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Phytoremediation: A Tool for Environmental Sustainability

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Abstract

Environment is a very significant and essential part for the survival of both man and other biotic organisms. The existence as well as security of the entire components is primarily based on the conservation of the physical environment. Due to industrial revolution, pollution in the environment has amplified enormously. Rise in population also causes strain on the environment with many commercial activities such as logging and mining. In fact, the elimination of harmful pollutants with any known method is just not sufficient. Therefore, the best practice for maintaining ecological balance is to use all the wastes in a recyclable manner which will assist the biotic and abiotic components to maintain visually attractive as well as healthy and perfect environment.

A novel holistic approach for “sustainable phytoremediation” or “phytomanagement,” is nowadays being recommended where economically as well as ecologically precious, natural colonizer species are being utilized for the remediation of contaminated sites, instead of introduced species. There is a broad variety of naturally colonizing vegetation on contaminated as well as waste dump sites which have phytoremediation potential. Of these, certain plants are suitable for sustainable phytoremediation in terms of creating a multifunctional ecosystem. Natural vegetation on contaminated sites as well as waste dump sites is the right choice for selecting a suitable candidate for phytoremediation plans. If scientific experts can choose ecologically and socioeconomically significant plants, like aromatic and energy plants among the natural vegetation, then sustainability in phytoremediation can be achieved.

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15.1 Introduction

Earth is gradually being polluted with inorganic and organic compounds mainly due to human activities. While inorganic contaminants are present as natural elements in the Earth's crust and atmosphere, human activities like industry, mining, motorized traffic, agriculture, logging, as well as military operations promote their discharge and accumulation in the environment, which leads to toxicity (Nriagu 1979). Organic contaminants in the environment are generally man-made and xenobiotic means not usually formed or expected to be found in organisms, of which several are toxic and/or carcinogenic. Organic pollutants are produced in the environment through accidental releases like fuels or solvents, industrial activities like chemical, petrochemical, agriculture like pesticides, herbicides, and military actions like explosives, chemical weapons besides others. In fact, contaminated sites mostly possess combination of both organic and inorganic pollutants (Ensley 2000). Around 6–8 billion dollars a year is spent on environmental remediation in the US, and 25–50 billion dollars per year worldwide (Glass 1999; Tsao 2003). Most of the remediation is still being done through traditional procedures like excavation and reburial, capping, and soil washing and burning. But, new developing biological remediation procedures, like phytoremediation, are generally easy to perform and economical. Phytoremediation includes variety of technologies which utilize plants to eliminate, lessen, degrade, or immobilize environmental contaminants from soil as well as water, therefore converting polluted sites in a relatively clean, nontoxic environment. Phytoremediation is based upon natural processes in which plants detoxify inorganic as well as organic pollutants, through degradation, sequestration, or transformation (Pilon-Smits and Freeman 2006; Thakare et al. 2021; Sarma et al. 2021; Sonowal et al. 2022). The uses of plants in contamination remediation have been tested since the 1970s, and in the 1980s, the governmental and commercial sectors started recognizing the concept of phytoremediation (Lu et al. 2018). Gradually this technology has been widely explored over the years, and there are over 100 soil heavy metal remediation pilot/field projects using the phytoremediation technology that have been reported (USEPA 2016). Based on the applicability, phytoremediation techniques are subdivided into different classes (Ali et al. 2013; Khalid et al. 2017; Mahar et al. 2016; Rezania et al. 2016; Yadav et al. 2018, Prabakaran et al. 2019).

Besides their conventional role for production of food, feed, fuel, and fibers, green plants can be employed to store toxic metals as well as organic contaminants from polluted soils and water for cleanup reasons, to stop further deterioration of our surroundings and to ameliorate the damage caused through increasingly industrialized society. The utilization of plants particularly selected or produced for the restoration of contaminated land and brownfields, water purification, and even elimination of indoor or outdoor air pollutants is becoming indispensable to achieve sustainable development (Conesa et al. 2008). Plants signify better environmentally suitable and cheaper technique for site renewal in comparison to physicochemical strategies, even if the time period needed to achieve the target is mostly a restrictive factor. Plants are already remediating our environment continuously, universally, working as "green livers," even if we do not identify or see it. Trace element storing species can accumulate arsenic, cadmium, cobalt, manganese, nickel, lead, selenium, thallium, or zinc up to 100 or 1000 times more than normally stored through plants (Al-Najar et al. 2005; Behmer et al. 2005; Caille et al. 2005; Comino et al. 2005; Jiang et al. 2005; McGrath et al. 2006; Zhao et al. 2006). People have started employing plants which hyperaccumulates particular metals in remediation processes in past few decades. Contrary to it, crops with a decreased ability to store toxic metals as well as organic contaminants in edible portion should be valued to increase food security. While crop plants with increased ability to store essential minerals in simple assimilated form can assist in giving nutritious food to the fast-growing global population and enhance human welfare via well-adjusted mineral nutrition. The concept of enriching food crops with the essential minerals needed for a balanced diet is comparatively new. Like in the case of iron and zinc deficiencies which are currently the prime nutritional ailments all over the world and most of the people get it through eating plants, enhancing the iron and/or zinc concentration in crop plants could improve their health significantly. Most metals which can be hyperaccumulated are also essential nutrients, and food fortification as well as phytoremediation are therefore two sides of the same coin (White and Broadley 2005). United Nations Environment Programme proposed "phytotechnologies as ecotechnologies related with the utilization of plants to settle environmental difficulties in a crisis management through prevention of site degradation, remediation and regeneration of damaged ecosystems, regulation of environmental processes, observation and valuation of the environmental quality." Phytotechnologies utilize natural methods and can be employed for remediating damaged lands like quarries and road sides, exclusion of unnecessary nutrient loads, i.e., phytoamelioration and the cleaning of wastewater such as road runoff, municipal as well as industrial wastes, landfill leachates, stormwater, surface, and seepage water. Phytotechnologies provide effective tools and environment-friendly solutions for remediating polluted sites and water, enhancement in food chain security, as well as development of renewable energy sources, which contributes towards sustainable utilization of water and land management (Domínguez et al. 2008; Schwitzguebel et al. 2009).

15.2 Phytoremediation

The term "phytoremediation" was derived from the Greek phyto, meaning "plant," and the Latin suffix remedium, "able to cure" or "restore," by Ilya Raskin in 1994, and is employed to mention those plants which can remediate polluted medium (Vamerali et al. 2010). Phytoremediation is also known as green remediation, botanoremediation, agroremediation, or vegetative remediation and can be described as an in situ remediation approach that utilizes plants and accompanying microbiota, soil amendments, and agronomical practices to eliminate, restrict, or make environmental pollutants harmless (Cunningham and Ow 1996; Helmisaari et al. 2007; Srivastava 2016).

Phytoremediation is a novel emerging field of science and technology (Salt et al. 1998) which utilizes plants to remediate contaminated soil, groundwater as well as wastewater. Phytoremediation is described as the utilization of green plants with grasses and woody species, to eliminate, restrict, or transform environmental pollutants like heavy metals, metalloids, trace elements, organic compounds, and radioactive compounds risk-free in soil or water. This definition comprises all plant-influenced biological (Zouboulis and Katsoyiannis 2005), chemical as well as physical methods that help in the intake, compartmentalization, decomposition, and metabolism of pollutants, through plants, soil microbes, or plant and microbial interactions. Phytoremediation takes advantage of the exclusive as well as selective uptake capacity of plant root systems, along with the translocation, bioaccumulation, and pollutant accumulation/decomposition capacity of the whole plant body. Plant-dependent soil remediation schemes can be seen as biological treatment schemes with a widespread, self-expanding uptake network, the root system which increases the underground ecosystem for successive fruitful application. Phytoremediation averts excavation as well as transportation of contaminated media which decreases the danger of dispersing the pollution and has the capacity to remediate sites contaminated with several varieties of contaminants. Certain disadvantages related with phytoremediation are dependance on the growing environment needed by the plant like climate, geology, altitude, temperature, extensive operations need accessibility of agricultural tools and information; plant resistance to the contaminant influences the remediation success; pollutants accumulated in senescing tissues may be discharged back into the surroundings in particular seasons; period taken to treat sites is more than other techniques; and pollutant solubility may be enhanced which leads to more environmental degradation and the probability of leakage (Mudhoo et al. 2010).

15.3 Mechanisms of Phytoremediation

There are various methods through which plants clean or remediate polluted sites. The plants uptake pollutants via the root system which possess the key mechanisms for averting toxicity. The root system offers large surface area which absorbs and stores water and nutrients vital for growth besides other nonessential pollutants (Raskin and Ensley 2000). There are several processes through which plants can influence pollutant quantity in soil, sediments, as well as water. While, there are several similarities in some of these processes, but the categorization varies (Table 15.1). Every process affects the amount, movement, or toxicity of pollutants, as the use of phytoremediation is projected to do (USEPA 2000).

Table 15.1 Types of phytoremediation (Susarla et al. 2002)

S. no	Phytoremediation type	Pollutants treated
1.	Phytoextraction/ phytoaccumulation	Cd, Cr, Pb, Ni, Zn, and other heavy metals, Se, radionuclides; BTEX (benzene, ethyl benzene, toluene, and xylenes), pentachlorophenol, short-chained aliphatic compounds, and other organic compounds
2.	Rhizofiltration	Heavy metals, organic chemicals, and radionuclides
3.	Phytovolatilization	Chlorinated solvents (tetrachloroethane, trichloromethane and tetrachloromethane); Hg and Se
4.	Phytostabilization	Heavy metals in mine tailings ponds, phenols and chlorinated solvents (tetrachloromethane and trichloromethane)
5.	Phytodegradation/ Phyto-transformation	Munitions (DNT, HMX, nitrobenzene, nitroethane, nitromethane, nitrotoluene, picric acid, RDX, TNT), atrazine; chlorinated solvents (chloroform, carbon tetrachloride, hexachloroethane, tetrachloroethene, trichloroethene, dichloroethene, vinyl chloride, trichloroethanol, dichloroethanol, trichloroacetic acid, dichloroacetic acid, monochloroacetic acid, tetrachloromethane, trichloromethane), DDT; dichloroethene; methyl bromide; tetrabromoethene; tetrachloroethane; other chlorine and phosphorus-based pesticides; polychlorinated biphenols, other phenols, and nitriles
6.	Rhizodegradation/ Phytostimulation	Polycyclicaromatic hydrocarbons; BTEX (benzene, ethylbenzene, toluene, and xylenes); other petroleum hydrocarbons; atrazine; alachlor; polychlorinated biphenyl (PCB); tetrachloroethane, trichloroethane; and other organic compounds

15.3.1 Phytoextraction

This process is also known as phytoaccumulation, where metal pollutants in the soil are taken up through plant roots in the aerial parts of the plants. Phytoextraction is mainly utilized for the remediating polluted soils (Zhang et al. 2010). This strategy employs plants to take up, collect, as well as precipitate harmful metals from polluted soils into the aerial parts like shoots, leaves. Detection of metal hyperaccumulator species shows that plants have the capacity for eliminating metals from polluted soils (Wuana et al. 2010). A hyperaccumulator is a plant species with capacity of storing 100 times more metal in comparison to a general non-accumulating plant. Metals like Ni, Zn, and Cu are the ideal elements for elimination through phytoextraction as they are preferred by most of plants (about 400) which uptake and absorb huge quantities of metals. There are various benefits of phytoextraction. The expenses in phytoextraction are quite less in comparison to traditional processes. One more advantage is that pollutant is permanently eliminated from the soil. Besides this, the quantity of waste material which has to be discarded is significantly reduced (EPA 2000) which is almost up to 95%, and in certain cases, the pollutant can be recycled from the pollutant plant biomass. The application of hyperaccumulator species is restricted because of slow growth, shallow root system as well as insignificant biomass yield. Besides this, the plant biomass should be collected and discarded appropriately. There are various reasons which restrict the range of metal phytoextraction like bioavailability of metals inside the rhizosphere, rate of metal uptake through roots, percentage of metal “fixed” inside the roots, rate of xylem loading/translocation into shoots, and cellular resistance to harmful metals. The process is also generally restricted to metals as well as other inorganic material in soil or sediment. For making remediation process possible, the plants should (1) extract heavy metals in big amount in the roots, (2) transfer the heavy metal in the surface biomass, as well as (3) produce a huge amount of plant biomass. Besides this, treated plants should have processes for detoxification and/or resisting greater level of metals stored in their shoots (Brennan and Shelley 1999).

15.3.2 Rhizofiltration

This is employed for treating extracted groundwater, surface water as well as wastewater with less pollutants. In this process, there is adsorption or precipitation in plant roots or absorption of pollutants around the root zone. Rhizofiltration is generally utilized in either in situ or extracted groundwater, surface water, or wastewater for eliminating metals or other inorganic materials. Rhizofiltration can be employed for lead (Pb), cadmium (Cd), copper (Cu), nickel (Ni), zinc (Zn), and chromium (Cr), which are mainly held within the roots. Rhizofiltration is just like phytoextraction, but the plants are utilizing polluted groundwater in place of soil. To adjust the plants, when a huge root system is produced, polluted water is collected from a waste site and transported to the plants where it is replaced for their water source. The plants are then grown in the polluted region where the roots extract the water as well as pollutants. When the roots become saturated with pollutants, they are collected. Sunflower, Indian mustard, tobacco, rye, spinach, and corn have proven their potential to eliminate lead from water, of which sunflower has the highest ability. The benefit linked with rhizofiltration is its capacity to employ both terrestrial and aquatic plants for either in situ or ex situ utilizations. Additional benefit is that pollutants are not being translocated into the shoots. Therefore, species other than hyperaccumulators should be employed. Terrestrial plants are favored as they possess fibrous as well as much bigger root system, enhancing the root area. Drawbacks of rhizofiltration are: the requirement of continuous adjustment of pH, requirement of plants to be grown first in a greenhouse or nursery, regular harvesting as well as plant disposal, and need of decent knowledge of the chemical speciation/ interactions.

15.3.3 Phytovolatilization

This process utilizes plants to take up pollutants from the soil, converting them into volatile forms and transpiring them into the surroundings. Phytovolatilization may also diffuse pollutants from the stems or other plant organs so that the pollutant moves through before reaching the leaves. Phytovolatilization may occur with pollutants found in soil, sediment, or water. Hg is the main metal pollutant where this process is employed. It occurs with volatile organic compounds also like trichloroethene, as well as inorganic chemicals which have volatile forms, like Se and As. The benefit of this process is that the pollutant, like mercuric ion, may be converted into a less harmful compound. The drawback is that the Hg discharged into the environment is expected to be recycled through precipitation and then redeposited back into lakes and oceans, repeating the formation of methylmercury through anaerobic bacteria.

15.3.4 Phytostabilization

This is in situ inactivation and is employed for treating soil, sediment, as well as sludge. In this process, some plant species are utilized to immobilize pollutants in the soil and groundwater by absorption and storage through roots, adsorption on roots, or precipitation inside rhizosphere. This method reduces the movement of the pollutant and inhibits transport in the groundwater, and it also decreases bioavailability of metal in the food chain. This process can also be employed for restoring vegetation cover at places where natural vegetation is unable to survive because of large amounts of metals in surface soils or physical disruptions to surface materials. Metal-resistant species is utilized to reestablish vegetation at pollutant locations, which reduces the possible transfer of contaminants by wind erosion and transfer of exposed surface soils as well as leakage of soil pollutants in the groundwater. Phytostabilization can take place via sorption, precipitation, or reduction in metal valence. It is valuable for the remediation of Pb, As, Cd, Cr, Cu as well as Zn. Benefit of this process is the differences in soil chemistry and environment caused by presence of plant. These alterations in soil chemistry may encourage adsorption of pollutants in the plant roots or soil or precipitate metals in the plant root. Phytostabilization is successful in attending metals as well as other inorganic pollutants in soil and sediments. Certain benefits linked with this technique are that removal of dangerous material/biomass is not needed and it is very effectual when quick immobilization is required to conserve ground as well as surface waters (Zhang et al. 2009). The plant's presence also restricts soil erosion and reduces the quantity of water present in the system. But this remediation technique has various key drawbacks like: pollutant residual in soil, massive use of fertilizers, or soil modifications, which need compulsory observation as well as the stabilization of the pollutants basically because of soil amendments.

15.3.5 Phytodegradation

This is also called as phytotransformation. It decomposes complex organic molecules into simple molecules or integrates these molecules into plant tissues

(Trap et al. 2005). In the phytodegradation process, pollutants are decomposed after their uptake by the plant. Like phytoextraction and phytovolatilization, in this process also plant uptake usually takes place only when the solubility and hydrophobicity of pollutant drop into a definite suitable range. Phytodegradation remediates certain organic pollutants, like chlorinated solvents, herbicides as well as munitions, and it can attend pollutants in soil, sediment, or groundwater.

15.3.6 Rhizodegradation

This is also known as phytostimulation. It decomposes pollutants inside the plant root zone, or rhizosphere. It is thought to be performed through bacteria or other microbes. There are almost 100 times more microorganisms in rhizosphere soil in comparison to the soil outside the rhizosphere. Microbes are present more in the rhizosphere as plant secretes sugars, amino acids, enzymes as well as other substances which can induce growth of bacteria. The roots also have extra surface area for development of microbes and a route for transfer of oxygen from the surroundings. The restricted nature of rhizodegradation implies that it is mainly valuable in polluted soil and found to be little bit successful in remediating a large variety of usual organic chemicals like petroleum hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), chlorinated solvents, pesticides, polychlorinated biphenyls (PCBs), benzene, toluene, ethylbenzene, as well as xylenes. It can be viewed as plant-supported bioremediation, the activation of microbial as well as fungal decomposition through discharge of exudates/enzymes in the rhizosphere (Zhuang et al. 2005; Sharma and Pandey 2014).

15.4 Environmental Sustainability

Sustainability is the ability to tolerate. The term “sustainability” is originated from the Latin sustinere (tenere, to hold; sus, up). In ecology, this means in what way biological systems stay diverse as well as fruitful all times. For human beings, it is the capacity for long-period maintenance of welfare, which is ultimately based upon the welfare of the nature and the responsible utilization of natural resources (http://en.wikipedia.org/wiki/Environmental Sustainability Index). Environmental sustainability is a method which ensures that existing methods of dealings with the surroundings are followed with the concept of keeping the surroundings as pure as naturally possible on the basis of perfect actions. An “unsustainable condition” arises when the entire resources of nature are utilized up earlier than it can be restored. Sustainability needs that humans just utilize natural resources at a speed at which they can be restored naturally. Hypothetically, the long-term consequence of environmental decomposition is the failure to nurture human life. Globally such decomposition could indicate loss of humanity (http://www.IndependentlySustainableRegion 2010). A healthy environment is that which gives essential commodities as well as facilities to humans and other creatures in its ecosystem. This can be attained by two routes and comprises finding ways of decreasing adverse human influence and increasing the welfare and life of all living creatures including plants as well as animals in the environment. Daly (1990) proposed three distinctive conditions for environmental sustainability: renewable sources should give a sustainable yield, i.e., the rate of yield should not be more than the rate of renewal; for nonrenewable sources, there should be equal growth of renewable replacements; waste production should not be more than the acclimatizing potential of the surroundings. It is essential to also distinctly describe what is the significance of the environment for humans who are in the center of it and are influenced positively as well as negatively according to their actions in the environment. Therefore, Bankole (2008) stated that "Environment" denotes the physical settings of man, where he is component as well as dependent for his functions such as physiological activities, production, as well as utilization. His physical surrounding ranges from air, water, and land to natural sources such as metals, energy carriers, soil, plants, animals, and ecosystems. For urban human being, major portion of his environment is man-made. But still, the nonnatural surroundings like buildings and roads as well as tools like clothes and automobiles are the outcome of both efforts and natural resources (Ezeonu et al. 2012).

15.5 The Sustainable Phytoremediation

For sustainable ecological as well as agricultural progress, it is essential to remediate polluted regions, and the entry of contaminants into the food chain should be reduced. Because of this, the plant-dependent remediation processes designated as phytoremediation got much recognition in the last few decades. It is an easy, dynamic, cheaper, requires less hard work, commonly accepted, well-suited, environmental-friendly, sustainable, dependable, as well as promising technique which can be applied in huge areas, especially when local, environmentally, and socioeconomically useful plants are utilized for the treatment of contaminated areas with which revenue is also generated through production of phytoproducts of polluted regions (Pandey et al. 2015, 2016). Phytoremediation is helpful in treating large number of contaminants and is about ten times less costly in comparison to traditional methods (do Nascimento and Xing 2006). Plants have the intrinsic potential to nullify both organic and inorganic contaminants through various methods like bioaccumulation, translocation, and degradation, therefore working as a crucial sink for biologically harmful contaminants (Pandey and Bajpai 2019).

It is well recognized that heavy metals are unable to be decomposed and demolished. They bioaccumulate via food chain and bring huge possibility of human health dangers. Among all the existing methods, phytoremediation is a cheap process for treating the polluted regions. Plants can treat contaminants by various methods such as adsorption, transport with translocation, hyperaccumulation or transformation as well as mineralization (Meagher 2000). A variety of naturally growing plant species have developed on heavy metals polluted areas. However, just a few of them are helpful in phytoremediation and makes a multifunctional ecosystem. The properties which make any species valuable in phytoremediation have rapid growth with capacity to store greater biomass, simple and quick proliferation, abundant root system, more metal storing ability, resistance to severe local soil conditions, and unacceptable by cattle (Pandey et al. 2012a). It is also required that they should be perennial, as well as should be capable of starting ecological succession. Additionally, the species chosen for remediation should also be beneficial in yield of commodities and facilities to the society. Extra advantages are carbon sequestration, increase in substrate quality, pleasant scenery, and biodiversity protection (Pandey 2002, 2013). Overlooking the problems of cost of inputs as well as maintenance, most of the existing research to date endorse introduced plant species for phytoremediation. For example, Vamerali et al. (2010) reported that worldwide introduced crop species are manly involved in phytoremediation. It obviously demonstrates that not naturally growing plants have not got much attention for the phytoremediation of polluted areas. But, employing introduced crop species to phytoremediate has several environmental, financial, and public challenges. The introduced crops need inputs as well as maintenances of their establishment on the severe environments that exist in heavy metals polluted regions. Moreover, if the introduced crops are edible, then there will be severe risk of heavy metals going in the food chain and ultimately affecting human health. These difficulties can be overcome by employing naturally developing species which can be inedible but financially as well as socially valuable for the public (Pandey and Singh 2011). Through our scientific work in creating appropriate information in this area and connecting this information to our action can assist us in decreasing the human health dangers and gaining further from the phytoremediation endeavors (Fig. 15.1).

15.5.1 Ecologically and Economically Useful Species

Naturally growing species are best and perfect choice for phytoremediation of polluted regions. If workers, by interdisciplinary work, are capable to select environmentally as well socioeconomically significant plant species or profitable crops like aromatic plants and energy crops among naturally growing species, then we can attain sustainable phytoremediation. Certain environmentally and socioeconomically significant plant species are munj (*Saccharum munja*), Kans (*S. spontaneum*), etc., which are excluders that restrict heavy metals toxicity. In the same way, certain aromatic plants like vetiver (*Vetiveria zizanioides*), lemon grass (*Cymbopogon flexuosus*), tulsi (*Ocimum basilicum*) are stress resistant in nature. The major product of aromatic crops is essential oil which is free from heavy metal dangers (Khajanchi et al. 2013). The potential energy crops such as *Ricinus communis* (Pandey 2013), *Jatropha curcas* (Pandey et al. 2012b), and *Miscanthus giganteus* (Nsanganwimana et al. 2014) have the capacity for phytoremediation of polluted areas with a variety of ecological as well as ecosystem services. All of these species are perennial as well as inedible by cattle. They are also environmentally suitable for phytoremediating heavy metals in contaminated areas,

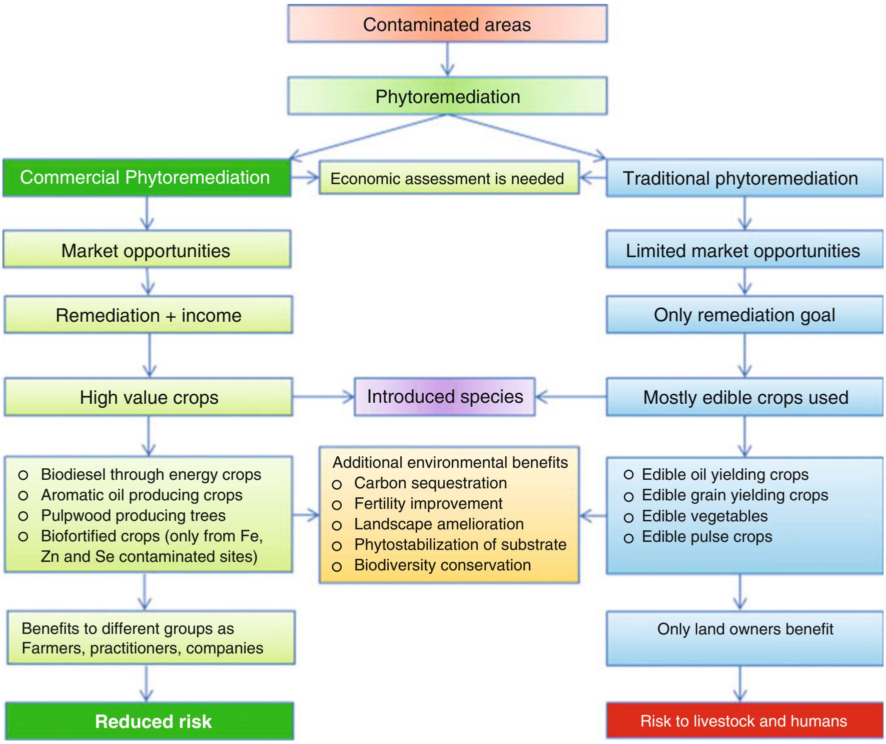

Fig. 15.1 A conceptual diagram showing comparison between the traditional phytoremediation and novel approach for sustainable phytoremediation. (Figure taken from Pandey and Souza-Alonso 2019 with permission)

and therefore present a new chance for their application in phytoremediation. More precisely, there is not much danger in utilization of major product of these species, e.g., essential oils and biodiesel (Pandey et al. 2015) (Fig. 15.2).

15.5.2 Plant Species Involved in Phytoremediation

Many plants had been identified and tested for phytoremediation work. Highly useful terrestrial as well as aquatic plant species have been recognized after challenging lab as well as field studies which are listed below (Table 15.2).

Certain other species are *Elodea canadensis*, *Ceratophyllum demersum*, *Potamogeton* spp., *Myriophyllum* spp., *Spartina alterniflora, Pinus sylvestris, Poa alpine,* and *Bouteloua gracilis* (Rice et al. 1997; Watanabe 1997). Lot of them are still wild, but others are domesticated because of their food value. They are high salt as well as toxicity resistant, have large root binding system, and were tested for restoration process. A variety of them quickly absorb, volatilize, and/or metabolize substances like tetrachloroethane, trichloroethylene, metachlor, atrazine,

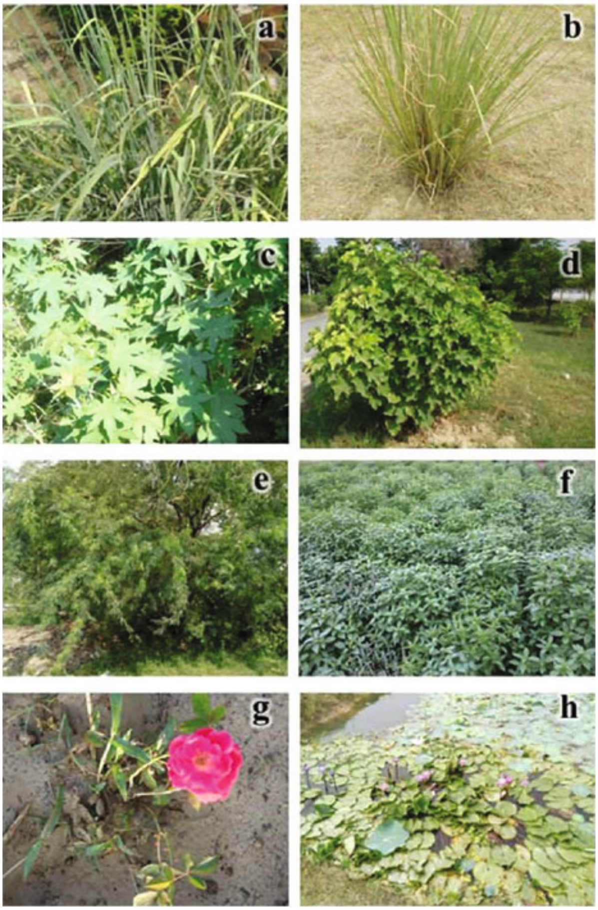

Fig. 15.2 Some important crops for the remediation of polluted sites with economic returns, because of their tolerant nature. These are (**a**) *Cymbopogon flexuosus* (Nees ex Steud.) Wats (lemon grass), (**b**) *Vetiveria zizanioides* (Linn) Nash, (**c**) *Ricinus communis* L. (castor bean), (**d**) *Jatropha curcas* L., (**e**) *Prosopis juliflora* (Sw) DC, (**f**) *Ocimum basilicum* L. (sweet basil), (**g**) *Rosa damascena* mill L., and (**h**) *Nelumbo nucifera* (sacred lotus). (Figure taken from Pandey and Bajpai 2019 with permission)

nitrotoluenes, anilines, dioxins as well as several petroleum hydrocarbons. Perfect plants for this work are members of grass family Gramineae with Cyperaceae as well as the members of Brassicaceae specially the Brassica, Alyssum and Thlaspi, and Salicaceae particularly willow and poplar trees. Grasses like the vetiver, clover and rye grass, Bermuda grass, tall fescue are specifically very effectual in treating soils polluted through heavy metals as well as crude oil (Kim 1996). Sunflower plants (*Helianthus annus*) were planted on large scale around Chernobyl (erstwhile USSR), where nuclear tragedy in 1985 discharged huge quantity of radioactive substances into the surroundings. The land as well as soil of the region area was severely polluted. Sunflower is observed to take up radionuclides from soil to clean it up. This phytoremediation method has a cost of about 2 dollar per hectare for remediating the soil which might be costing millions of dollars through other methods. Duckweeds can “absorb” and “adsorb” total of dissolved gases as well as other substances, with heavy metals, from the wastewater. Just in 2–3 weeks, the condition of wastewater enhances considerably in terms of biological oxygen demand as well as dissolved

Table 15.2 Highly useful plant species for phytoremediation (Adapted from Sinha et al. 2007)

S. no.	Plant name	S. no.	Plant name
1.	Vetiver grass (*Vetiveria zizanioides*)	16.	White radish (*Raphanus sativus*)
2.	Bermuda grass (*Cynodon dactylon*)	17.	Catnip (*Nepeta cataria*)
3.	Bahia grass (*Paspalum notatum*)	18.	Big bluestem (*Andropogan gerardii*)
4.	Sunflower oil plant (*Helianthus annus*)	19.	Indian grass (*Sorghastrum nutans*)
5.	Poplar tree (*Populus* spp.)	20.	Canada wild rye (*Elymus canadensis*)
6.	Mustard oil plant (*Brassica juncea*)	21.	Nightshade (*Solanum nigrum*)
7.	Periwinkle (*Catheranthus roseus*)	22.	Wheat grass (*Agropyron cristatum*)
8.	Cumbungi (*Typha angustifolia*)	23.	Alfalfa (*Medicago sativa*)
9.	Water hyacinth (*Eichhornia crassipes*)	24.	Tall fescue (*Festuca arundinacea*)
10.	Duck weed (*Lemna minor*)	25.	Lambsquarters (*Chenopodium berlandieri*)
11.	Red mulberry (*Morus rubra*)	26.	Reed grass (*Phragmites australis*)
12.	Kochia (*Kochia scoparia*)	27.	Tall wheatgrass (*Thynopyron elongatum*)
13.	Foxtail barley (*Hordeum jubatum*)	28.	Rhodes grass (*Chloris guyana*)
14.	Switch grass (*Panicum variegatum*)	29.	Flatpea (*Lathyrus sylvestris*)
15,	Musk thistle (*Carduus nutans*)	30.	Carrot (*Daucus carota*)

oxygen values, heavy metals, and suspended solids and can be utilized for irrigation, industrial uses, and aquaculture. It decontaminates the wastewater having high concentration of P, NO_3^- as well as K till the water is clean with P and N contents falling close to 0.5 mg/L in just 20 days. Many microbes reside in the roots of water hyacinths in symbiotic relationships which flourish on minerals as well as organic pollutants present in the effluents. Water hyacinth can eradicate heavy metals by 20–100%. Within 24 h, the weed can remove more than 75% of Pb from polluted water. It also absorbs Cd, Ni, Cr, Zn, Cu, Fe as well as pesticides and various harmful substances from the sewage. Within 7 days of exposure, it can reduce about 97% BOD and eliminate over 90% of NO_3^- and PO^{4-}. It can also eliminate radioactive pollutants (Sinha et al. 2007).

15.6 Conclusions

In spite of the variety of possible choices, phytoremediation is still in its initial stages. Most of the studies have been done in labs in comparatively ideal situation for brief periods of time. There is need of better exhaustive studies in fields for more time periods to clearly know about the possible function of phytoremediation. There is a limitation in phytoremediation method that a particular phytoremediation treatment cannot be applied in all situations with a specific chemical pollutant due to diverse site-specific circumstances of soil and climate which may not be appropriate for the target plant. Plants also have interaction with and are influenced by other living beings like insects, pests, and pathogens, and plants exposure to pollutants and linked stresses can make the phytoremediation more vulnerable to these other agents, which subsequently affects the result of phytoremediation efforts. In addition to it, phytoremediation usually is limited to those areas where the quantity of pollutants is not dangerous to the plants planned for remediation. Lastly, the pollutants must be available to the tissue accountable for uptake like root system in plants. Consequently, in situ phytoremediation utilizing living plants is limited to areas favorable to development of the particular plant with the pollutant present within the potential root area of the specific plant.

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