Phytoremediation of Lead: A Review

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Abstract Environmental pollution is the most important problem faced by modern civilization among all other concerns. Metals are normal components of the crust of Earth. Due to erosion of rocks, volcanic activity and many more natural and anthropogenic activities metals and other contaminants are discharged and found in almost all environmental compartments and strata. Among these heavy metals, lead is the most considerable toxic pollutant which is coming from diverse sources into the surrounding environment and consequently goes into the various components of the food chain. Industrialisation, urbanization, technological spreading out, increased use of fossil fuel, chemical fertilizer and pesticide use, mining and smelting and inappropriate waste management practices stay put the foremost reasons of extremely high levels of toxic quantities of lead in the environment. Mined ores or recycled scrap metal and batteries are the sources that fulfil the industrial lead requirement. Lead mining-smelting, industrial processes, batteries, colour-paints, E-wastes, thermal power plants, ceramics, and bangle manufacturing are the important point sources of lead. Huge quantities of lead in the air are from combustion of leaded fuel. The key reason for prolonged persistence of lead in the environment is the non-biodegradable character of this metal. This has led to manifold increased levels of lead in the environment and biological systems. Lead has no known biological requirement and is highly toxic even at low concentrations. Lead is looked upon as a strong occupational toxin and its toxicological manifestations are very well documented. Lead toxicity and poisoning has been recognized as a major community health threat all around in developing countries. Lead moves into the ecosystem and creates toxic effects on the microorganism as well as on all living organisms including plants. Conventional or traditional techniques of heavy metal quenching and putting out of contaminants from the contaminated sites have jeopardy to leave go of looming heavy metals in the environment and these are costlier as well as unsafe additionally. Use of microbes and green plants for clean-up purposes is therefore, a promising solution for onslaught of heavy metal polluted sites

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in view of the fact that they include sustainable ways of repairing and re-establishing the natural status of soil and environment. The future outlook of phytoremediation depends on ongoing research and development. The science of phytoremediation has to go through numerous technical obstacles and developmental stages and better outcomes can be achieved by learning and knowing more and more about the variety of biological processes participating in phytoremediation programmes. For successful future of phytoremediation a number of attempts yet to be require with multidisciplinary approach. This review comprehensively presents the background, concepts, technical details, types, strategies, merits and demerits, and upcoming path for the phytoremediation of lead pollution.

Keywords Heavy metals · Lead pollution · Ecotoxicology · Bioremediation · Phytoremediation

1 Introduction

The most important problem faced by modern society today among all other concerns is environmental pollution. Naturally, metals are normal components in soils and in the crust of Earth. Metals are released and are present in various concentrations in different environmental components (water, soil) through a number of discharge processes such as erosion of rocks and volcanic activity. The widespread heavy metals found in contaminated localities are described to be lead, chromium, cadmium, copper, mercury and nickel (Jagetiya and Aery 1994; Jagetiya and Bhatt 2005, 2007; Jagetiya et al. 2007, 2013; Kapourchal et al. 2009; Gupta et al. 2013b). Among these, lead and few other heavy metals are the most significant poisonous and deadly pollutants that come from diverse origin points into the surrounding milieu, plant systems and subsequently come into the food chain. The important lead ore is galena (PbS). Galena has cubic form, low hardness and high density (Reuer and Weiss 2002). Lead has been kept in the category of heavy metal and it is a malleable and soft metal. The average concentration of lead in the soil is about 13 mg kg^{-1} and its values are found to be ranged between 1 and 200 mg kg^{-1}. The ultimate recipient of numerous wastes is soil which comes through various anthropogenic actions, chiefly from mining, industrial discharge and disposal/outflow of wastes from manufacturing, and many more doings. Anthropogenic sources of lead include mining, smelting, electroplating and atmospheric deposition due to petrol and use of pesticides, fertilizers. Atmospheric deposition due to petrol comprises anti-knocking additive lead (Tiwari et al. 2013). Huge quantity of lead into the air entered through combustion of leaded fuel these lead particles then settle down on surface of the soil and goes into the soil with precipitation and irrigation practices. Large sized particles of lead discharged from exhaust of the vehicles by and large go away in the expanse of about 50–100 m from the highways and settled on the surface of soil. On the other hand much farer distance is travelled from these sites by the particles with 2 and less than 2 µm in size (Kapourchal et al. 2009). Soil that contaminated by firing range represent a long term source of lead (Okkenhaug et al. 2016). Hair colouring contributed additionally to lead in environment (permanent colouring has lead acetate combined with SH-group of hair protein to form black insoluble lead sulphides) (Cohen and Roe 1991). Lead mining-smelting, industrial processes, batteries, colour-paints, E-wastes, thermal power plants, ceramics, and bangle manufacturing, etc. are the important point sources of lead pollution (Fig. 1) (Singh et al. 2015). Heavy metal pollution is a worldwide problem because these metals are everlasting and nearly every one of these have lethal and deadly impact on all living being, when their quantity go beyond the threshold limits (Ghrefat and Yusuf 2006; Yadav et al. 2017). Plants as well as animals absorb these toxic heavy metals from surrounding sediments, water, and soils, through ingestion, contact and inhaling of airborne suspended tiny metal particles (Mudgal et al. 2010). Heavy

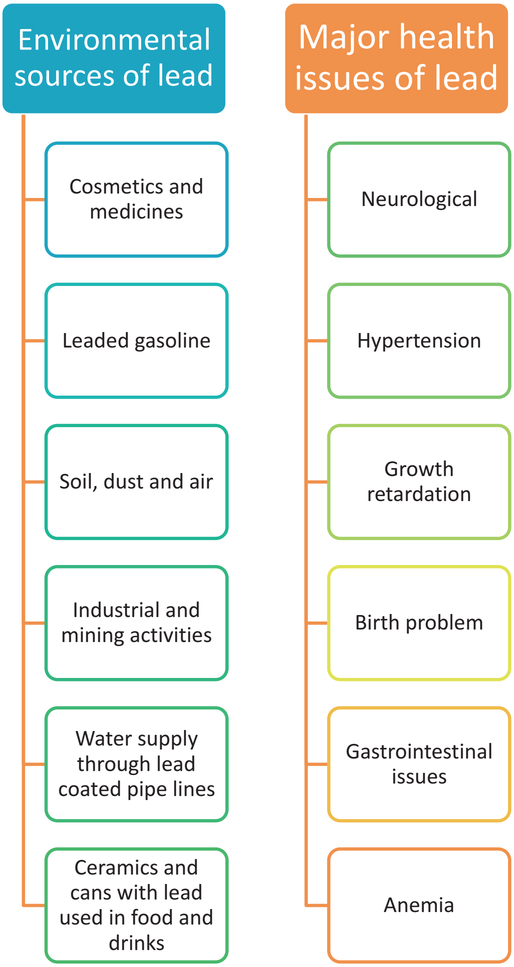

Fig. 1 Major environmental sources and health effects of lead

metals toxicity has reported as the great threat for the health of plant and animals and most of them may disturb important biochemical processes of these organisms. Toxicity due to heavy metals in plants has restraining effect on enzymatic action, stomatal task, photosynthesis, accumulation and uptake of nutrient elements and root system and ultimately on growth (Addo et al. 2012). Heavy metals such as mercury, cadmium and lead do not have any known biological requirement and very much venomous yet at lower concentrations of 0.001–0.1 mg L^{-1}(Aery and Jagetiya 1997; Wang 2002; Alkorta et al. 2004). Cadmium is responsible for carcinogenicity, mutagenicity, endocrine disruptor, lung damage in human (Degraeve 1981; Salem et al. 2000). The major health effect due to mercury toxicity are depression, fatigue, insomnia, drowsiness, hair loss, restlessness, loss of memory, tremors, brain damage, temper outbursts, lung and kidney failure and autoimmune diseases (Neustadt and Pieczenik 2007; Gulati et al. 2010). Excess exposure of lead in kids causes various diseases such as poor intelligence, memory loss, developmental impairment and disabilities in learning, coordination dilemma, and cardiovascular ailment (Fig. 1) (Padmavathiamma and Li 2007; Wuana and Okieimen 2011). Exposure of human beings to these heavy metals that have a number of perilous effects on human health are mostly comes from polluted food chain (Mudgal et al. 2010). A number of heavy metals amputation technologies including ultrafiltration, chemical precipitation, ion-exchange, adsorption, electrodialysis, coagulation-flocculation, reverse osmosis and flotation are generally bring into play. These technologies are too expensive, unfavourable and unsafe to do away with heavy metals from contaminated sites. Above discussed techniques are very costly and has much disadvantage but rather than eco-friendly and cost-effective. Exploiting micro-organisms and plant systems for remediation intentions is therefore a potential way out for pollution due to heavy metal in view of the fact that it includes sustainable decontamination methods to repair and restore the normal state of the rhizosphere and top soil (Jagetiya and Purohit 2006; Jagetiya and Porwal 2019; Jagetiya and Sharma 2009, 2013; Jagetiya et al. 2011, 2012, 2014; Yadav et al. 2017). The efficient and most attractive alternative is plant based remediation or phytoremediation which has already been used of years is environment pleasant, inexpensive and safer modus operandi. It has minimal vicious impact on the ecosystem (Kapourchal et al. 2009; Singh 2012; Ali et al. 2013). A large number of studies have been successfully carried out for phytoremediation of lead and number of plant species are being used for this purpose (Prasad and Freitas 2003; Kapourchal et al. 2009; Malar et al. 2014; Arora et al. 2015; Mahar et al. 2016; Wan et al. 2016; Fanna et al. 2018; Chandrasekhar and Ray 2019).

2 Lead Enrichment in the Environment

Lead is present in Earth's crust as a bluish-grey, low melting, heavy metal and it is exceptionally found as a natural metal and present frequently combined with two or more elements to constitute compounds of lead (ATSDR 2005). It is one of the metals usually present in the environment for the reason that it is in the list of the earliest discovered metals and most far and wide utilized in history of human beings (Shoty et al. 1998). It is becoming severe menace to human health in view of the fact that it's continued to go into the environment as an automobile exhaust emission and widespread exploitation in industry (Juberg et al. 1997). Mined ores (primary) or recycled scrap metal and batteries (secondary) are the sources of lead used in industries. It is reported that about 97% of lead-acid batteries are recycled and lead predominantly found nowadays is "secondary" type and accrued from lead-acid batteries (ATSDR 2005). Manufacturing of lead batteries, extensively used in automobiles is the main use of lead in the industries. Lead is also used for shielding of X-ray machines, alloy making, manufacturing of corrosion and acid resistant stuffs and soldering materials manufacturing etc. (Patil et al. 2006). Lead pollution in air, water, soil and agricultural fields is an ecological concern due to its severe impact on human health and environment since among heavy metals lead is most hazardous. Mining-smelting, industrial effluents, fertilizers, pesticides, and municipal sewage sludge are the main sources of lead pollution in the environment (Aery et al. 1994; Sharma and Dubey 2005; Malar et al. 2014). Negatively charged solid surfaces such as clays, carbonates, oxides and hydroxides of iron, manganese as well as organic carbon of water column rapidly scavenge soluble lead. Consequently non-chelated/dissolved lead has a short water column dwelling duration in ocean. Settling of lead associated particulate stuff by and large regulates the distribution of lead in specific ocean basin (Chakraborty et al. 2015). In maritime sediments, lead may be found in diverse physico-chemical varieties and it has differential affinities for various binding-phases of coastal sediments. Carbonate phase in coastal sediments plays an imperative role in regulating lead distribution (Fulghum et al. 1988) and scavenging nature of lead by Fe/Mn oxy-hydroxide phase in residue has also been identified as a crucial process (Jones and Turki 1997). Distribution and speciation of lead has been demonstrated to be regulated by organic binding phase of it (Krupadam et al. 2007; Chakraborty et al. 2012). Geogenic or anthropogenic activities turned lead contamination into a severe large-scale worldwide environmental apprehension. Industrialisation, uncontrolled use of fossil fuel resources, urbanization, technological expansion, use of pesticides and fertilizers, mining and smelting and poor waste management are the foremost reasons of extremely high quantities of lead in the environment (Lajayer et al. 2017; Chandrasekhar and Ray 2019). Enormous mining activities, paper, metal coating, fertilizer and other industries resulted in the diffusion of lead and allied heavy metals into the environment and their concentrations is escalating bit by bit (Fu and Wang 2011; Wang et al. 2016). Increased lead levels in the water reservoirs is taking place due to residential dwellings, groundwater infiltration, mining drains and manufacturing discharges and over the most recent years, growing human population and industrial expansion have led to a boost of lead contamination in aquatic ecosystems. For that reason, studies reporting the effects of lead and other toxic heavy metals on aquatic organisms are presently attracting added contemplation, predominantly those focusing on urban and industrial contamination (Rocchetta et al. 2007; Akpor and Muchie 2011; Sadik et al. 2015; Dogan et al. 2018). The blemish of coastal waters with trace and heavy metals through anthropogenic spring and sewage has turn into a ruthless predicament (Mamboya et al. 1999). Heavy metals, such as lead is among the most widespread pollutants at hand in equal amounts in urban and industrial discharge (Sheng et al. 2004; Santos et al. 2014). Environmental degradation from heavy and toxic metal contaminants in aqueous water streams and groundwater as well as in soil posing a major community problem is mainly due to worldwide technological progress, unprecedented anthropogenic activities (over exploitation of metal-mineral resources, over use of fertilizers and pesticides, increased household activities and automobiles exhaust) and natural phenomenon (forest fires, volcanic eruption and seepage from rocks) that needs to be addressed seriously. Heavy metals and minerals especially lead, mercury, chromium, cadmium, copper, arsenic and aluminium is a serious threat to the environment and human health. These toxic substances enter into the human body mainly through contaminated water, food and air, leading to numerous lethal health complications (Singh et al. 2015). Some other reports also states that sources of heavy metals in the environment are mainly industry, municipal wastewater, atmospheric pollution, urban runoff, river dumping, and shore erosion and stated that anthropogenic inputs of metals exceeds natural inputs. Higher volumes of cadmium, copper, lead and iron may be act like ecological poisons in terrestrial and aquatic ecosystems (Balsberg-Påhlsson 1989; Guilizzoni 1991). The water, sediments and plants in water bodies receiving municipal and domestic runoff contain higher quantity of heavy metals in comparison to those not getting runoff from urban areas and this process leads into surplus metal levels in surface water which cause a health risk to human beings and to the environment both (Vardanyan and Ingole 2006). Higher levels of lead in the forest flooring and relatively porous soils in forest ecosystems has been documented that lead is released from the forest flooring to the mineral soil or into the surface waters. Continued accrual of lead in forest ecosystems consequently may pose upcoming threat to water quality (Johnson et al. 1995). Lead reaches to the soil and environment through pedogenic processes (depends on the nature and origin of the parent substances) and through anthropogenic activities. Anthropogenic processes, primarily involve manufacturing activities and the disposal of industrial and municipal waste materials and these are the major source of lead contamination of environment (Adriano 2001). Foremost important sources of lead enrichment in the environment are presented in Fig. 2.

3 Ecotoxicology of Lead

Lead is one of the earliest metals discovered by the human and its distinctive nature, such as pliability, ductility, higher malleability, low melting point and corrosion resistant, make its widespread usages in numerous industrial process (colour-paint, automobiles, plastics, and ceramics). The key cause for long-lasting persistence of lead in the ecosystem is due to its non-biodegradable character; consequently it has led to a manifold quantity of free lead in the environment and living beings. Lead is considered as a powerful/potent occupational pollutant and its toxicological

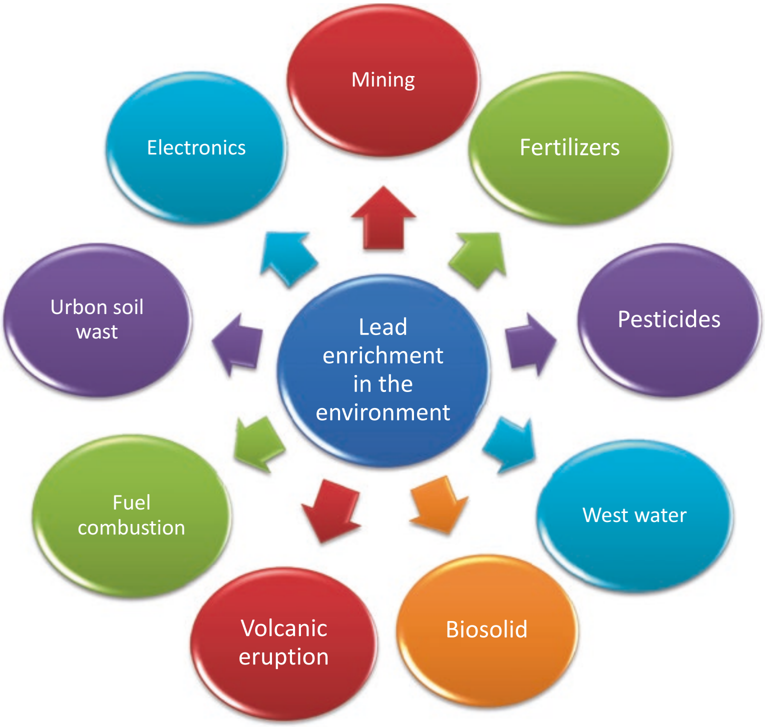

Fig. 2 Various sources of lead enrichment in the environment

manifestations are very well recognized. Lead poisoning has been documented as a major public and community health peril for the most part in developing countries of the world. Nevertheless, a variety of community health and occupational approaches have been taken on in order to control and regulate the lead toxicity, many more cases of lead poisoning are yet to be accounted (Flora et al. 2012). Diverse sources together with industrial activities including smelting of lead and coal burning, colour-paints containing lead, pipes having lead or lead based soldering in water supplying system, recycling of batteries, bearings and grids, lead-based gasoline, etc. are the reasons for human exposure to lead. Though lead toxicity is a decidedly explored and meticulously published topic, full control and preclusion concerning on exposure to lead is yet far from being accomplished. Lead is a non-essential element and has no advantage on to the biological systems and no "safe" level of exposure to lead has been reported. There is even no such concentration of lead is reported to found essential for it to require by living beings and toxicity of lead have been reported as specific menacing hazard with the potential of causing irreversible health consequences. Lead moves into and throughout the ecosystem and creates toxic effects on the microorganism and all living organisms. It is a highly toxic heavy metal that affects human beings, animals, plants and phytoplankton by incorporating into food chain (Truhaut 1977; Chapman 2002; Huang et al. 2011; Singh et al. 2012).

3.1 Effects of Lead on Living Beings and Human Health

No function of lead is known for biological systems, likewise it causes many irreversible health problems once it taken up in the tissues of living systems. Lead toxicity in the environment is an ancient and continual community health concern for all the countries of the world. All the important organs such as hematopoietic, renal, nervous and cardiovascular systems are affected by lead toxicity. Oxidative stress has been reported as pronounced and severe effect of lead toxicity. Biomolecules such as enzymes, proteins, membrane lipids and DNA are damaged by excess lead toxicity which is responsible for generating ROS that impairs the antioxidant defence system (Fig. 3) (Flora et al. 2012; Inouhe et al. 2015). All the way through the evolutionary process lead incorporates into the tissues of living organisms and thus has

Fig. 3 Possible mechanisms of lead toxicity on human health

become crucial element. Lead particles may enter into residential houses through windows, shoes, air, and so on (Patel et al. 2006). Improvement of technology over the time has appreciably decreased the discharge of lead but still conditions at local sites may be present causing a potential risk due to exposure in surrounding environment. Children are more susceptible to lead toxicity because of their activities of hand to mouth, high rates of respiration and additional absorption by gastrointestinal systems per unit body weight. For certain at-risk groups of children lead toxicity continues to be an main community health issue and impacts of lead on intellectual development has been remained a major concern forever (Ahamed and Siddiqui 2007). Lead affects the nervous system of vertebrates and cause diseases in fingers, wrists or ankles. Accumulation of lead in invertebrates above a particular level becomes toxic to their predators. Elevated blood levels of lead just >10 μg dL^{-1} cause anaemia in children (Tiwari et al. 2013). Two types of anaemia reported, haemolytic anaemia and frank anaemia due to lead poisoning effect on the enzyme δ-aminolevulinic acid dehydrates (ALAD), aminolevulinic acid synthetase (ALAS), ferrochelatase involved in haem synthesis but mainly affects the cytosolic enzyme ALAD. Lead nitrate induce the rate-limiting enzyme ALA synthetase (S-aminolevulinic acid synthetase) of the haem biosynthesis at the post transcriptional level (Kusell et al. 1978). Lead exposure had decreased the permanency of the spermatozoa and reduced secretory function of the accessory genital glands (Wildt et al. 1977). Nutrients factors or deficiency (some vitamins and essential elements) affects the susceptibility to lead toxicity (Ahamed et al. 2005). Renal effects of Pb poisoning (>60 μg dL^{-1}) causes Fanconi's syndrome which is represented by the combined excretion of phosphates, glucose and amino acids at an abnormal rate. It also affects the ROS production and antioxidant defence, causing cell death due to oxidative stress (Gupta et al. 2009; Flora et al. 2012). A variety of immune responses such as differentiation of B cell, MHC class II molecule on the surface of B lymphocytes' increased expression, lymphocyte proliferation, inhibition and targeted first suppressor T cell and then Th cells are the poisonous effects of lead. Lead also affects the nuclear factor-kb, CD 4, natural killer cells (NKC) and nitric oxide (Singh et al. 2003). Lead may cause cytotoxicity and genotoxicity, which can be determined through histopathology, proteomics and cell growth (Pan et al. 2010).

3.2 *Effect of Lead on Microorganisms*

Elevated level of lead near smelter decrease the microorganism population and inhibited the germination of fungal spore and mycelium growth (Bisessar 1981). Lead toxicity turn into inhibited cell division, protein denaturation, cell membrane disruption, inhibition of enzyme activity, translation inhibition and transcription inhibition by damaging of DNA (Yadav et al. 2017). Pb caused short term (<24 h, 5 mg L^{-1}) and long term impact on microorganisms. After long term lead exposure on sludge bacterial viability decreased linearly (Yuan et al. 2015). E-waste recycling sites produce different lead contaminants that effects the soil microorganisms by decrease biomass, enzyme activity (covalently bind with –SH, –OH, –COOH, –NH_2 group on active site of enzymes) and enhance soil basal respiration, metabolic quotient (Zhang et al. 2016). Lead affects the algae by inhibiting growth and primary metabolite accumulation (Piotrowska et al. 2015). Lead accumulations in zooplankton were lower than in bacteria and in phytoplankton (Rossi and Jamet 2008).

3.3 *Effects of Lead on Ecosystem*

Industrial fine particles are toxic for ecosystem (Schreck et al. 2011). Lead stored in the O horizon of soil in forest floor from input deposition of alkyl-lead additives gasoline due to this lead release in the mineral soil or surface water from forest floor with high concentration threat to water quality in ecosystem (Johnson et al. 1995). Acute/chronic toxicity concentration or threshold concentration of dissolved lead in fresh water ecosystem is calculated between 6.3 mg dissolved Pb L^{-1} and 31.1 mg dissolved Pb L^{-1}. It is influenced by many reported factors effects of pH, alkalinity, dissolved organic carbon and concentration of Mg and Ca cations in aquatic toxicity of lead at EU scenarios (Sprang et al. 2016). Some widely used applications like UV coating, polishers and paints used Meo and NPs species that release cerium oxide (CeO_2NPs) which deposit on aquatic sediments and therefore making potential risk of lead in aquatic ecosystem (Wang et al. 2018). Lead toxicity affects aquatic organisms such as blackening in the tail and spinal deformity (Singh et al. 2012). Some physiological and biochemical changes have also been reported in hydrophytes such as water hyacinth (Malar et al. 2014).

3.4 *Ecotoxicology of Pb-210*

Pb-210 is the most important to study in relation to its behaviour in soils and plants. Short-lived progeny of radon decay gives rise to ^{210}Pb. This radioactive isotope exhibits the chemical characteristics of lead because it has sufficient time to decay, which results in the production of Po-210 which tends to be mobile in the substratum. The most common redox state encountered in the environment is the divalent form of lead, out of the three known oxidation states, 0, +2 and +4. Lead is found adsorbed on the surface of oxides, hydroxides, oxyhydroxides, clays and organic matter. The adsorption is highly associated with the cation exchange capacity of and pH of the soils. Phosphate, chloride, and carbonate and other soil constituents affect lead reactions in the soils by precipitation and reducing adsorption due to ligand forming (Mitchell et al. 2013). Pb-210 produced in the atmosphere from ^{222}Rn and this phenomenon increases the concentration of ^{210}Pb with decrease in Ra-226. Pb-210 will decay to give rise ^{210}Po (Sheppard et al. 2008). A major contributing way to plant uptake of ^{210}Pb is aggregating from surrounding atmosphere (Ham et al. 2001). Po-210 to Pb-210 equilibrium studies established the trail of ^{210}Pb settling. Po-210 to Pb-210 ratios less than 1 demonstrate inadequate time for ^{210}Po to equilibrate subsequent uptake by plants. The ratio for shoots was found to be between 0.35 and 0.72 during a study (Pietrzak-Fils and Skowronska-Smolak 1995). Canadian annual plants showed a median value of 0.6 (Sheppard et al. 2004, 2008). Relative concentrations of radionuclides in the medium, individual Fv values, rate of deposition of radionuclides on the shoots from atmosphere and further withholding determined the ratio. Higher Pb-210 Fv values were noticed relative to stable lead due to atmospheric deposition (Sheppard et al. 2004). In contrast, an excess of ^{210}Po over ^{210}Pb was observed in wild berries from a boreal ecosystem (Vaaramaa et al. 2009). To look into phytoremediation of lead a vibrant model developed that gave a mechanism of lead behaviour within soil–plant system (Brennan and Shelley 1999). Limited studies are available for radio-ecological research (Hovmand et al. 2009; Sheppard et al. 2008; Vaaramaa et al. 2009). Atmospheric settling of ^{210}Pb was found the major route under a study when uptake under covered tent was compared to that in open field (Pietrzak-Fils and Skowronska-Smolak 1995). The effects of soil texture on transfer were the highest when plants were grown on sandy soils. There were few noteworthy differences between crop groups, and no correlations were found between numerous soil characteristics (cation exchange capacity, pH, clay and organic matter) and the Fv values for the crop sets. Significant dissimilarity was noticed in Fv values among soil types for leafy vegetables, root crops and tubers (Vandenhove et al. 2009). The Fv value may be increased up to 20-fold from atmospheric settlement of ^{210}Pb (straw of cereals, grasses and vegetables) (Vandenhove et al. 2009). The accumulation of lead and other radionuclides in spring wheat exhibited the following relationship: root > stem > grain (Nan and Cheng 2001), while the beet of red beet had a lower value than the leaves (Pietrzak-Fils and Skowronska-Smolak 1995). On the other hand, in beans ^{210}Pb was largely absorbed and held in the roots without translocation to aerial plant parts (D'Souza and Mistry 1970). Red kidney bean showed that 100% was retained by the leaf with an application of ^{210}Pb as nitrate to the leaves. This has been known as immobile isotope and trapped at the sites of applications (Athalye and Mistry 1972). Type of the plant and part of the plants plays important role for plant ^{210}Pb content (Pietrzak-Fils and Skowronska-Smolak 1995). In crops grown under ordinary field conditions, washing may take away about 10% of plant radioactivity; radioactivity values were found 6–10-fold high in plants grown in the open in contrast to crops kept in the cover-up tents. During dry time radioactivity of ^{210}Pb on plant leaves was found at climax, while during wet times it was observed to be decreased and attributed that during wet of aerosols wash-off from the surface of the leaves (Sugihara et al. 2008; Mitchell et al. 2013). Transfer factors of ^{210}Pb from contaminated soil in oil fields located in a semiarid area to some pasture species were determined and it was found that uptake of ^{210}Pb from soil to plants increased with the time of the first planting. Among the studied plants *Medicago sativa* (alfalfa) and Bermuda grass were found to have the highest transfer factor (Al-Masri et al. 2014). In *Typha latifolia* L. in a study conducted in an environment with a higher quantities of radionuclides and heavy metals, many structural alterations; synthesis and presence of numerous antistress substances (anthocyanin, ferritin, etc.) as well as the occurrence of various exogenous particles in the epidermal and parenchyma cells were observed (Corneanu et al. 2014).

4 Remediation Techniques of Lead

The method in which contaminants from soils, water and air are removed is known as remediation**.** Heavy metal such as lead is one of the most dangerous contaminant. Electrokinetic remediation (EKR) uses many electrolytes to bind contaminants and make them immobile in soil by the influence on soil conductivity ($H^+$and Fe^{2+}) and current by replaced soil ions from EKR ions (e.g., KNO_3, $NaNO_3$, Na_2CO_3, K_2HPO_4, KH_2PO_4, sodium acetate acid (NaAc), H^+, EDTA, Na/HAc, citric acid, Tris–acetate-starch, ammonium, nitrate, lithium lactate, $MgSO_4$, and NH_4NO_3) (Li et al. 2014).

4.1 Conventional Remediation Techniques

In situ vitrification, excavation and landfill, soil incineration–washing–flushing–reburial, solidification, stabilization of electrokinetic system, pump and treat system, ion exchange chemical precipitation, ultrafiltration, adsorption, electrodialysis, flocculation, and so on are mostly used decontamination methods for metal polluted sites; out of these, ion exchange, adsorption, ultrafiltration, chemical precipitation, electrodialysis, and flocculation are more useful for lead removal.

Chemical precipitation: Coagulants such as lime, alum and iron salt are used for precipitation of metal ions.

Ion exchange: Electrostatic force on ion exchange in a dilute solution is applied.

Adsorption: A molecular or atomic film is formed by accumulation of gas or liquid solutes on the surface of an adsorbent.

Ultrafiltration: It is used to remove heavy metal ions; 0.1–0.001 micron pore size membrane used in ultrafiltration.

Eletrodialysis: This method is applied when separation of cations and anions through electrical potential to remove metal ions by the use of semipermeable ion selective membranes.

Flocculation: This method makes flocs in water using a coagulant to attract suspended metal ions by these flocs (Yadav et al. 2017).

These methods have a threat of releasing potentially dangerous metals into the environment as well as unsafe, high-priced and inadequate.

4.2 Bioremediation Techniques

Use of microbes and green plants for clean-up purposes is therefore, a promising solution for onslaught of heavy metal polluted sites in view of the fact that they comprise sustainable ways of repairing and re-establishing the natural status of soil and environment. The employment of primarily microbes, to clean up contaminated soils, aquifers, sludge, residues and air, termed as “bioremediation”, is a rapidly changing and expanding branch of environmental biotechnology that offers a potentially more effective and economical clean up method. The use of microorganisms to control and destroy toxic substances is of growing attention to minimize a number of pollution issues. Bacteria, algae, fungi and yeast and some other microbes have been found to absorb and break down many metal compounds (Dixit 2015). Green plants may be used to remove effluents and contamination from soil. This may be called as "phytoremediation" (Jagetiya et al. 2011, 2014; Gupta et al. 2013a, b).

4.2.1 Remediation of Lead by Bacteria

Many bacterial species accumulate lead from polluted soil and water system by the process of bioaccumulation and bio-sorption through active and passive process. To survive in the toxic environment these species develop resistance to toxicity of heavy metals. Some potential bacterial species being used for lead remediation are listed in Table 1.

4.2.2 Remediation of Lead by Algae

Algae remove lead by the process of chemisorption in which metal ion transport into cytoplasm and physical adsorption in which ion adsorbed over the surface quickly (Dwivedi 2012). The mechanism of remediation depends on anatomy of algae and environmental conditions in growing medium (Yadav et al. 2017). In recent years many researchers have used various algal species for removal of lead from contaminated sites (Table 2).

4.2.3 Remediation of Lead by Fungi

Comparatively fungi are the good alternative for removal of heavy metal from the environment and more tolerant to heavy metals than the bacterial species (Rajapaksha 2004). Some fungi work as hyper-accumulator of heavy metals (Purvis and Halls

Table 1 Some bacterial species with potential of Pb bioremediation.

Bacterial species	References
Bacillus firmus	Salehizadeh and Shojaosadati (2003)
Bacillus licheniformis	Basha and Rajaganesh (2014)
Corynebacterium glutamicum	Choi and Yun (2004)
Escherichia Coli	Basha and Rajaganesh (2014)
Pseudomonas aeruginosa	Lin and Lai (2006)
Pseudomonas fluorescens	Basha and Rajaganesh (2014)
Pseudomonas putida	Uslu and Tanyol (2006)
Salmonella typhi	Basha and Rajaganesh (2014)

Table 2 Some algal species with potential of Pb bioremediation

Algae species	References
Ascophyllum nodosum	Holan and Volesky (1994)
Chlorella vulgaris	Aung et al. (2012); Edris et al. (2012)
Cladophora fascicularis	Deng et al. (2007)
Cladophora glomerata	Dwivedi et al. (2012)
Oedogonium rivulare	Dwivedi et al. (2012)
Oscillatoria quadripunctulata	Rana et al. (2013); Azizi et al. (2012)
Oscillatoria tenuis	Ajavan et al. (2011)
Sargassum natans	Holan and Volesky (1994)
Sargassum vulgare	Holan and Volesky (1994)
Spirogyra hyalina	Kumar and Oommen (2012)

Table 3 Some fungal species with potential of lead bioremediation

Fungal species	References
Aspergillus niger	Kapoor et al. (1999)
Aspergillus flavus	Dwivedi et al. (2012)
Aspergillus terreus	Joshi et al. (2011); Massaccesi et al. (2002)
Mucor rouxii	Yan and Viraraghavan (2001)
Saccharomyces cerevisiae	Damodaran et al. (2011)
Saprolegnia delica	Ali and Hashem (2007)
Trichoderma viride	Ali and Hashem (2007)

1996). Cell wall lipids, carbohydrates and proteins bind with the metals (Veglio and Beolchini 1997; Beolchini 2006). Potential fungal species used for lead remediation are given in Table 3.

4.2.4 Phytoremediation (Green Technology)

When conventional remediation methods are unfeasible due to the extent of the polluted region or cost and safety issues, phytoremediation is advantageous (Garbisu and Alkorta 2003). Phytoremediation involves different methods where green plants efficiently decontaminate polluted sites at relatively low cost and good public acceptance. Phytoremediation is an aesthetically pleasing, safer and non-destructive, sustainable technology which has commercial acceptability (Sheoran et al. 2011). In this modern technology accumulation power of plants is used to detoxify essential and non-essential heavy metals from contaminated soils (Djingova and Kuleff 2000). Some most important families of plant that have been identified to accumulate heavy metals are Fabaceae, Euphorbiaceae, Asteraceae, Brassicaceae, Lamiaceae and Scrophulariaceae and mangrove plants (Lacerda 1998). Plants used in phytoremediation accumulate toxic heavy metal in varied concentrations at same

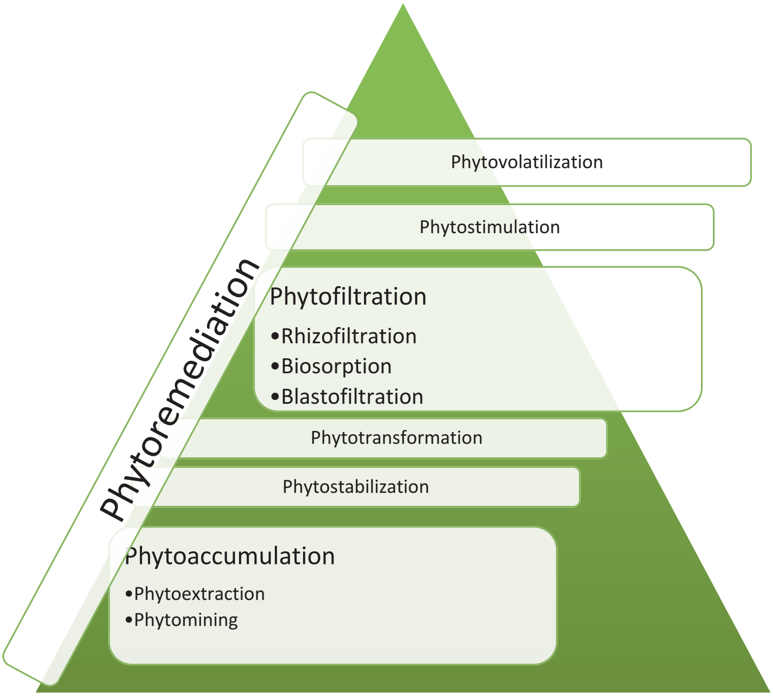

Fig. 4 Various methods of phytoremediation

contaminated site and some plant work as hyper accumulators that absorb 100-fold greater amount than those of non-accumulator plants of heavy metals (Peer et al. 2005). Toxic heavy metals from underground water, dregs, top soil, and brown fields can be removed by various methods of phytoremediation (Fig. 4). Reported values of conventional remediation technologies are always higher than the phytoremedial techniques which is commercially applicable and having all adequate possibilities to be applied successfully. Mostly around the world phytoremediation studies are confined only to the organic chemistry and bio-agro processes. However, individual monetary and financial analysis for this process is largely unavailable (Ali et al. 2013). Economics of phytoremediation consists of two types of costs, that is, initial capital and running or operational costs. The mandatory materials involved in initial capital may be pollution analysis and preliminary testing, planning and setting up of decontamination or removal tactics, preparation of soil, nursery tools (quantitative) procurement, creation of storing facility, irrigation facility, incineration utensils and apparatus, road construction, bridge construction, and drain facility. Operational cost mostly have the cost of ploughing, seedling, plantation programmes, irrigation, fertilizers-pesticides-insecticides-herbicides purchase and application, produce harvesting with a number of less considerable things. Benefit of cost includes both of benefits during remediation and after remediation. Therefore, phytoremediation

Table 4 Some higher plant species with potential of Pb phytoremediation

Plant species	References
Alyssum lesbiacum	Baker et al. (1991)
Alyssum murale	Baker et al. (1991)
Ambrosia artemisiifolia	Huang and Cunningham (1996)
Arabidopsis thaliana	Baker et al. (1991)
Astragalus bisulcatus	Baker et al. (1991)
Brassica juncea	Kumar et al. (2002)
Brassica oleracea	Baker et al. (1991)
Euphorbia cheiradenia	Chehregani and Malayeri (2007)
Jatropha curcas	Abhilash et al. (2009); Jamil et al. (2009)
Populus deltoides	Ruttens et al. (2011)
Populus nigra	Ruttens et al. (2011)
Populus trichocarpa	Ruttens et al. (2011)
Raphanus sativus	Baker et al. (1991)
Thlaspi caerulescens	Baker et al. (1991)
Trifolium alexandrinum	Ali et al. (2012)
Zea mays	Huang and Cunningham (1996); Meers et al. (2010)

technology is price efficient compared to conventional remediation technologies (Wan et al. 2016). Some potential plant species used for lead phytoremediation are listed in Table 4.

Phytoaccumulation

Translocation and uptake of metal from contaminated soil or water by plant root and accumulation in above ground biomass is the basic concept of phytoaccumulation and this has been described in literature as many other terms such as phytoabsorption, phytoextraction and phytosequestration (Chou et al. 2005; Eapen et al. 2006; Singh et al. 2009). Metal accumulation in shoot is an effective biochemical process (Zacchini et al. 2011). Natural/continuous or induced (driven by chelators) are the two techniques of phytoextraction (Hseu et al. 2013). Certain plants work as hyperaccumulators because of having 100 times more absorbing power (Table. 5). In *Zea mays,* which is a high biomass crop, can accumulate higher lead in shoots than in roots (Brennan and Shelley 1999; Gupta et al. 2009) whereas, plants such as *Thalspi rotundifolium* are low biomass plants can hoard lead higher in roots than shoots. For better performance plant should have stumpy growth rate, elevated production of biomass, property of hyper-accumulation of metals or contamination to be removed, branched roots, higher root to shoot translocation of heavy metals, high tolerance and adaptability, pests and pathogen resistance, easy to cultivate and harvest (Adesodun et al. 2010; Sakakibara et al. 2011). Phytomining is a type of phytoextraction that involves extracting of heavy

Table 5 Hyperaccumulator plant species for phytoextraction of lead

Plant	Family	References
Arabis paniculata	Brassicaceae	Tang et al. (2009)
Noea mucronata	Amaranthaceae	Chehregani et al. (2009)
Baccharis latifolia	Asteraceae	Bech et al. (2012)
Onchus oleraceus	Asteraceae	Bech et al. (2012)
Bidens triplinervia	Asteraceae	Bech et al. (2012)
Brassica juncea	Brassicaceae	Zaier et al. (2010)
Buckwheat	Polygonaceae	Chen et al. (2004)
Cynara cardunculus	Asteraceae	Epelde et al. (2009)
Helianthus annuus	Helianthoideae	Chen et al. (2004)
Hemidesmus indicus	Apocynaceae	Sekhar et al. (2005)
Lepidium bipinnatifidum	Brassicaceae	Bech et al. (2012)
Indian mustard	Brassicaceae	Chen et al. (2004)
Poa pratensis	Poaceae	He et al. (2009)
Pisum sativum	Fabaceae	Chen et al. (2004)
Plantago orbignyana	Plantaginaceae	Bech et al. (2012)
Sedum alfredii	Crassulaceae	Gupta et al. (2010)
Sesuvium portulacastrum	Aizoaceae	Bech et al. (2012)
Sonchus oleraceus	Asteraceae	Xiong (1997)
Tagetes minuta L.	Asteraceae	Salazar and Pignata (2014)
Thlaspi rotundifolium	Brassicaceae	Reeves and Brooks (1983)
Zea mays	Poaceae	Huang and Cunningham (1996)
Phaseolus vulgaris	Fabaceae	Luo et al. (2005)
Raphanus sativus	Brassicaceae	Chen et al. (2003)

metal from substratum, harvesting the plant produce and burning it for bio-ore (recovery of heavy metals) using specialist hyperaccumulator plant species (Ali et al. 2017; Ha et al. 2011). Phytomining gives precious metals, biofuel as well as increased soil nutrients and soil carbon contents (Brooks and Robinson 1998). Metal concentrations in the substratum and plant system, yearly productivity of plants, the biomass combustion energy and cost of recovered metal at international level influence the economics of phytomining (Brooks and Robinson 1998). Some biogeochemical factors viz. rhizobiological activity, exudates release, extended time, temperature, pH, damping of soil are some of the rate limiting factors for phytomining (Ali et al. 2013; Bhargava and Srivastava 2014). It is very difficult to remove lead once lead introduced into the soil matrix. Enhanced uptake of lead from the soil medium was observed at increased pH value, cation exchange capacity; soil/water Eh, content of organic carbon and phosphate levels (USEPA 1992). A model suggests that precipitation of lead as Pb-phoshate and effective roots mass are important factors for uptake and accumulation of lead into the plants (Brennan and Shelley 1999). Lead accumulation was highest in *Agrostemma githago* which is an herbaceous plant species, some of which produce enough biomass to be of practical use for phytoextraction of lead (Pichtel et al. 2000). *T. officinale* and *Ambrosia artemisiifolia* were reported as lead accumulator species in a study (Pichtel et al. 2000). Many members of families Brassicaceae, Euphorbiaceae, Asteraceae, Lamiaceae, and Scrophulariaceae were recognized as good accumulator of lead (Alkorta et al. 2004). Good amount of lead translocation from roots to the shoots is a well-known ability of *Brassica juncea* (Liu et al. 2000). In lead polluted soils *T. rotundifolium* has also been found to grow. Low metal bioavailability is the key reason limiting the potential of plant uptake for lead phytoextraction. Synthetic or natural chelators have been suggested to be mixed to the farm soil to trounce the said restraints (USEPA 2000a, 2000b). *Sesbania drummondii* accumulates up to 10,000 mg Pb kg^{-1} in aerial parts after exposure to a Pb-contaminated solution in hydroponic conditions (Sahi et al. 2002). Uptake of lead was found to increase by 21% after addition of EDTA (100 μM) to a medium containing 1 g Pb^{-1}. *Nicotiana glauca* R. Graham (shrub tobacco) a genetically modified variety has enormous ability to uptake lead, and found useful phytoremediation programmes (Gisbert et al. 2003). A protein (NtCBP4) that can alter plant tolerance to heavy metals was discovered by Arazi et al. (1999). For enhanced phytoremediation this gene may be valuable. Superior tolerance to nickel and hypersensitivity to lead, which are associated with inhibited nickel uptake and improved lead accumulation, respectively has been demonstrated in many separate transgenic lines expressing higher NtCBP4 gene (Arazi et al. 1999).

Phytostabilization (Phytoimmobilization)

In this technique plants reduce the mobility and migration of contaminants to soil, groundwater and food chain or stabilization the contaminants in contaminated soil through sorption, precipitation, accumulation and absorption by root (Erakhrumen 2007; Wuana and Okieimen 2011; Singh et al. 2012). Leachable constituents of contaminated environment make up a stable mass by absorption and binding around the plant system out of which the toxic pollutants cannot release in the surrounding environment. It is a management strategy only and cannot be a permanent solution for clean up contaminated sites (Vangronsveld et al. 2009). *Chrysopogon zizanioides* (vetiver grass) is an excellent option for phytostabilization, a method in which plants are used for the immobilization of pollutants in situ because it has ability to accumulate large concentrations of lead (Wilde et al. 2005) (Table 5). A small portion is transferred into the shoots while the majority of lead accumulated in the roots of vetiver grass. The solutions in the intercellular spaces in the roots have higher pH and comparatively higher levels of and carbonate-bicarbonates and phosphate; consequently accumulated lead is precipitated in the forms of phosphates/carbonates and prohibits translocation of lead in to the aerial parts (Danh et al. 2009, 2012). Extraordinary higher concentrations of lead are accumulated in the biomass of vetiver and can accumulate lead at least 1000 mg kg^{-1} DW. Vetiver can uptake over 10,000 and 3000 mg kg^{-1} Pb in roots and shoots, respectively, and accumulation of lead depends on the bioavailability of lead (Antiochia et al. 2007; Andra et al. 2009). Among many chelators, EDTA has been proved to be the most useful in the translocation of lead and a noteworthy increase of lead values in biomass of vetiver was observed when EDTA was applied in lead polluted medium (Danh et al. 2009, 2012).

Phytotransformation

Phytodegradation/phytotranformation refers to the mobilization and degradation of organic contaminants taken up by plants from soil and water and subsequently breaking down of pollutants at outside environment by various enzymes (dehalogenase and oxygenase) released by the plant systems. The characteristics of plants as well as the properties of the contaminants (solubility, hydrophobicity, polarity, etc.) affect the uptake of toxicants. Phytotransformation is independent from the activities of microorganisms that present around root and in rhizosphere (Vishnoi and Srivastava 2008). The limitation of this technique is that it can be used for removal of heavy metal only, due to non-biodegradable nature of heavy metals. To short out this problem some synthetic herbicides, insecticides and transgenic plants are used by researchers recently (Doty 2008).

Phytofiltration

During this operation movement of toxic substances into underground waters is minimized through absorption or adsorption of contaminants. It is the elimination of contaminants from polluted water reservoirs or wastewaters using plant systems. On the basis of application of plant organs, phytofiltration has been classified as blast filtration when seedlings are in use; caulofiltration when plant shoots are in use and rhizofiltration when plant roots are in use (Ali et al. 2013). Contaminants in the soil solution adjacent the zone of roots are adsorbed or precipitated on roots or assimilation of these pollutants into the plant roots keep ongoing during the process of rhizofiltration. The plants to be made use for this intention are grown in green houses allowed to grow their roots rather in water in place of soil substratum. Once an outsized root system built up; from the polluted sites tainted water is collected and poured at these acclimatized plants for their water requirement. Root systems of plants growing in the contaminated region started to take up the contaminants along water. Saturated roots are used for the recovery of contaminants after harvesting and incinerated or composted (Singh et al. 2009; Pratas et al. 2012; Jagetiya et al. 2014)

Phytostimulation or Rhizodegradation

It is the breaking up of toxicants and pollutants in soil through microbes present in the rhizosphere. This phenomenon is also termed as plant-assisted bioremediation/degradation or improved rhizosphere biodegradation (Mukhopadhyay and Maiti 2010) and always works at slow rates than phytodegradation. Plant roots secretes many natural biological compounds including sugars, alcohols, amino acids, and flavonoids. which provides nitrogen and carbon for rhizosphere microbes, and makes a nutrient affluent situation. Organic substances like solvents or petroleum fuel that is hazardous to living beings may be digested by various microbial species and they may breakdown these into nontoxic products through biodegradation. A large number of microbial species have been reported that have the ability to facilitate the oxidation of Fe^{2+} to Fe^{3+} (Jagetiya and Sharma 2009; Jagetiya et al. 2014).

Phytovolatilization

For removal of organic contaminants and volatile heavy metals such as Se and Hg, phytovolatilization is a preferred solution. Plants take up the contaminants from the environment and convert these into volatile form or a modified form with release into the atmosphere during transpiration. This process does not take away the contaminants thoroughly for that reason there are chances of re-deposition are always there (Ali et al. 2013).

5 Bioavailability of Lead

Bioavailability represents the amount of an element or compound available in soil system that is approachable to uptake by plant across its plasma membrane. Process in which plant absorb contaminants from soil through physiological membrane involve following four steps:

1. Solid-bound contaminant
2. Subsequent transport
3. Transport of bound contaminants (symplast/apoplast)
4. Uptake across a physiological membrane

Bioavailability of lead depends on physic-chemical properties of soil and activity of soil micro-and macro-organisms. Soil pH, ion exchange capacity, texture, porosity, age, adsorption capacity and environmental condition influence bioavailability of lead. Absorption efficiency or bioavailability of metal can be increased in soil by using some chelators consequently it facilitates the process of uptake of metals by plants. Stabilization of lead in contaminated soils can be achieved by adding phosphorus that reduces bioavailability (Chen et al. 2006). Lime and red mud also decrease lead availability to plants (Garau et al. 2007). Temperature also affect the bioavailability of lead, it is higher in warm than in cold environment (Hooda and Lloway 1993). Size and composition of lead particles affects the lead bioavailability to the plants (Walraven et al. 2015). Bone char addition in soil decreases the availability of lead. Free ionic form of lead (Pb^{2+}) is the largely bio-available and most toxic form which is present in the water whereas, chlorides, carbonates, and lead-organic matter complexes in fresh water or marine are other forms readily available to plants. Glomalin protein that is produced by AM fungi is binds mainly with lead in soil and reduces its bioavailability (Vodnik et al. 2008). Bio-surfactants (e.g. Di-rhamnolipid from *Pseudomonas aeruginosa*) or surfactants (e.g. DPC, DDAC, SDS and Gemini) facilitate the bioavailability process of lead in soil without effecting soil microorganisms and soil structure (Juwarkar et al. 2007; Mao et al. 2015). In some methods like sequential extraction, X-ray diffraction analysis, bioassay (Chen et al. 2006), and sorption processes, lead stabilization can be followed to examine the bioavailability of lead (Kumpiene et al. 2008). Bioavailability of lead can also be determined by bioluminescent bacterial reporter strains (Magrisso et al. 2009).

6 Lead: Uptake, Translocation and Accumulation

Uptake, translocation and accumulation of lead involve absorption of lead from soil into the plants and further transport into the xylem and phloem of plant systems (Dalvi and Bhalerao 2013). After accumulation of lead in roots the primary bulk flow of lead occurs into the xylem and the secondary bulk flow of lead occurs into the phloem (Marschner 1986; Mengel and Kirkby 1987). Uptake and transport of metal ion through root surface to vascular system is passive (pores of cell wall) or active (symplast). In this process metal ion and different special plasma membrane protein bind each other according to their analogous structure for transportation. Model plant *Arabidopsis thaliana* has 150 different cation transporter proteins. For example in *Thalspi rotundifolium* (lower biomass plant) can accumulate more lead in the roots than the shoots. In *Zea mays* (higher biomass plant) lead can move efficiently into shoots. To overcome this problem, soil amendments are performed (addition of chelators) to increase bioavailability of lead (Brennan and Shelley 1999). Heavy metals sequestration usually takes place in the vacuoles of the plant cells, where the metal/metal-ligand have to be brought across the tonoplast, the membrane of the vacuoles (Peer et al. 2005; Jagetiya and Sharma 2013).

7 Phytoremediation of Lead: Future Prospects

Phytoremediation is used for clean up toxic contaminants from environment with little environmental disturbance and good public perception. It has some limitations such as this process is very time consuming and toxic substances are accumulated in lower quantity which does not give large scale production in short time (Liu et al. 2000; Tangahu et al. 2011; Fukuda et al. 2014; Ali et al. 2017). To overcome this problem use of chelators that are biodegradable may enhances the process of phytoextraction as well as use of fast growing and hyperaccumulator-high biomass plants is recommended (Tandy et al. 2006; Evangelou et al. 2007). Advancement in molecular biology and genetic engineering can be make use to prepare genetically modify crops and transgenic plants that will helpful in further improvement in efficiency of phytoremediation (Tong et al. 2004; Ali et al. 2013). Many plant cultivars like

Cynodon dactylon, Vetiveria zizanioides, Festuca rubra and *Typha latifolia* are highly tolerant to temperature, flood, drought and toxic metals have been used recently. Vetiver grass (*Vetiveria zizanioides*) has reported to exhibit as a fine plant in phytoremediation of lead in china (Oh et al. 2014). In order to develop commercially and economically viable practices we need to optimize the agronomical systems, plant–microbe combinations in better way as well as plant genetic abilities (Jagetiya and Sharma 2009; Jagetiya et al. 2014). Genetic transformation of plant will help to overcome the limitation of this green technology through integrating some alien gene in plants for transporter proteins of metals, biosynthesis of enzymes required for sulphur metabolism (Kotrba et al. 2009). These modifications may enhance tolerance, uptake rate, detoxification capabilities of plants and biodegradation competence of microorganisms. Production of genetically modified plant can be successfully employed to promote some processes such as phytoextraction of metals (mainly Cd, Pb, Cu), breakdown of explosives and removal of carbon tetrachloride, vinyl chloride, benzene and chloroform (toxic volatile organic pollutants). These contaminants may be partially metabolized inside the plant tissues through “green liver” concept which involves three different steps, activation, conjugation and sequestration. A family of many enzymes normally involved in the metabolism of lethal and deadly contaminants has been recognized in *Populus angustifolia*. Enhanced heavy metal accumulation capability is proved in *Nicotiana tabacum* and *Silene cucubalus* (Fulekar et al. 2009). Advanced genetic strategies, use of transgenic plants and microbe will be able to contribute to the safer and wider applications of phytoremediation (Pence et al. 2000; Krämer and Chardonnens 2001; Ali et al. 2013; Jagetiya and Porwal 2019).

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