation

Ex situ bioremediation techniques implicate excavation of polluted soils from contaminated sites and its subsequent transportation to another site for treatment. The techniques are usually preferred after envisaging the type of pollutant, depth and degree of pollution, geology of the polluted site, geographical location and the cost of treatment (Philp and Atlas 2005). Following ex situ bioremediation techniques are:

a. *Biopile*: It is a bioremediation technology where excavated soils are amended with nutrient to form a compost piles and enclosed for further treatments. The entire setup composed of a treatment bed, aeration, irrigation and a leachate collection system. An aeration and irrigation system is buried under the soil to pass through air and nutrients. Moreover, pH, oxygen, heat and nutrients are controlled factors to enhance biodegradation. The biopile technique is mainly applicable to polluted sites having VOCs with low molecular weight (Whelan et al. 2015). In the process, airstream-containing VOCs when leave the soil are treated to remove or destroy before being discharged into the atmosphere.

b. *Windrows*: Microbial degradation of pollutants relies on periodic turning of piled polluted soil together with added water through increased aeration and uniform distribution of pollutants and nutrients (Barr et al. 2002). As compared to biopile, windrows exhibit higher efficiency towards removal of hydrocarbon in soil (Coulon et al. 2010). The use of windrow technique is more associated with the release of greenhouse gases due to reduced aeration in anaerobic zone within piled polluted soil (Hobson et al. 2005).
c. *Bioreactor*: It is a system mainly composed of batch, fed-batch, continuous and multistage. Controlled bioaugmentation, nutrient addition, increased pollutant bioavailability and mass transfer between pollutant and microbes facilitate efficient microbial degradation of pollutants in soil under specific set of conditions (temperature, pH, agitation, aeration rates, and substrate and inoculum concentrations). It is widely used in treatment of soil or water polluted with VOCs (Table 16.3) including toluene, benzene, ethylbenzene and xylene (Azubuike et al. 2016).
d. *Land farming*: It is the simplest technique owing to less equipment requirement and low cost. It is considered under both in situ and ex situ. In former case, bioremediation proceeds without excavation of soil when pollutants lie <1 m of the surface of the ground and vice versa (Nikolopoulou et al. 2013). Excavated polluted soils are treated with autochthonous microorganisms for aerobic biodegradation of pollutants (Silva-Castro et al. 2012), whereas in situ land farming is facilitated by ploughing, addition of nutrients and irrigation to stimulate biodegradation of pollutants using autochthonous bacteria.

16.6.2.3 Bioremediation Using Microbes, Plants and Their Association

Depending upon the types of biological organisms used, bioremediation is categorized into following:

a. *Microbial Bioremediation*

Microorganisms are omnipresent and considered to be the first evolved life forms on the earth. They are versatile and tolerant towards wide range of environmental conditions, i.e. from the small intestines of animals to frozen environments, hydrothermal vents, acidic lakes and bottoms of deep oceans (Seigle-Murandi et al. 1996). Table 4 illustrates certain microorganisms widely used for remediation of contaminants in soil and are resistant to adverse environmental conditions. Various factors such as pH, temperature, soil type and texture, nutrient amendments and oxygen significantly influence the microbial remediation process in soil (Vásquez-Murrieta et al. 2016; Sharma 2012). In order to thrive under extreme environmental conditions, microorganisms exhibit certain morphological adaptation at both cellular and colony levels (such as in shape, colour, texture, opacity, convexity, margin appearance, etc.) (Jeanson et al. 2015). Due to their adaptability, microorganisms are widely used for bioremediation of heavy metal(loid)s, hydrocarbons, polythenes, food wastes, greenhouse gases, etc. (Das 2014). A large number of microbial enzymes have been known in degradation and detoxification of organic and inorganic pollutants to safer or less toxic intermediates (Dash and Das 2012). Ligninolytic enzymes (e.g., manganese peroxidase, lignin peroxidase and laccase), monooxygenase, chrome reductase, azo-reductase and dioxygenase secreted by rhizospheric microbes have been found to be effectively used in bioremediation of various pollutants (Dash and Das 2012). Microbial bioremediation of organic compounds implicates either partial or complete mineralization by complex and genetically regulated physiological reactions (Joutey et al. 2013).

Metal(loid)s cannot be destroyed like organic contaminates, rather they are either removed or biotransformed to a stable form (Tangahu et al. 2011). Remediation of metal(loid)s includes biosorption, bioleaching, biomineralization, intracellular accumulation and enzyme-catalyzed transformation through redox reactions (Lloyd and Lovely 2001). Besides, microorganisms develop certain mechanisms such as uptake, adsorption, oxidation, reduction and methylation to protect them from metal toxicity (Igiri et al. 2018). Several metal-resistant bacteria (*Bacillus* sp., *Pseudomonas* sp., *Saccharomyces* sp., etc.) have been reported to thrive under metal-stressed condition by their accumulation and complexation into less toxic form (Díaz-Ramírez et al. 2008).

b. *Phytoremediation*

The term “phytoremediation” was initiated by the Environmental Protection Agency (EPA) in 1991 and was first addressed in open technical literature in 1993 by Cunningham and Berti. Phytoremediation, also referred to as botano-, green-, vegetative- or agro-remediation, is collectively used for green plant-based technologies for in situ and ex situ remediation of contaminated soil (Mahjoub 2013). It is publicly appealing remediation technology that utilizes plants, associated microbiota, various soil amendments and agronomic techniques to extract, contain, degrade, detoxify or immobilize organic (hydrocarbons, pesticides and chlorinated solvents) and inorganic contaminants in the soil (Helmisaari et al. 2007; Vyslouzilova et al. 2003). For developing countries, phytoremediation is an eco-friendly, aesthetically pleasing and cost-effective approach, but despite its potentiality, it is yet to become a commercially viable technology (Ghosh and Singh 2005; Sharma et al. 2021). Phytoremediation approach is further classified into various applications such as phytostabilization, rhizodegradation or phytodegradation, rhizofiltration or phytofiltration, phytoextraction and phytovolatilization (Fig. 16.6).

Phytostabilization The approach utilizes plant roots to confine the mobility and availability of contaminants in soil (Jadia and Fulekar 2009). Pollutants from soil are absorbed through roots and restricted in rhizospheric zone, rendering them harmless by preventing their leaching (Ekta and Modi 2018). Phytostabilization was found to be a most suitable technique to remediate Cu, Zn, Cd, Cr and As (Moosavi and Seghatoleslami 2013). Bacchetta et al. (2018) showed that *Helichrysum microphyllum* subsp. *tyrrhenicum* grown on mine wastes dumps of Sardinia in Europe can tolerate high concentration of Zn, Pb and Cd, thus appearing as a species

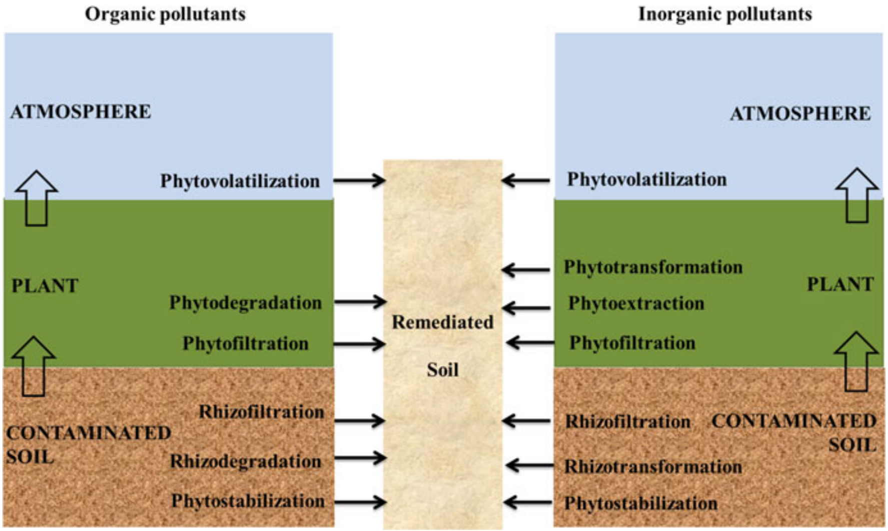

Fig. 16.6 Phytoremediation technologies for remediation of organic and inorganic pollutants from contaminated soil

suitable for phytostabilization. *Conocarpus erectus* grown in soil spiked with Ni (0, 50, 100 and 200 mg kg^{-1}), Pb (0, 600, 1200 and 2400 mg kg^{-1}), Cd (0, 20, 40 and 80 mg kg^{-1}) and Cr (0, 150, 300 and 600 mg kg^{-1}) has enormous potential for the phytostabilization of Cr, Ni and Cd in its roots (Tauqeer et al. 2019). Ferro et al. (1997) observed that alfalfa (*Medicago sativa*) did not cause the degradation of volatile organic constituents in soil treated with 40 and 660 μg kg^{-1} of ^{14}C-benzene, rather it enhanced its phytostabilization in soil.

Phytoextraction Plants absorb organic and inorganic chemical species from soil and translocate them to the aboveground harvestable parts to accumulate. In general, roots contain higher levels of contaminants than shoot despite the translocation is high which is primarily attributed to maximum accumulation capacity of the aboveground biomass (Suman et al. 2018; Wuana and Felix 2011). Malik and Ravindran (2018) reported that *Suaeda maritima* was found efficient in phytoextraction of metals (Zn, Cu, Cd, Cr, Mg, calcium (Ca) and potassium (K)) and chloride salts from soil contaminated with paper mill effluents. *Cymbopogon citratus* showed potentiality in extraction of Al, Zn, Ni, Pb, Cd, Pb, Cr and As, while *Chrysopogon zizanioides* was found efficient in extraction of Mn and Cu from soil mixed with sewage sludge at different red mud combinations (Gautam et al. 2017; Gautam and Agrawal 2017). White et al. (2003) in their study revealed that amongst 21 cultivars of *Cucurbita pepo* grown at Lockwood Farm of Hamden, CT, USA (contaminated with p, p′-DDE levels ranged from 200 to 1200 ng g^{-1}), cultivar ssp pepo had potentiality to phytoextract POPs from soil and translocate large quantities to aerial tissues. Moreover, plant species such as *C. pepo*, *Carex normalis* and *Festuca* *arundinacea* collected from the PCB storage site at Ontario (0.6–200 μg g^{-1} of total PCBs (Aroclor 1254/1260)) ascended as potential PCBs phytoextractors (Åslund et al. 2007).

Phytofiltration or rhizofiltration This technology involves use of plant roots for removing chemical species from aqueous wastes. According to United States Environmental Protection Agency (2000), rhizofiltration or phytofiltration can be used for Zn, Cu, Ni, Cd, Pb and Cr which are principally retained within the roots. Plants such as mustard, sunflower, spinach, rye, tobacco and corn have been identified as suitable candidates for infiltration of Pb from water (Mukhopadhyay and Maiti 2010). Abhilash et al. (2009) found maximum Cd content in roots followed by leaves and peduncle of *Limnocharis flava* grown in Cd-contaminated water, thus showing the efficacy of *L. flava* in phytofiltration of Cd (>93%). *Micranthemum umbrosum* was found effective in removing organic As species such as monomethylarsenic acid (CH_5AsO_3) and dimethylarsenic acid ($C_2H_7AsO_2$) from oxic environment through phytofiltration process (Islam et al. 2017).

Phytovolatilization The technique uses green plants to extract contaminants such as As, Hg, Se and volatile organic compounds from polluted soils, transform them into volatile forms and transpire them into the atmosphere from their leaves or stem (Limmer and Burken 2016; Karami and Shamsuddin 2010). According to Sakakibara et al. (2010), *Pteris vittata* was found efficient in remediating about 90% As from soil containing 37% of arsenite and 63% of arsenate. Similarly, *Lepidium latifolium*, *Artemisia douglasiana*, *Caulanthus* sp., *Fragaria vesca* and *Eucalyptus globulus* were grown in soil contaminated with mercury (450–1605 mg kg^{-1}, where *Caulanthus* sp. showed a higher proficiency in removing mercury from soil (emission rate 92.6 ng m^{-2} h^{-1}) as compared to other plant species (Wang et al. 2012). Limmer and Burken (2016) highlighted the phytovolatilization efficiency of several plants, i.e. *Eucalyptus* sp., *Populus* sp., *Salix* sp. and Pine, in remediating volatile organic compounds in soil.

Phytodegradation or phytotransformation Plants and its associated microorganisms are involved in uptake, metabolization and degradation of pollutants especially organic compounds (Ekta and Modi 2018; Thakare et al. 2021). Phytoconversion of Cr (VI) (more toxic) to Cr (III) (less toxic) form using halophytes was reported by Cacador and Duarte (2015). Some plants are successfully used to decontaminate polluted soil and sludge dumps using root exudates (Ekta and Modi 2018). Newman and Reynolds (2004) enlisted the plants, i.e., *Leucaena* sp., *Populus* sp., *Brassica* sp., *Helianthus* sp., *Secale cereale*, *Cucurbita* sp., *Arabidopsis* sp., *Bruguiera* sp., *Kandelia* sp., *Nicotiana tabacum*, *Sorghum* sp., etc. commonly used in phytodegradation of organic pollutants (such as pesticides, PAHs, PCBs, chlorinated compounds, gasoline additives and de-icing agents) in soil.

Typically, four main strategies currently exist to augment phytoremediation of organic as well as inorganic pollutants from soils: (1) use of natural phytoaccumulators, (2) enhancement of phytoremediation process by soil amendments, (3) microbe-assisted phytoremediation and (4) genetic alterations in plants used for remediation purposes (McGrath et al. 2002).

Use of Natural Phytoaccumulators There are about 400 plant species belonging to 45 plant families known to be effectively used in remediation of polluted soil (Ekta and Modi 2018). Some of the families are Asteraceae, Brassicaceae, Convolvulaceae, Euphorbiaceae, Fabaceae, Lamiaceae, Poaceae and Scrophulariaceae (Gautam and Agrawal, 2019; Ekta and Modi 2018). Plants such as *Ludwigia* sp., *Dracaena* sp., *Phragmites australis*, *Rhizophora mangle*, *Sparganium* sp., *Aegiceras corniculatum*, *Cannabis sativa, Arrhenatherum elatius*, *Arabidopsis halleri*, *Brassica* sp., *Corrigiola telephiifolia, Raphanus sativus*, *Thlaspi caerulescens*, *Alyssum* sp., *Arabidopsis* sp., *Eichhornia crassipes*, *Salix* sp., *Euphorbia* sp., *Helianthus annuus*, *Pteris vittata*, *Jatropha curcas*, *Populus* sp., *Spartina maritima*, *Potamogeton pectinatus*, *Ricinus communis*, *Trifolium alexandrinum*, *Zea mays*, *Spinacia oleracea*, *Verbascum speciosum*, *Vetiveria* sp., *Ambrosia artemisiifolia, Lycopersicon esculentum*, etc. have very high bioaccumulation potential for organic pollutants (POPs, PAHs and PCBs) and heavy metals (Cd, Zn, As, Cu, Fe, Pb, Hg, Mn, Mg, Cr and Ni) in soil (Table 16.4).

Brassica juncea cultivar Pusa Bold grown in soil amended with cow dung manure exhibited high potential towards extraction of Cu, Fe, Cd, Zn, Mn, Cu, Pb and Cr when compared to the cultivar Kranti (Gautam and Agrawal 2019). A study conducted by Gautam and Agrawal (2019) on the herbaceous community at abandoned red mud dumps showed that dominant species, viz. *Brachiaria mutica*, *Cynodon dactylon*, *Dactyloctenium aegyptium*, *Digitaria ischaemum*, *Digitaria longiflora*, *Eragrostis cynosuroides*, *Launaea asplenifolia*, *Parthenium hysterophorus*, *Sporobolus diander* and *Stylosanthes scabra* (with high IVI), exhibited high metal accumulation and tolerance capabilities. Plant species were recommended to be used in sustainable phytomanagement of abandoned red mud dumps.

Enhancement of Phytoremediation Using Soil Amendments Bioavailability of pollutants in soil can be controlled by the amalgamation of either organic or inorganic amendments. Organic amendments include animal manure, sewage sludge, biochar, vegetative dry dust, bacteria and plant-growth promoting rhizobacteria (PGPR), litter waste, woodchips, rice husks, straw, etc. (Gautam et al. 2017; Wiszniewska et al. 2016). Inorganic amendments include bauxite residue, fly ash, ethylenediaminetetraacetic acid (EDTA), oxides of iron and aluminium, silicon (Si), inorganic fertilizers, liming agents (calcium carbonate, $CaCO_3$; and calcium oxide, CaO) and sulphur-containing compounds (hydrogen sulphide, H_2S) (Vu and Gowripalan 2018; Gautam and Agrawal 2017). Shrestha et al. (2019) showed reduced phyto-uptake of metals (Zn, Cd, Pb, Co and Ni) by switchgrass (*Panicum virgatum*) grown in soil amended with vermicompost, thermophilic compost and coconut coir. In a study conducted by Gautam and Agrawal (2017), sewage sludge addition to soil (1:2 (w/w)) enhanced the uptake of Fe, Zn, Cu, Ni, Cr, Pb, Cd

Table 16.4 Plants and microorganisms widely used in remediation of organic and inorganic pollutants from soil

Types of biological organisms	Organic and inorganic pollutants	References
Microorganisms		
Bacillus sp., *Bordetella* sp. and *Pseudomonas* sp.	Co, Zn, Cd and Ni	Das and Dash (2014)
Staphylococcus aureus and Methylococcus capsulatus	Cr	Bawa and Omairi (2017); Das and Dash (2014)
Penicillium chrysogenum and *Pseudomonas putida*	Monocyclic aromatic hydrocarbons	Abatenh et al. (2017)
Pseudomonas sp., *Achromobacter* sp., *Flavobacterium* sp., *Acinetobacter* sp., *Bacillus* sp., *Alcaligenes odorans*, *Arthrobacter* sp., *Citrobacter koseri* and *Serratia ficaria*	Crude oil, petrol and diesel	Abatenh et al. (2017)
Pseudomonas alcaligenes, *Pseudomonas mendocina* and *P. putida*, *Pseudomonas veronii*, *Achromobacter* sp., *Flavobacterium* sp., *Acinetobacter* sp., *Coprinellus radians*, *Candida viswanathii* and *Bacillus licheniformis*	PAHs	Abatenh et al. (2017), Mardani et al. (2016)
Myrothecium roridum, *Pycnoporus sanguineus*, *Phanerochaete chrysosporium*, *Trametes trogii*, *Exiguobacterium* sp., *Bacillus cereus* and *Acinetobacter baumannii*	Industrial dyes	Abatenh et al. (2017)
P. chrysosporium	PCBs	Elangovan et al. (2019)
Aspergillus niger, *Aspergillus fumigatus*, *Fusarium solani*, *Penicillium funiculosum*, *Tyromyces palustris*, *Gloeophyllum trabeum*, *Trametes versicolor*, *Acinetobacter* sp., *Pseudomonas* sp., *Ralstonia* sp. and *Microbacterium* sp.	Aliphatic and aromatic hydrocarbon	Abatenh et al. (2017)
A. odorans, *Bacillus subtilis*, *Corynebacterium propinquum* and *Pseudomonas aeruginosa*	Phenol	Abatenh et al. (2017), Hasan and Jabeen. (2015)
Saccharomyces cerevisiae, *Cunninghamella elegans* and *Escherichia coli*	As	Abatenh et al. (2017), Su et al. (2009)
Pseudomonas fluorescens, *P. aeruginosa* and *Aeromonas* sp.	Cu	Abatenh et al. (2017)
P. fluorescens, *P. aeruginosa*, *Lysinibacillus sphaericus*, *Aerococcus* sp., *Azotobacter* sp. and *Rhodopseudomonas palustris*	Pb	Abatenh et al. (2017), Ashraf (2017)
P. fluorescens, *P. aeruginosa*, *B. subtilis*, *B. cereus*, *Bordetella* sp., *Microbacterium* sp. and *Pseudomonas* sp.	Zn	Abatenh et al. (2017), Ashraf et al. (2017)

(continued)

Table 16.4 (continued)

Types of biological organisms	Organic and inorganic pollutants	References
Aerococcus sp., *R. palustris*, *Bacillus* sp., *Bordetella* sp. and *P. aeruginosa*	Cd	Abatenh et al. (2017), Chellaiah (2018)
P. fluorescens, *P. aeruginosa*, *Geobacter* sp., *Leptospirillum ferrooxidans*, *Acidithiobacillus thiooxidans*, *Acidithiobacillus ferrooxidans* and *A. niger*	Fe	Abatenh et al. (2017), Nguyen and Lee (2015)
Lysinibacillus sphaericus	Co	Abatenh et al. (2017)
P. aeruginosa, *Aeromonas* sp., *B. subtilis*, *B. cereus*, *Bordetella* sp. and *Pseudomonas* sp.	Ni	Abatenh et al. (2017), Ashraf (2017)
S. cerevisiae	Mg	Joutey et al. (2013)
Vibrio alginolyticus, *Brochothrix thermosphacta* and *Moraxella urethralis*	Al	Kurniawan et al. (2018), Titah et al. (2019)
P. fluorescens and *P. aeruginosa*	Mn	Abatenh et al. (2017)
Plants		
Ludwigia octovalvis and *Dracaena reflexa*	Crude oil, petrol and diesel	Almansoory et al. (2015), Agamuthu and Dadrasnia (2013)
Phragmites australis	PAHs	Di Gregorio et al. (2015)
Populus sp. and *Arabidopsis thaliana*	Silver nanoparticles	Wang et al. (2013)
Rhizophora mangle	Total petroleum hydrocarbon	Moreira et al. (2013)
Sparganium sp. and *Aegiceras corniculatum*	PCBs and PBBs	Chen et al. (2015), Gregorio et al. (2015)
Luffa acutangula	Anthracene and fluoranthene	Somtrakoon et al. (2014)
Spartina maritime, *Arabidopsis* sp. and *Corrigiola telephiifolia*	As	Azubuike et al. (2016), Rezania et al. (2016)
S. maritime, *Eichhorina crassipes*, *Cannabis sativa*, *Haumaniastrum katangense* and *Vetiveria zizanioides*	Cu	Gautam and Agrawal (2017), Azubuike et al. (2016)
Spartina maritime, *Plectranthus amboinicus*, *Carex pendula*, *Sorghum halepense* and *Betula occidentalis*, *Helianthus annuus*, *Brassica nigra*, *Medicago sativa* and *Cymbopogon citratus*	Pb	Gautam et al. (2017), Azubuike et al. (2016)
S. maritime, *E. crassipes*, *C. citratus* and *Nicotiana glauca*	Zn	Gautam et al. (2017), Azubuike et al. (2016), Rezania et al. (2016)
E. crassipes, *C. sativa*, *Thlaspi caerulescens*, *Solanum photeinocarpum*, *Rorippa globosa*, *Arabidopsis* sp. and *C. citratus*	Cd	Gautam et al. (2017), Azubuike et al. (2016), Rezania et al. (2016)
E. crassipes and *C. citratus*	Cr	Gautam et al. (2017), Azubuike et al. (2016)

(continued)

Table 16.4 (continued)

Types of biological organisms	Organic and inorganic pollutants	References
Limnocharis flava and *Elodea canadensis*	Fe	Rezania et al. (2016)
E. canadensis	Co	Rezania et al. (2016)
Amaranthus paniculatus, *Nicotiana glauca* and *Alyssum markgrafii*	Ni	Azubuike et al. (2016), Rezania et al. (2016)
C. citratus	Al	Gautam et al. (2017)
C. citratus,	Mg	Gautam et al. (2017)
Vetiveria zizanioides	Mn	Gautam and Agrawal (2017)

PBBs polybrominated biphenyls, *PCBs* polychlorinated biphenyls, *PAHs* polycyclic aromatic hydrocarbons, *Al* aluminium, *Zn* zinc, *Cu* copper, *Mg* magnesium, *Mn* manganese, *Fe* iron, *Co* cobalt, *Ni* nickel, *Cr* chromium, *Cd* cadmium, *As* arsenic, *Pb* lead

and As by *C. zizanioides*; however, their phyto-uptake was decreased significantly with increase in red mud addition (5, 10 and 15% (w/w)) to sludge-amended soil. Similarly, increased phytoavailability of heavy metal(loid)s (Al, Fe, Zn, Co, Cu, Ni, Mn, Mg, Cd, Cr, Pb and As) to lemongrass due to biowaste amendments (cow dung manure and sewage sludge) in soil was remarkably reduced by red mud treatments which was mainly accredited to increased soil pH and oxides of iron and aluminium (Gautam et al. 2017).

Highest accumulation of Pb in roots and shoot was attained by *Eucalyptus camaldulensis* cultivated in Pb-contaminated soil inoculated with *Alcaligenes eutrophus* when compared to other soil amendments (EDTA, compost, Hoagland solution and their mixture). Crude oil-polluted soil of Akala-Olu, Nigeria, characterized by the presence of ten non-carcinogenic and six carcinogenic PAHs was efficiently remediated by *Fimbristylis littoralis* (87%), *Hevea brasiliensis* (92%), *C. citratus* (85%) and *Vigna subterranea* (89%) grown in soil amended with organic as compared to inorganic amendments (Nwaichi et al. 2015). Plants used for phytoremediation of PCBs in contaminated soil include *Lespedeza cuneate*, *Phalaris arundinacea*, *M. sativa*, *Lathyrus sylvestris*, *Salix alaxensis*, *Sparganium* sp. and *Picea glauca* (Jing et al. 2018). Tu et al. (2011) validated a significant reduction in PCB content of soil by 31.4 and 78.4% after the first and second years of study using *M. sativa*.

Microbe-Assisted Phytoremediation The effectiveness of bioremediation could be enhanced using integrated approach of plants and microbes (Qi et al. 2019; Hussain et al. 2018). Microbial community in the rhizospheric region is stimulated by the release of plant rhizodeposits, thus establishing a gradient of interactions between both (Tabassum et al., 2017). The plant-microbe associations influence the pH and composition of root exudates, thereby affecting the bioavailability and phyto-uptake of pollutants in the soil (Sarwar et al. 2017). Non-symbiotic and symbiotic relationships between plants and microbes are making them a single candidate for bioremediation of contaminated soil. Microbes specifically plant growth-promoting rhizobacteria (PGPR) enhance plants' growth and tolerance towards varying environmental stresses by different action mechanisms (solubilizing phosphates, producing phytohormones or fixing nitrogen) or by altering the plant metabolism (increasing the absorption of water and minerals) that consequently increases root development, enzymatic activities of the plant, support growth and development of other microorganisms beneficial to plants and suppress plant pathogens (Jacoby et al. 2017).

Genetic Alterations in Plants for Effective Remediation Many organic and inorganic pollutants are recalcitrant to phytoremediation (Doty 2008). There are many genes involved in metabolism, uptake, translocation and sequestration of pollutants. Thus, the most feasible method for enhancing the effectiveness of phytoremediation is to overexpress those genes in transgenic plants through genetic engineering (Cherian and Oliveira 2005). Depending upon the strategy, transgenic plants can be genetically modified for enhanced accumulation of contaminants in different parts of the plant. There are several available reports on bioremediation of pollutants through transgenic plants (Agnihotri and Seth 2019; Shah and Pathak 2019). Transgenic plants such as *Brassica juncea*, *Arabidopsis thaliana* and *Thlaspi caerulescens* have been reported to effectively remove the heavy metals (Cd, Cr, Pb, Zn and As) from soil (Agnihotri and Seth 2019). Genetically engineered plant (*Arabidopsis thaliana*) with two expressed bacterial genes (one gene converts arsenate into arsenite and the second binds to the arsenite) have been reported to absorb arsenic efficiently from polluted soil and store in the vacuoles (Finnegan and Chen 2012). Phytoremediation of organic pollutants is significantly improved with transgenic plants (Hannink et al. 2002). For an instance, explosives such as 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX) and glycerol trinitrate (GTN) are phytotoxic, and phytoremediation of such pollutants through non-transgenic plants is relentlessly hindered (Van Aken 2009). But expression of bacterial genes (nitroreductase, cytochrome P450 and pentaerythritol tetranitrate reductase) specifically involved in degradation of TNT, RDX and GTN, respectively, enables the plants, viz. *Nicotiana tabacum*, *Arabidopsis thaliana* and *Populus* sp., to be more tolerant of the pollutant in phytoremediation.

16.7 Future Prospects

A large area of land has been impacted by the organic and inorganic pollutants due to anthropogenic activities which have become a major environmental issue and health concern worldwide. The analysis for pollutants in soil would be useful in reassuring the soil quality, food and health security of mankind. Several advanced technologies are available to manage waste and contaminated sites, but there is growing interest in in situ and ex situ remediation techniques using green plants, microbes and microbe-assisted phytoremediation. Plants with high biomass production should be accentuated and enhanced through genetic engineering for effective remediation of pollutants from the environment. Similarly, genetic modification of microorganisms used in bioremediation to compete with indigenous microbial population is essential for the successful bioremediation. Bioremediation approach would showcase sustainable and revitalizing strategies to escalate the options for reutilization of contaminated sites, thus impacting the economic gains of the country. Besides, it offers a build-up of stronger communities through partnerships amongst organizations and individuals keeping the socio-economic and environmental concerns in the centre of the table.

16.8 Conclusions

Contamination of soil with organic and inorganic pollutants is the major cause for alteration in plant community structure pattern and crop loss worldwide. Such pollutants beyond threshold levels for animals may lead to several toxic effects through food chain contamination. Remediation of contaminated sites requires attention towards inculcation and development of sustainable approach because although several advanced technologies exist, they are very costly, labour-intensive and also not environmentally benign options. Therefore, utilization of microorganisms, plants and their integrated approach could make a better tactics to degrade xenobiotic compounds. However, phytoremediation using naturally growing hyperaccumulators, different soil amendments, microbial assistance and transgenic plants are the most sustainable and viable approaches to remediate the extensively large areas of polluted land without causing any environmental harm. Thus, there is the need of upcoming era to focus on the research initiatives on the exploration of different bioremediation techniques in stress environment and to unravel the mechanisms involved. Such studies would be helpful in identifying efficient microbe and plant species for effectual bioremediation of contaminated sites. Nonetheless, bioremediation also provides economic, efficient and sustainable remediation technology to manage contaminated sites at global level.

Acknowledgements Authors are thankful to the head and the coordinator, CAS in Botany, coordinators, ISLS, DST-FIST, UGC-UPE, DST-PURSE, Institute of Science, Banaras Hindu University and Varanasi for basic facilities. Meenu Gautam is thankful to the Council of Scientific and Industrial Research (File No. 09/013(0857)/2018-EMR-I), New Delhi, for research associateship.

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