Chapter 7
Phytoremediation Crops and Biofuels

M.N.V. Prasad

Abstract Environmental decontamination is an integral part of sustainable development. In recent years there has been growing interest in using plants for decontamination. On the other hand, water, soil and air are increasingly contaminated. Large amounts of toxic waste have been dispersed in thousands of contaminated sites spread all over the globe. These pollutants belong to two main classes: inorganic and organic. The challenge is to develop innovative and cost-effective solutions to decontaminate polluted environment. Phytoremediation is emerging as an invaluable tool for environmental cleanup. Various strategies are being applied to reduce the accumulation of toxic metals in plants. Cultivation of edible crops in contaminated soils is a subject of human health concern if the contaminant concentration in the edible parts of crops plant exceed the permissible level. In such cases non-food crop production viz. value chain and value additions appears profitable. In this review: (1) the contamination due to industrial effluents in peri urban region of greater Hyderabad, and (2) the strategies to use contaminated soil and water for raising phytoremediation crops, and generation of value products. Crops and products include medicinal and aromatic plants, ornamental plants, biofuels, tree crops, fiber crops, dyes, and plants for carbon sequestration.

Keywords Biodiesel • Bioeconomy • Biomass conversion • Biorefinery • Carbon sequestration • Circular economy • Constructed wetlands • Energy crops • Environmental cleanup • Industrial crops • Ornamental crops • Value additions • Value chain products

7.1 Introduction

Environmental (Soil, water and pollution) (conflict between agro-ecosystems and urbanization) is not only a subject of pan-Indian concern, but also for the entire world. Consequently, developing eco-innovative remediation technologies to re-use

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contaminated substrates (land and water) in line with biomass production for the bioeconomy are gaining considerable global attention (Prasad 2015). Rapid industrialization and extraction of large quantity of natural resources is the main cause of environmental contamination and pollution. Thus, every one of us are being exposed to contamination from past and present industrial practices, emissions in natural resources (air, water and soil) even in the most remote regions. The risk to human and environmental health is rising and there is evidence that this cocktail of pollutants is a contributor to the global epidemic of cancers, and other degenerative diseases.

Plant based technologies are emerging as viable alternatives to conventional remediation techniques when time constraint is low, being more energy-efficient and less disruptive to contaminated sites. Based on small-scale studies, annual and perennial accumulators are suitable candidates for these plant based technologies (= Phytotechnologies). Plant-associated microbes are also implicated in enhancing plant performance, reducing contaminant phytotoxicity or modifying (degrading) (organic) contaminants. These innovative phytotechnologies can be *in-situ* or *ex-situ* (Conesa et al. 2012), remediate soil layers explored by roots and at the same time provide plant biomass, contributing towards achieving envisaged targets on the use of renewable plant-based feedstock for various purposes (renewable energy sources, ecomaterials, biomass for bioreffineries, green fine chemistry, bioplastics, etc. (Prasad 2014b)) in substitution to fossil fuels and other non-renewable raw materials. They can also reduce the diversion of croplands to bioenergy and other non-food crops (Liu et al. 2011, 2012; Sheng et al. 2012; Zhang et al. 2014a). Development of economically sound valorisation pathways for complete chain of phytoproducts of value addition and value chain from phytoremediated plants would go a long way (Grison 2015; Prasad 2015; van der Ent et al. 2015) (Fig. 7.1).

Energy and environment are interlinked complex issues. Population explosion (~7.2 billion) on plant earth and excessive use of natural resources resulted in environmental pollution and contamination with inorganic and organics (Prasad 2011; Xu et al. 2006). Pollution in environment is an ever increasing phenomenon and often regulatory systems and cleaning operations are not commensurate with waste

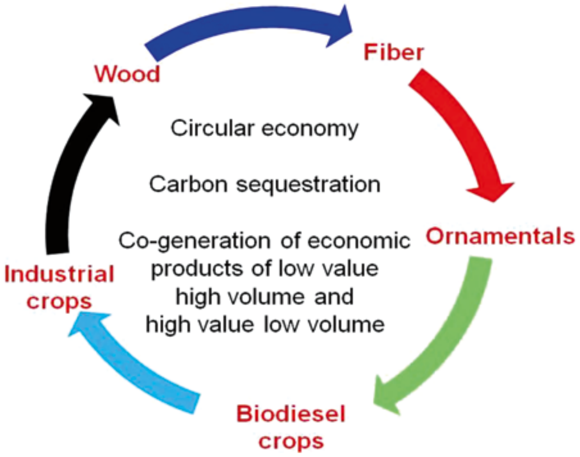


Fig. 7.1 Environmental crops boosting circular economy, carbon sequestration and co-generation of phytoproducts

generation. It is therefore, necessary to search for effective technologies for decontaminating the natural resources. Biodiversity has immense potential not only for monitoring and abatement of environmental pollution but also in generating a wide variety of by-products. Breakthrough research innovations that are amenable for field applications of pollution abatement are discussed with specific examples in several papers (Conesa et al. 2012; Prasad 2011; Prasad and Freitas 2003; Prasad and Prasad 2012; Prasad et al. 2010; Prasad 2013; Puhui et al. 2011).

The growing need for biomass for conversion to biofuels, require lignocellulosic-rich raw materials. Phytoremediated phytomass is one such option used to produce fuel like methanol, biodiesel, synthetic gas, and hydrogen (using thermal and thermo-chemical processes by direct or indirect liquefaction or gasification) and ethanol (through hydrolysis and subsequent fermentation). Biorefinery processes (the sustainable processing of biomass to a spectrum of marketable products and energy) is an absolute necessity and it is the key to meet this vision towards bio-based economy.

Brassica juncea (Indian mustard) *Helianthus annus* (Sunflower), *Prosopis juliflora*, bamboo, and *Pistia stratiotes* (water lettuce), could be grown for different purposes including energy generation Annual and perennial crops, including algae in wastewater ponds are potential candidates. Management and production of phytoremediation crops in contaminated substrates serves as a sink for contaminants with possibility for co-generation of economic products. Economics and byproduct generation with the overall success level of integration in the bioremediation fostering circular economy (Prasad 2015) (Fig. 7.2).

The challenge for environmental decontamination of inorganic and organic pollutants and contaminants is to develop innovative and cost-effective solutions to decontaminate polluted environments. Biodiversity is the raw material for environmental cleanup and is an invaluable tool box with wider application in the field of pollution abatement (Witters et al. 2012). Phytoremediation includes variety of technologies using plants and microbes to remediate or contain contaminants in soil, groundwater, surface water, and/or sediments including air. These technologies have become attractive alternatives to conventional cleanup technologies due to relatively low capital costs and the inherently aesthetic nature (Fig. 7.3).

Phytoremediation is a sustainable environmental cleanup technology. This approach is based on a wide range of plants that include terrestrial, aquatic, weeds, annuals, perennials (agricultural, tree and field crops) and ornamentals (Poonam

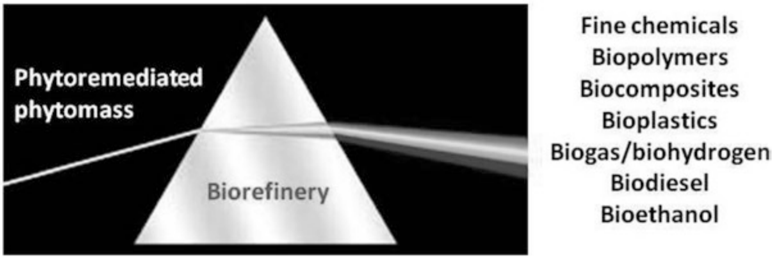


Fig. 7.2 "Biorefinery" is the sustainable processing of conversion of phytoremediated phytomass into a spectrum of marketable products for e.g. chemicals, composite materials, and energy

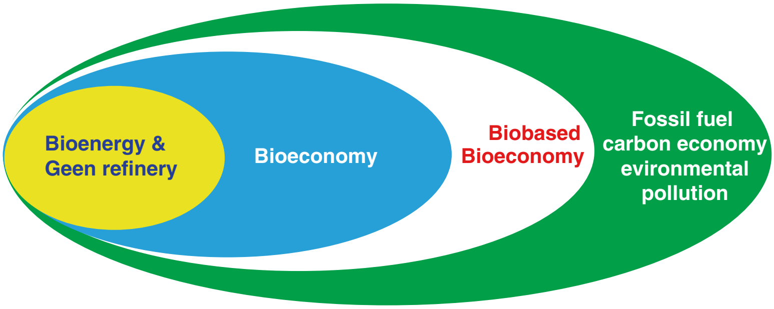


Fig. 7.3 Bioremediation and biobased economy. A biobased economy is a sustainable economy, optimising economic value through valorization of bimass. The new wave in this direction is to use phytoremediated phytomass as substrate in biorefinery for replacing fossil resources and to produce a variery of economic products

et al. 2014; Vamerali et al. 2011, 2014). Plants applied in phytoremediation have several beneficial uses. Nature cure mechanisms for natural resources and environmental protection viz. phytosequestration, rhizodegradation, phytohydraulics, phytoextraction, phytodegradation and phytovolatilization are well established with suitable examples (Shekhar 2012).

Arsenic, Mercury, Chromium, Fluoride, Cyanide, abandoned mines, fly ash disposed sites, engineered phytotreatment technologies, biological permeable barriers and degradation of Organics viz., petroleum hydrocarbons, pesticides and explosives are some of the contaminants subjected to bioremediation and promising results have been obtained.

Quite a variety of plants, natural, transgenic, and/or associated with rhizosphere micro-organisms are extraordinarily active in these biological interventions and cleaning up pollutants by removing or immobilizing. While diverse microbes are the most active agents, fungi and their strong oxidative enzymes are key players as well in recycling recalcitrant polymers and xenobiotic chemicals following systems biology and biotechnology interventions (de Lorenzo 2008; Dowling and Doty 2009; Wood 2008). Constructed wetlands are the result of human skill and technology integrating the geology, hydrology and biology (Prasad 2004a, b, 2007a, b). Constructed wetlands have been designed centuries ago by mankind to treat wastewater (Bi et al. 2007; Türker et al. 2013). Bioeconomy is a solution for clean air, water and environmental sustainability (Prasad 2015).

Bioremediation approach is currently applied to contain contaminants in soil, groundwater, surface water, or sediments including air. These technologies have become attractive alternatives to conventional cleanup technologies due to relatively low capital costs and the inherently aesthetic nature. Nature's cure using plant resources (= Phytoremediation) is a sustainable solution for environmental decontamination (Bañuelos et al. 1997; Bitterli et al. 2010). As of now about 20,000 research papers have been published on various aspects of using biological resources for environmental cleanup starting with only 11 in 1989. Environmental sources of heavy metals are shown in Table 7.1.

Table 7.1 Environmental sources of heavy metals (Prasad 2011)

Cadmium (Cd)	Production of stainless steel, alloys, storage batteries, spark plugs, magnets and machinery, Cadmium (Cd) Cd-Ni battery production, pigments for plastics and enamels, fumicides, and electroplating and metal coatings.
Molybdenum (Mo)	Spent catalyst.
Zinc (Zn)	Brass and bronze alloys production, galvanized metal production, pesticides and ink. Zinc smelting, waste batteries, e-waste, paint sludge, incinerations, fuel combustion and electroplating.
Tin (Sn)	Soft drink, beer and beverage can production.
Cobalt (Co)	Steel and alloy production, paint and varnish drying agent and pigment and glass manufacturing.
Chromium (Cr)	Corrosion inhibitor, dyeing and tanning industries, plating operations, alloys, antiseptics, defoliants and photographic emulsions. Mining, industrial coolants, chromium salts manufacturing, and leather tanning.
Lead (Pb)	Lead battery industry, fuel additives, paints, herbicides manufacturing of ammunition, caulking compounds, solders, pigments, and insecticides, Smelting operations, coal- based thermal power plants, lead acid batteries, paints, and E-waste.
Mercury (Hg)	Electrical apparatus manufacture, electrolytic production of Cl and caustic soda, paints, pharmaceuticals, plastics, paper products, batteries, pesticides and burning of coal and oil chlor-alkali plants, thermal power plants, fluorescent lamps, hospital waste (damaged thermometers, barometers, sphygmomanometers), electrical appliances etc.
Arsenic (As)	Production of pesticides, veterinary pharmaceuticals and wood preservatives, geogenic/natural processes, smelting operations, thermal power plants, and fuel burning.
Copper (Cu)	Textile mills, cosmetic manufacturing and hardboard production sludge, mining, electroplating, and smelting operations.
Vanadium (Va)	Spent catalyst, sulphuric acid plant.
Nickel (Ni)	Smelting operations, thermal power plants, and battery industry.

Biodiversity and ecosystem services offer means and ways to render the usage of natural resources more sustainably. This can be achieved by using the soil and ecosystem to generate solutions for modern-day challenges such as industrial pollution and the growing demand for natural resources (Aparna et al. 2010). Thus, there is a need to develop appropriate tools with like minded parties and allied disciplines. This kind of action plan would assist planners in calculating the social benefits of green missions in urban environments. The nexus of ‘Biodiversity *vs* Industry’ consortium and knowledge based systems for better understanding of production chains would contribute to sustainable development.

Industrial and urban activities impact our environment, especially in terms of polluting soil, air and water. Large numbers of sites are nowadays contaminated/polluted by inorganic and/or organics. Treating these pollutants represents an economic need, which often remains unanswered by conventional civil/chemical engineering methods, due to their inappropriateness, their environmental impact and costs (notably for large sites) (Figs. 7.4 and 7.5).

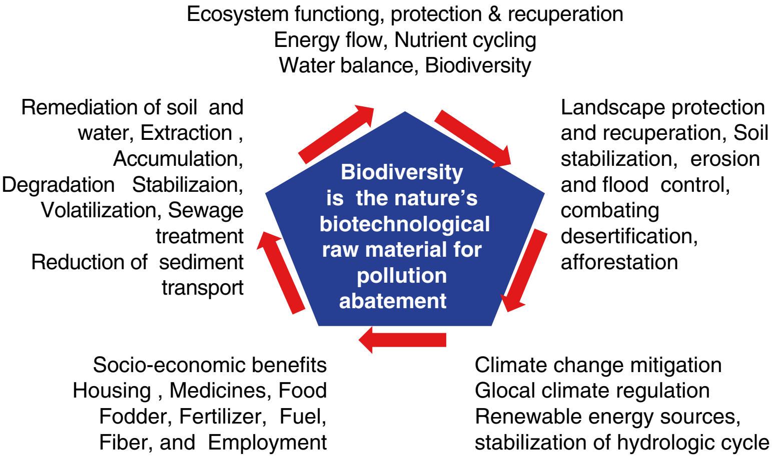


Fig. 7.4 Nature's biotechnology involves biodiversity as raw mterial for pollution abatement. During the last two decades, we have witnessed the emergence of gentle soil remediation techniques using various plant species and the combination of microbial biotechnologies

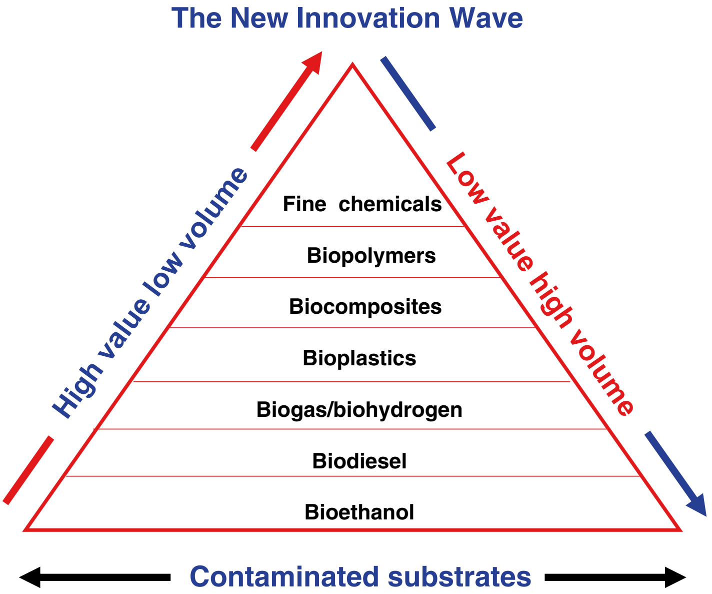


Fig. 7.5 Utilization of contaminated substrates for boosting bioeconomy through cascading approach is a new innovation wave. The added value is the highest at the *top* of the pyramid and the lowest at the *bottom*. On the contrary, the volume of biomass needed for the application is the lowest at the *top* of the pyramid and the highest at the *bottom* of the pyramid

7.2 Study Area

Major contaminated sites in Greater Hyderabad = Tri cities (Hyderabad, Secunderabad and Cyberabad) are selected for this study (Figs. 7.6–7.12).

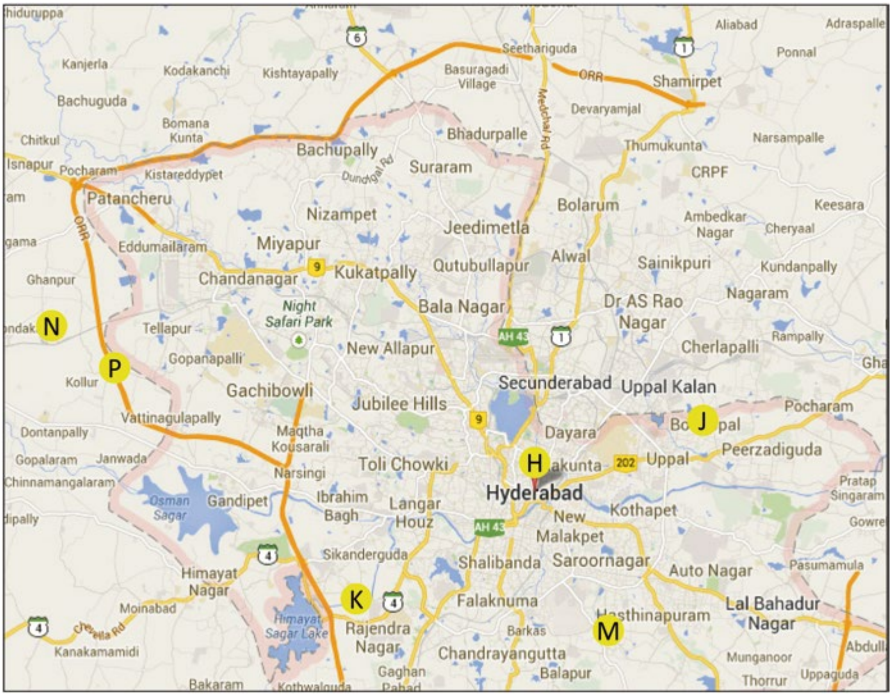


Fig. 7.6 Major contaminated sites in Greater Hyderabad = Tri cities (Hyderabad, Secunderabad and Cyberabad)
H Hussain Sagar, *J* Jawaharnagar, *K* Katteda
M Musi river, *N* Nakkavagu, *P* Patancheru
Bholakpur area – Abdul et al. (2012)
Municipal solid waste dumping sites – Jawaharnagar – Ahmed et al. 2011; Parth et al. 2009, 2011
Industrial waste contaminated areas – Ahmed et al. (2011), Balanagar, Machender et al. (2011, 2012)
Kattedan – Sekhar et al. (2006), Govil et al. (2008, 2012)
Hussainsagar lake sediments – PTE – Gurunadha Rao et al. (2004, 2008), Jain et al. (2010), Suneela et al. (2008), Vikram Reddy et al. (2012)
Industrially contaminated sites of Hyderabad – Sekhar et al. (2003, 2005)
Patancheru Industrial Area – Dasaram et al. (2011), Govil et al. (2001)

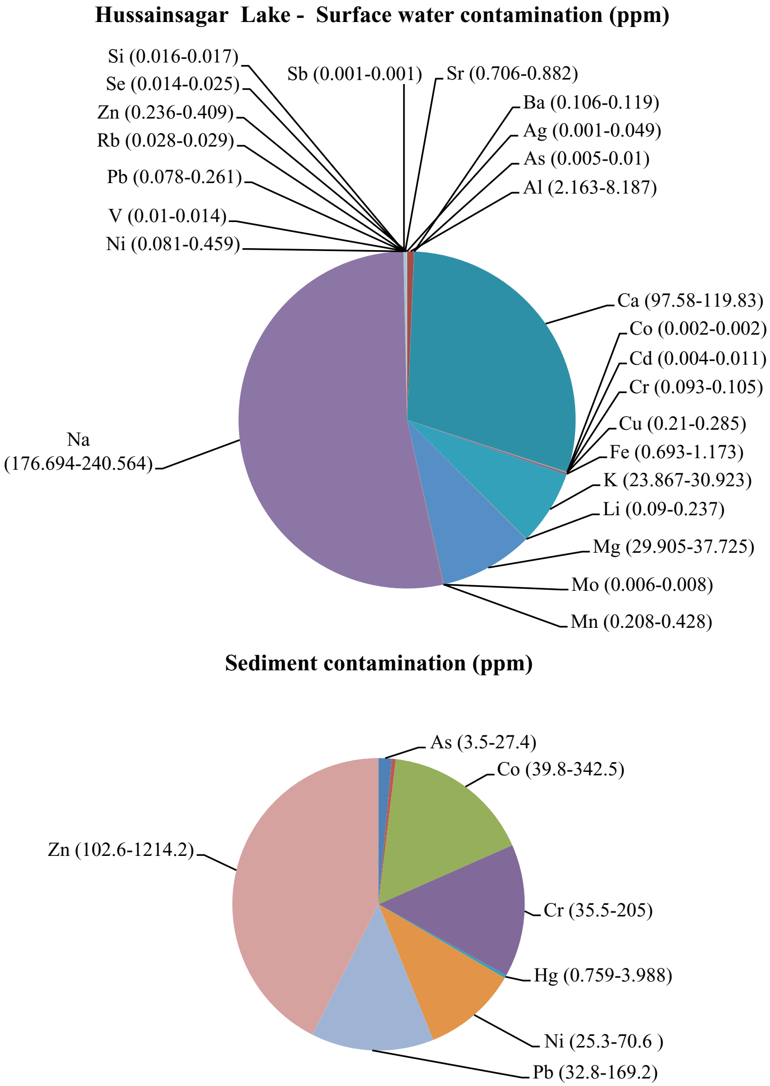


Fig. 7.7 Hussainsagar metal contamination budget (**a**) Surface water and (**b**) sediment

7.3 Products from Plants Applied in Phytoremediation

The objective of this paper aims at highlighting the sustainable valorization of phytoremediated phytomass for production of value additives and value chain products for boosting bio-economy (Bañuelos 2002, 2006) (Fig. 7.13).

India is forging ahead to attain high GDP growth rate to achieve the status of industrialized and developed nation by 2020. In order to achieve this, heavy

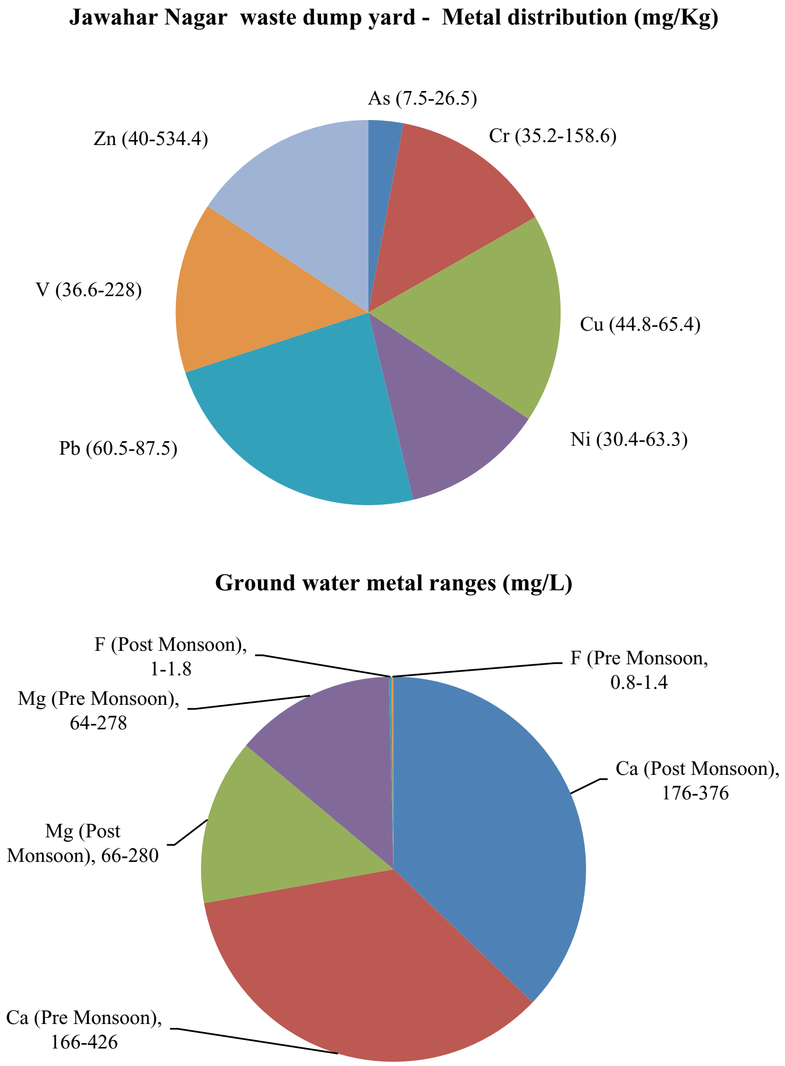


Fig. 7.8 Jawaharnagar waste dump site (**a**) Soil and (**b**) ground water

consumption of natural resources is inevitable. The other side of the coin of this task is enormous waste generation. The waste management summit, held in 2012 has estimated that the poised industrial growth would generate 100 million tons of non-hazardous solid waste, 6–7 million tons of hazardous waste annually. Thus, soil pollution, land-use and land cover change (conflict between agro-ecosystems and urbanization) are of pan-Indian concerns. Consequently, developing eco-innovative soil remediation technologies to re-use contaminated lands in line with biomass production for the bioeconomy are priority objectives.

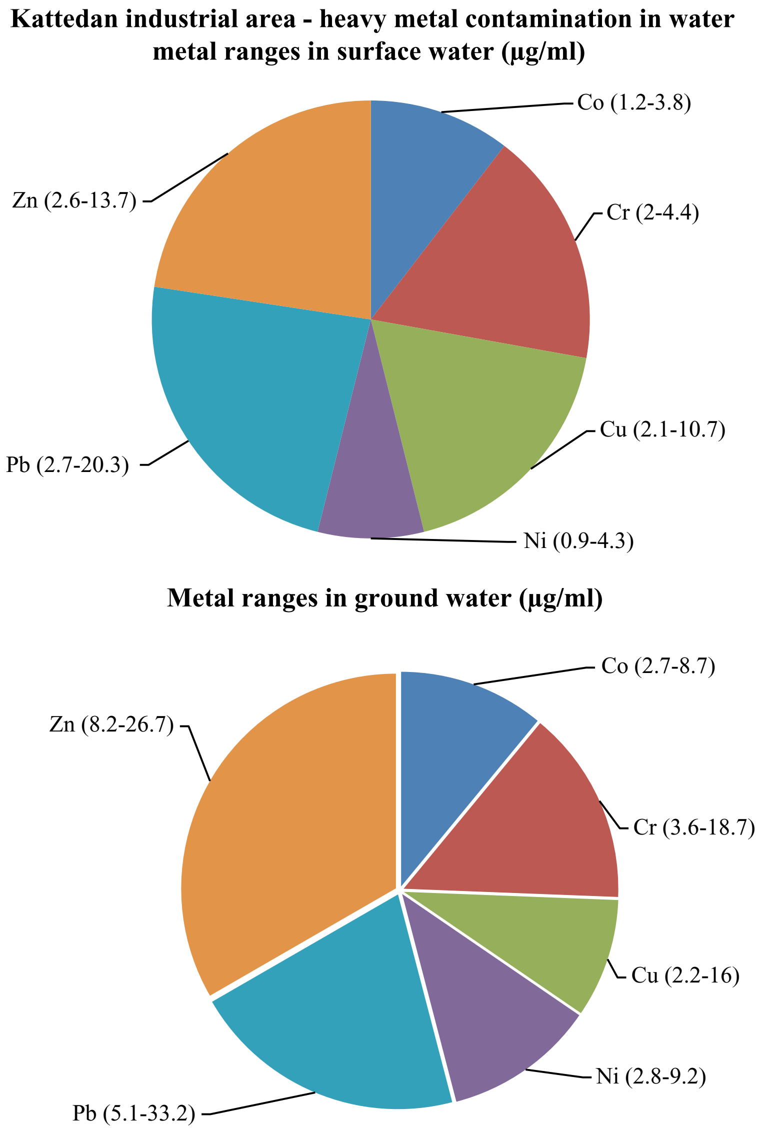
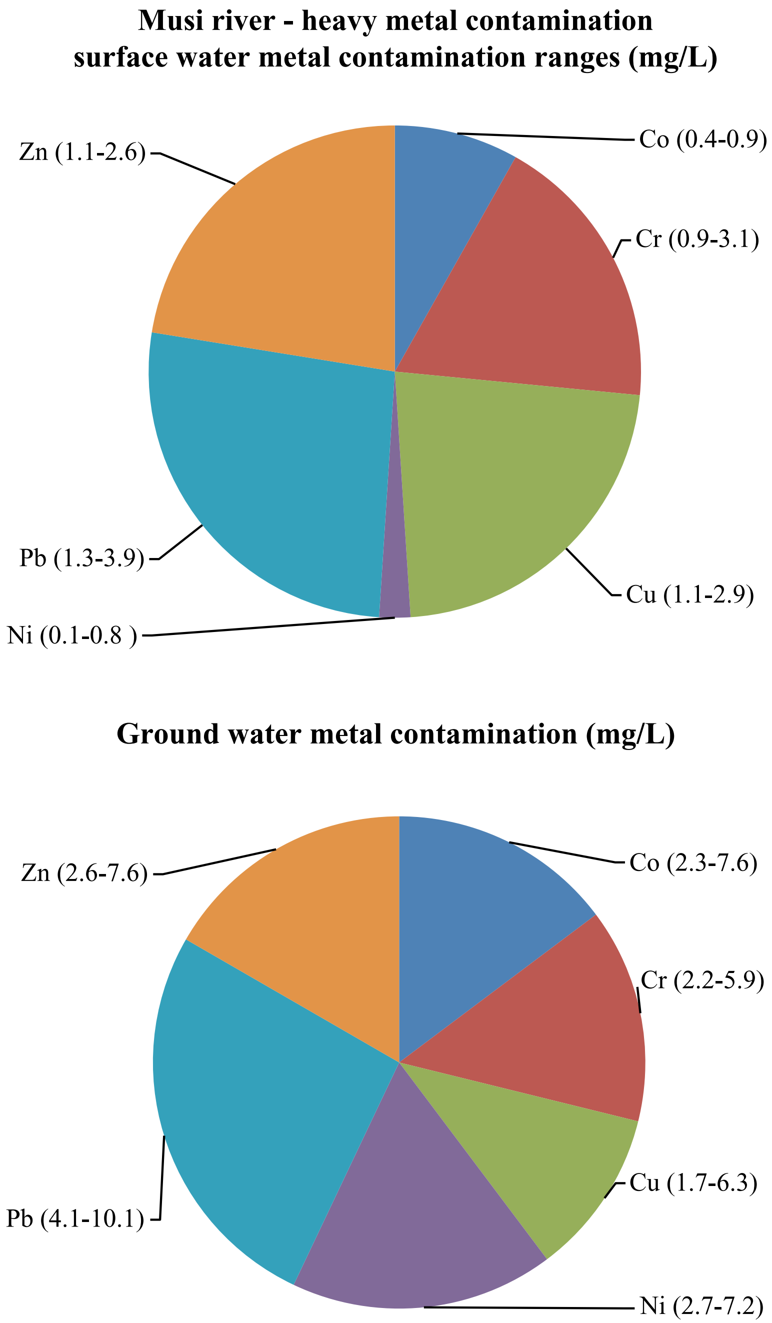


Fig. 7.9 Kattedan industrial area metal contamination (**a**) Surface water and (**b**) ground water

Land resources on a global perspective are under immense pressure. Soil remediation is a solution to reduce the pressure on land resources. Land degradation is due to: (a) Natural processes, (b) erosion, (c) nutrient depletion, (d) loss of organic matter, (e) structural losses, (f) Induced land degradation, (g) irrigation with waste waters, (h) atmospheric deposition of pollutants, (i) poor agricultural practices and (j) climate change increases the intensity of land degradation.



Musi river - heavy metal contamination
surface water metal contamination ranges (mg/L)

Ground water metal contamination (mg/L)

Fig. 7.10 Musi river heavy metal contamination (**a**) Surface water (**b**) Ground water

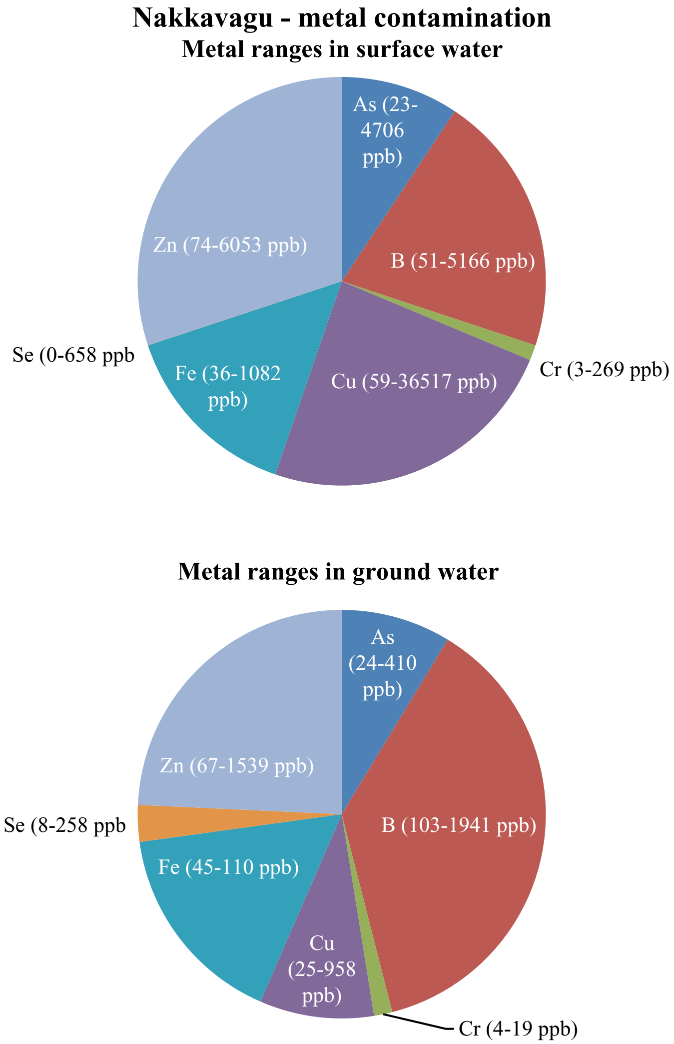


Fig. 7.11 Nakkavagu – Metal contamination (**a**) Surface water and (**b**) Ground water (ppb)

Of the 92 known elements in earth crust, 35 metals that concern us because of occupational or residential exposure, 23 of these are “heavy metals”: Ag, As, Au, Bi, Cd, Ce, Co, Cr, Cu, Fe, Ga, Hg, Mn, Ni, P, Pb, Sb, Sn, Te, Tl, U, V, and Zn (Glanze 1996). Heavy metals are among the contaminants in the environment. Beside the natural activities, almost all human activities also have potential contribution to produce heavy metals as side effects. Migration of these contaminants into non-contaminated areas as dust or leachates through the soil and spreading of heavy metals containing sewage sludge are a few examples of events contributing towards contamination of the ecosystems (Gaur and Adholeya 2004; Peña et al. 2014). From a chemical point of view, the term heavy metal is strictly ascribed to transition met-

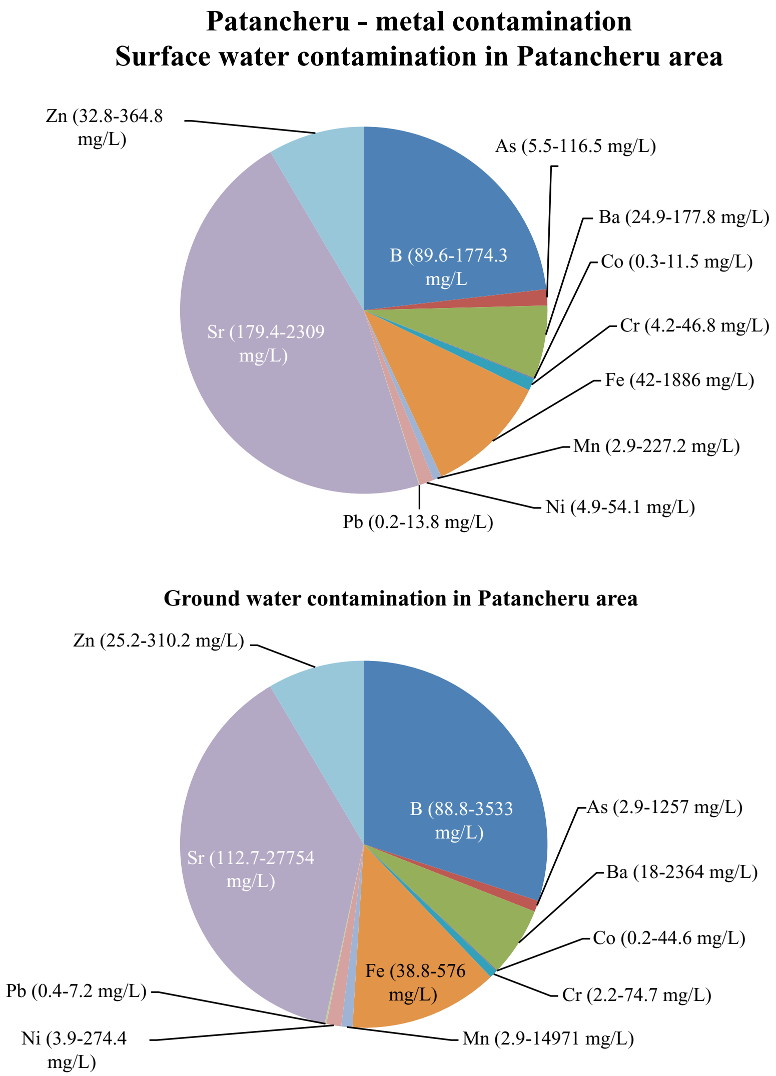
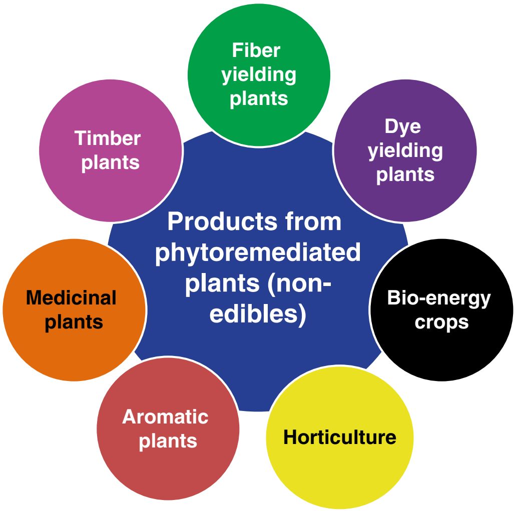


Fig. 7.12 Patancheru – Metal contamination (**a**) Surface water (**b**) Ground water

als, metalloids, with atomic mass over 20 and specific gravity >5. Here the term "heavy metals" will be for these potentially phytotoxic elements. Some of these heavy metals do not perform any known physiological function in plants. However, others such as micronutrients and beneficial elements are required for plant growth and metabolism, but these elements can easily lead to phytotoxicity when their concentration rises above optimal ranges. Heavy metal phytotoxicity may result from alterations of numerous physiological processes caused at cellular/molecular level by inactivating enzymes, blocking functional groups of metabolically important molecules, displacing or substituting for essential elements and disrupting membrane

Fig. 7.13 Products from phytoremediated plants



integrity. A rather common consequence of heavy metal poisoning is the enhanced production of reactive oxygen species (ROS) due to interference with electron transport activities, especially that of chloroplast membranes (Pagliano et al. 2006; La Rocca et al. 2009). This increase in ROS exposes cells to oxidative stress leading to lipid peroxidation, biological macromolecule deterioration, membrane dismantling, ion leakage, and DNA-strand cleavage (NavariIzzo et al. 1998, 1999; Quartacci et al. 2001). Plants resort to a series of defence mechanisms that control uptake, accumulation and translocation of these dangerous elements and detoxify them by excluding the free ionic forms from the cytoplasm. One commonly employed strategy lies in hindering the entrance of heavy metals into root cells through entrapment in the apoplastic environment by binding them to exuded organic acids (Watanabe and Osaki 2002) or to anionic groups of cell walls (Dalla Vecchia et al. 2005; Rascio et al. 2008). Most of the heavy metals that enter the plant are then kept in root cells, where they are detoxified by complexation with amino acids, organic acids or metal-binding peptides and/or sequestered into vacuoles (Hall 2002). This greatly restricts translocation to the above-ground organs thus protecting the leaf tissues, and particularly the metabolically active photosynthetic cells from heavy metal damage. A further defence mechanism generally adopted by heavy metal-exposed plants is enhancement of cell antioxidant systems which counteracts oxidative stress (Navari-Izzo et al. 1998; Sgherri et al. 2003).

Several methods are already being used to clean up the environment from these contaminants, but most of them are costly and far away from their optimum performance. The chemical technologies generate large volumetric sludge and increase the costs (Rakhshaee et al. 2009). Both chemical and thermal methods are technically difficult and expensive, and can also degrade the valuable component of soils (Hinchman et al. 1995). Conventionally, remediation of heavy-metal contaminated soils involves either onsite management or excavation and subsequent disposal to a landfill site. This method of disposal solely shifts the contamination problem elsewhere along with the hazards associated with transportation of contaminated soil and migration of contaminants from landfill into an adjacent environment. Soil washing for removing contaminated soil is an alternative way to excavation and disposal to landfill. This method is very costly and produces a residue rich in heavy metals, which will require further treatment. Moreover, these physio-chemical technologies used for soil remediation render the land usage as a medium for plant growth, as they remove all biological activities (Gaur and Adholeya 2004).

Recent concerns regarding the environmental contamination have initiated the development of appropriate technologies to assess the presence and mobility of metals in soil (Shtangeeva et al. 2004), water, and wastewater. Since, these heavy metals cannot be degraded from the nature, at great extent we can take the advantage of natural solar driven process of plants for translocating these contaminants to various parts from the soil or water. Hence, this process is called phytoremediation. Presently, phytoremediation has become an effective and affordable technological solution used to extract or remove inactive metals and metal pollutants from contaminated soil. The term phytoremediation ("phyto" meaning plant, and the Latin suffix "remedium" meaning to clean or restore) refers to a diverse collection of plant based technologies that use either naturally occurring, or genetically engineered, plants to clean up the contaminated soil or water environment (Flathman and Lanza 1998). Phytoremediation is natural, simple, cost effective, non environmentally disruptive green technology and most importantly, its by products can find a range of other economical uses (Truong 1999, 2003). Phytoremediation takes the advantage of the unique and selective uptake capabilities of plant root systems, together with the translocation, bioaccumulation, and contaminant degradation abilities of the entire plant body (Hinchman et al. 1995).

The main objective of this work is to highlight the potential of phyto-products from various plants applied in remediation of heavy metal contaminated soils as well as the usage of the polluted water for co-generation of biofuels using algae (Samardjieva et al. 2011).

Phytoremediation is the use of plants to accumulate, remove or render harmless toxic compounds contaminating the environment. Plants absorb/exclude, translocate, store or detoxify inorganic and organic. Thereby they contribute significantly to the fate of these contaminants from the biosphere. Thus, contaminants (inorganic and organic) can enter the food chain when bio-available, which would cause unwanted effects (Abhilash and Yunus 2011). Many think that phytoremediation is a temporary solution and often the following questions are posed:

(a) There has been a disbelief among scientists and regulators about phytoremediation
(b) How does phytoremediation works?
(c) How to select plants suitable for fostering remediation?
(d) Will phytoremediation work on every heavy metal contaminated/polluted site?
(e) How to dispose of the plants contaminated in this decontamination process?
(f) How to manage the risk based phytoremediation?

Often policy and decision makers, academia and civic governance think that phytoremediation is a temporary solution of transferring the pollutants and contaminants are transferred from one place to another. Scientists and academia are no exception to this feeling. Regulators have expressed apprehensions about phyto-remediation due to lack of knowledge of contemporary knowledge of environmental sustainability. Often, it is generally believed that this kind of environmental decontamination is a temporary solution. How to dispose of the contaminated phytomass is a puzzling question by environmental managers and regulators.

Soil, water and air are the important natural resources that must be cleaned. Unfortunately, natural resources are polluted globally. Rapid industrialization and extraction of large quantity of natural resources including indiscriminate extraction of ground water have resulted in environmental contamination and pollution. Large amounts of toxic waste have been dispersed in thousands of sites spread across the globe resulting in varying degrees of contamination and pollution. Thus, every one of us are being exposed to contamination from past and present industrial practices, emissions in natural resources (air, water, and soil) even in the most remote regions. The risk to human and environmental health is rising and there is evidence that this cocktail of pollutants is a contributor to the global epidemic of cancers, lungs and other degenerative diseases. These pollutants belong to two main classes: inorganic and organic. The challenge is to develop innovative and cost-effective solutions to decontaminate polluted environments.

Bioremediation includes variety of technologies using plants and microbes to remediate or contain contaminants in soil, groundwater, surface water, and/or sediments including air. These technologies have become attractive alternatives to conventional cleanup technologies due to relatively low capital costs and the inherently aesthetic nature.

Bioremediation is the use of biological interventions of biodiversity for mitigation (and wherever possible, complete elimination) of the noxious effects caused by environmental pollutants in a given site. It operates through the principles of biogeochemical cycling. If the process occurs in the same place affected by pollution then it is called *in-situ* bioremediation. In contrast, deliberate relocation of the contaminated material (soil and water) to a different place to accelerate biocatalysis is referred to as *ex-situ* bioremediation. Bioremediation has been successfully applied for cleanup of soil, surface water, groundwater, sediments and ecosystem restoration. It has been unequivocally demonstrated that a number of xenobiotics including nitro-glycerine (explosive) can be cleaned up through bioremediation. Bioremediation is generally considered to include natural attenuation (little or no human action), bio-stimulation or bio-augmentation, the deliberate addition of natural or engineered micro-organisms to accelerate the desired catalytic capabilities. Thus bioremediation, phytoremediation and rhizoremediation contribute significantly to the fate of hazardous waste and can be used to remove these unwanted compounds from the biosphere (Rajkumar et al. 2009, 2010, 2012).

Hibiscus cannabinus (Kenaf), *Brassica juncea* (Indian mustard), *Helianthus annus* (Sunflower), *Ricinus communis* (Castor), *Vetiveria zizanioides* (Khus Khus grass) and *Prosopis juliflora* (Velvet Mesquite) are considered as environmental/ phytoremediation crops. Therefore, phytoproducts (value additives) from the plants that are applied in phytoremediation and safe disposal of contaminated phytomass (risk based remediation) would propel bioeconomy.

7.3.1 Products from Phytoremediated Crops

Due to rapid globalization of the current century, the demand for energy is steeply increasing. Use of fossil fuels have an adverse environmental impact although economic viability and efficiency are in favour of fossil fuels. To reduce the negative impact of fossil fuels, use of contaminated substrates for bioenergy is being researched globally (Meers et al. 2010). This strategy avoids competition over land use for food crops. Further, vast resources that can be harvested from contaminated substrates, conversion through efficient biorefineries via research and development is being tapped in many countries. Technically, biomass and the conversion products can be used as supplemental sources for conventional fuels (fossil fuels) and chemical feedstock for various industries. This approach is promising in the area of alternate sources of energy and dependency on fossil fuels can be minimized to a considerable extent. The production of biomass involves the use of abundantly available and rapidly growing non-agricultural plants, preferably with good coppicing and nitrogen fixing capabilities to produce energy products by suitable conversion technologies (Table 7.2).

The annual photosynthetic storage of energy in biomass is eight times more that of energy use from all sources. This estimate clearly illustrates the immense potential of biomass resources, if harnessed and managed sustainably. Further, biomass derived constituents serve as analogues of fossil fuel derivatives. Sunflower and Indian mustard are popular energy and environmental crops (Fozia et al. 2008; Madejón et al. 2003).

Large tracts of contaminated sites are available in different agro-climatic zones of our country. A number of multiuse plant species with energy rich chemicals have been identified. It is therefore, necessary to integrate such energy plantations into a system of rotational cycle to suit socio-economic aspects of the people. Broad areas of biomass energy sources.

Energy crops include corn, sugar cane, sugar beet, cassava, soyabean and other sugar and starch producing crops. In Brazil, sugar cane cultivation was expanded to some extent at the expense of food crop. Brazil, USA, Philippines, Germany use blended mixture of gasoline and alcohol. Such a blended fuel was termed Gasohol or alcogas. Brazil's National alcohol and pure alcohol programmed "Proalcool" aims at running cars on gasohol and pure alcohol. Cassava (mandioca, tapioca), grown in many developing countries is rich in starch. It can be cultivated

Table 7.2 Metal accumulation reports with reference to *Brassica juncea* (Indian mustard)

As	Srivastava et al. (2013)
As, Cd, Cu, Fe, Mn, Pb, Zn,	Clemente et al. (2005, 2006)
Au	Bali et al. (2010)
B	Giansoldati et al. (2012)
Cd	Schneider et al. (1999), Lee and Leustek (1999), Qadir et al. (2004), Quartacci et al. (2005), Minglin et al. (2005), Nouairi et al. (2006), Manciulea and Ramsey (2006), Mobin and Khan (2007), Hayat et al. (2007), Seth et al. (2008), Szőllősi et al. (2009), Hong-Xia et al. (2009), Ahmad et al. (2011); Bauddh and Singh (2012a, b)
Cd, Zn	Sridhar et al. (2005)
Cd, Co, Cr, Cu, Fe, K, Mn, Na, Ni, Pb, Zn,	Gupta and Sinha (2007)
Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn,	Gupta and Sinha (2006)
Cd, Cr, Cu, Pb, Zn	Quartacci et al. (2006)
Cd, Cu, Ni, Zn,	do Nascimento et al. (2006)
Cd, Cu, Pb, Zn,	Wu et al. (2004)
Cd, Cu, Zn	Schafer et al. (1997)
Cd, Fe	Qureshi et al. (2010)
Cd, Ni	Cao et al. (2008)
Cr	Pandey et al. (2005), Pandey (2013), Rajkumar et al. (2006), Sinha et al. (2009)
Cr, Ni	Hsiao et al. (2007)
Cu	Fariduddin et al. (2009), Singh et al. (2010), Chigbo et al. (2013)
Cu, Fe, Mn, Pb, Zn	Walker et al. (2003)
Hg	Shiyab et al. (2009), Meng et al. (2011), Cassina et al. (2012)
Mo, Se	Schiavon et al. (2012)
Ni	Rajkumar and Freitas (2008a, b), Ali et al. (2008), Kanwar et al. (2012)
Pb	Liua et al. (2000), Lim et al. (2004), Meyers et al. (2008), Zaier et al. (2010), Ghnaya et al. (2013)
Pu	Lee et al. (2002)
Se	Grant et al. (2004), Kahakachchi et al. (2004), Yathavakilla et al. (2005), Hladun et al. (2011), Jaiswal et al. (2012)
Zn	Alia and Saradhi (1995), Prasad et al. (1999), Saxena et al. (2005)

in wide range of agroclimatic situations and does not require high dosage of fertilizer and pesticides to produce high yields. The notable examples of biomass conversion to biofuels are sweet sorghum and *Miscanthus* (Babu et al. 2014; Brosse et al. 2009; Chami et al. 2014; El Hage et al. 2010; Pavel et al. 2014; Płażek et al. 2014; Sharmin et al. 2012).

Bioenergy is renewable alternative fuel/energy produced from materials derived from biological sources such as plants, animal oils or fermentation. Biomass is any organic material which has stored sunlight in the form of chemical energy. As a fuel it may include wood, wood waste, straw, manure, sugarcane, and many other byproducts from a variety of agricultural processes. Energy is a key to socio-economic development (Figs. 7.14–7.16).

Sunflower crop can be grown in the pollution affected areas. The root system of the plan develops well in varying soil pH conditions. Moistening and acidification of the rhizosphere could enhance the nutrient uptake mechanism of the crop, inducing a 'fertilising' effect (Junkang Guo et al. 2014; Juwarkar et al. 2008; Khouja et al. 2013; Kötschau et al. 2014; Liphadzi and Kirkham 2006; Madrid et al. 2008; Rajkumar et al. 2009; Stanbrough et al. 2013). Sunflower is a multipurpose crop producing a variety of industrial feed stock.

In recent years environmental crops for e.g. Indian mustard, sunflower and sweet sorghum etc. have gained considerable attention. The primary goal of this exercise is to cultivate these crops using contaminated substrates with two objectives. (a) to combat environmental pollution, and (b) to produce beneficial and regenerable products.

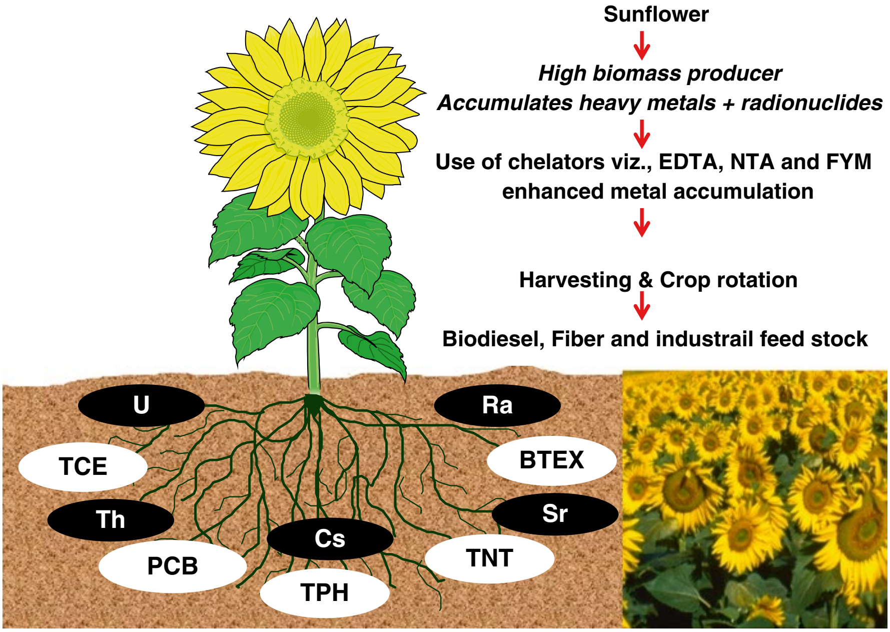


Fig. 7.14 Sun flower as environmental crop for cultivation on inorganic and organics contaminated environment. Biodiesel, fiber and industrial feed stock are the phytoproducts. *BETX* Benzene, Ethylbenzene, Toluene and Xylenes, *Cs* Cesium, *Ra* Radium, *Sr* Strontium, *TCE* Trichloroethylene, *Th* Thorium, *TNT* Trinitrotoluene, *TPH* Total petroleum hydrocarbons, *U* Uranium

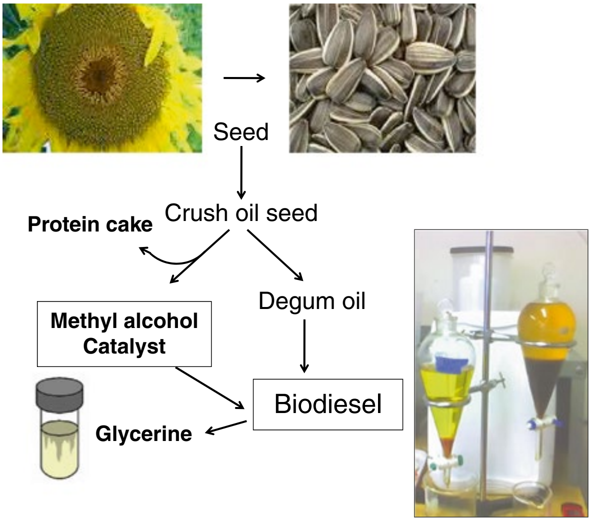


Fig. 7.15 Biodiesel and cogeneration of industrial feed stock from sun flower from phytoremediated crop produce

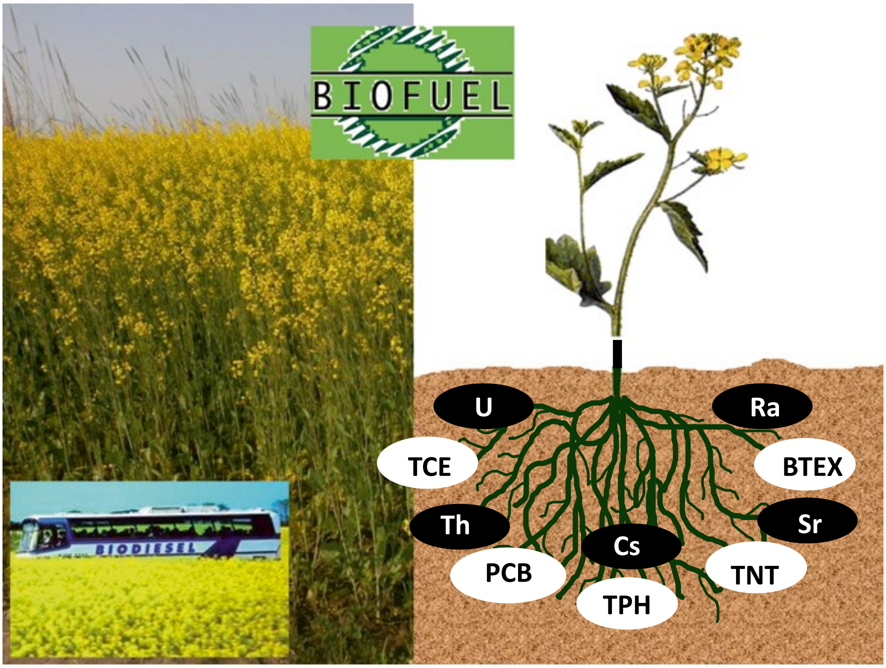


Fig. 7.16 *Brassica juncea* (Indian mustard) as environmental crop for cultivation on inorganic and organics contaminated environment. Biodiesel is the main byproduct (Marillia et al. 2014; Tomé et al. 2009). *BETX* Benzene, Ethylbenzene, Toluene and Xylenes, *Cs* Cesium, *Ra* Radium, *Sr* Strontium, *TCE* Trichloroethylene, *Th* Thorium, *TNT* Trinitrotoluene, *TPH* Total petroleum hydrocarbons, *U* Uranium

The biofuel generations are the following:
1st generation – Jatropha based
2nd generations – lignocellulosic ethanol
3rd generation – algal biofuels
4th generation – Bio-butanol, bio-hydrogen, biomethyl furan etc.

7.3.2 Medicinal and Aromatic Plants on Contaminated Soils

Aromatic crops, used for production of essential oils as opposed to food or feed, may be suitable alternative crops in heavy metal contaminated agricultural as well as non-agricultural soils. Essential oils are low-volume, high value products that are widely used as aromatic agents in various non-food industries, such as perfumery, cosmetics, and aromatherapy suggesting the possibility that such plants could be used in phytoremediation of contaminated soils. The use of aromatic plants for phytoremediation may have several advantages over other crop plants in that the harvested foliage is a source of essential oils, which are the marketable revenue-generating products of aromatic crops. Growing of these aromatic crops in metal contaminated areas may not introduce heavy metals into the food chain and may not result in an economic penalty compared to most other edible crops. In the process of oil extraction by distillation, heavy metals remain in the extracted plant residues, limiting the quantities of heavy metals in the commercial oil product (Zheljazkov and Nielsen 1996; Scora and Chang 1997; Zheljazkov and Warman 2004). Thus, significant amounts of heavy metals could be removed from the soil through proper disposal of the metal contaminated plant residues, while the metal-free, extracted oils could be safely marketed. High-value aromatic crops may be a better alternative for heavy metal contaminated agricultural soils than the suggested woody species such as *Salix* and *Betula* (Hammer et al. 2003; Rosselli et al. 2003), or other plants like *Sesbania drummondii* that have been shown to hyperaccumulate Pb (Sahi et al. 2002). For disposal of metal contaminated phytomass, several approaches such as composting, incineration, ashing, pyrolysis, direct disposal and liquid extraction have been proposed (Sas-Nowosielska et al. 2004; Keller et al. 2005).

Some aromatic plants appear capable of accumulating heavy metals from contaminated soil (Chand et al. 2012; Zheljazkov and Nielsen 1996; Zheljazkov and Warman 2004; Zheljazkov et al. 2008b; Chaiyarat et al. 2011; Aziz et al. 2011; Amirmoradi et al. 2012), and some might demonstrate significant phytoremediation potential if coupled to other means for increasing bioavailability and uptake of Cd, Pb, and Cu, such as chelates (Schmidt 2003) or biosurfactants (Mulligan et al. 2001) (Fig. 7.17).

The effects of these metals on growth, essential oil production, and metal accumulation of most commercially important essential oil producing aromatic crops, such as coriander (*Coriandrum sativum* L.), dill (*Anethum graveolens* L.), chamomile (*Chamomilla recutita* (L.)K.), peppermint (*Mentha x piperita* L.), basil (*Ocimum basilicum* L.), hyssop (*Hyssopus officinalis* L.), lemon balm (*Melissa officinalis* L.), and sage (*Salvia officinalis* L.) are, however, largely

Fig. 7.17 *Commiphora wightii*, a source of guggul steroids capable of growing on lime stone quarry waste

unknown. Coriander, dill, chamomile, peppermint, basil, hyssop, lemon balm, and sage are aromatic crops that have been traditionally grown as cash crops in Europe (Topalov 1962), and North America. Coriander, dill, chamomile, peppermint, basil, hyssop, lemon balmand sage have very high phytoremediation potential (Brown et al. 1998) (Table 7.4).

Traditionally, peppermint, basil, and sage tissue wastes after distillation are used as feed for sheep (Topalov 1962). Results of experiments demonstrated that if peppermint, basil, and sage are grown in highly heavy metal contaminated medium, Cd, Pb, and Cu may accumulate in shoots and wastes from distillation above the maximum permissible concentrations for these elements in animal feed (NRC 1985), making these waste products unsuitable as animal feed. To reduce the amount of Cd, Pb, and Cu and produce usable final product, metal contaminated distillation wastes could be composted after mixing with wastes from other low metal feedstock.

Trace elements in the healing plants can act as remedies (Prasad 2008). Trace elements accumulated in medicinal plants have healing power in numerous ailments and disorders. Herbal preparation known as ‘bhasmas’ (ash of the polyherbals and specific plants and or their parts) are popular in Ayurveda, Indian traditional medicinal system. According to this medicinal system, metal based drugs known as ‘bhasma’ involve the conversion of a metal into its mixed oxides. Plants that accumulate metals and metalloids have gained considerable significance and are implicated in healing function. Plants that accumulate essential trace elements are implicated in propelling metabolic processes (metallomics) (Prasad 2008).

7.3.3 Ornamentals for Environmental Moderation and Toxic Trace Metal Cleanup

Several ornamental plants have been successfully applied in environmental toxic cleanup (Figs. 7.17–7.25) (Abad et al. 2001; Bosiacki 2009a, b; Ding and Hu 2012). For e.g. Lemon-scented geraniums (*Pelargonium* sp. 'Frensham', or scented geranium) accumulated large amounts of Cd, Pb, Ni and Cu from soil in greenhouse experiments (Bosiacki 2008; Dan et al. 2000; Saxena et al. 1999). Biotechnological interventions through hairy root regenerants are useful in floriculture (Giri and Narasu 2000; Giovanni et al. 1997). Pellegrineschi et al. (1994) improved the ornamental quality of scented *Pelargonium* spp. This plant has pleasant odor that adds scent to the toxic metal contaminated soil.

Vetiveria zizanioides (Vetiver grass): It is known to have multiple uses. This plant had several popular names such as 'the miracle grass', 'a wonder grass', 'a magic grass', 'an unique plant', 'an essential grass', 'an amazing plant', 'an amazing grass', 'a versatile plant', 'a living barrier', 'a living dam', 'a living nail', 'a living

Fig. 7.18 Cultivation of ornamentals on contaminated soils in peri urban Greater Hyderabad. (**a**) *Chrysanthemum* sp. (*pink* flowers) (**b**) *Chrysanthemum* (*Yellow* flowers), (**c**) *Gaillardia* sp. and (**d**) *Rosa* sp. (Colour figures online)

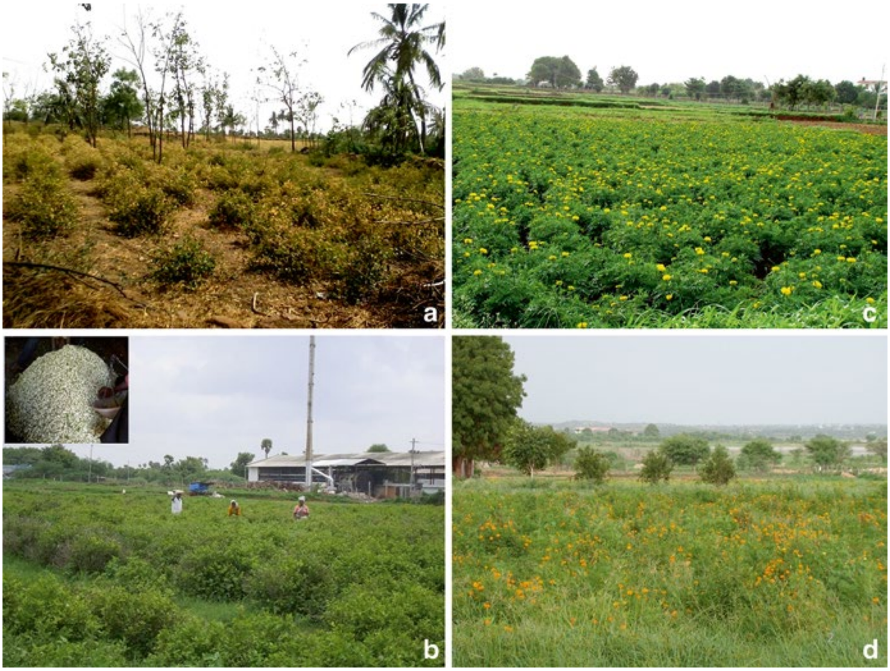


Fig. 7.19 Cultivation of ornamentals on contaminated soil in perdi urban Greater Hyderabad (**a**) and (**b**) Jasminum *officinale* L. with Musi river contaminated water. (**c**) and (**d**) *Tagetes* sp. (Patel and Patra 2014)

Fig. 7.20 Cultivation of (**a**) *Crossandra infundibuliformis* (L.) Nees with Musi river contaminated water (**b**) flowers of *C. infundibuliform* (**c**) *Asparagus setaceus* (Kunth) Jessop and (**d**) *Origanum majorina*

Fig. 7.21 Ornamentals in commercial market (**a**) *Chrysanthemum* sp. (**b**) *Alternanthera* sp.

wall', 'an eco-friendly grass'. This extraordinary grass is adaptable to multiple environmental conditions and it is globally recognized as an easy and economical alternative to control soil erosion and to solve a variety of environmental problems. It has been used for restoration, conservation and protection of land disrupted by man activities like agriculture, mining, construction sites, oil exploration and extraction, infrastructure corridors, as well as used for water conservation in watershed management, disaster mitigation and treatment of contaminated water and soil. Research at the global level has proved the relevance of vetiver in multiple applications. *Vetiveria zizanioides* exhibited high metal tolerance (Andra et al. 2009, 2010, 2011; Chintakovid et al. 2008; Chen et al. 2012; Chiu et al. 2006; Chong and Chu 2007; Danh et al. 2011; Rotkittikhun et al. 2007; Makris et al. 2007; Pang et al. 2003; Truong 2000; Wilde et al. 2005) and is used in stabilization of mine tailings in different parts of the world (Frérot et al. 2006; Pérez-López et al. 2014; Rocio et al. 2013).

The debris generated from the ornamentals containing the toxic metal residues can be treated easily as the biomass would be relatively less in view of high water content. Appropriate techno-economic feasible options based on integrated model systems was recently suggested for the appropriate use of *Eichhorinia crassipes*

Fig. 7.22 Ornamentals in commercial market (**a**) *Rosa* sp. (**b**) *Lilium* sp. (**c**) *Jasminum officinale* L.

Fig. 7.23 Water ornamentals. (**a**) *Pistia stratiotes* L. dry phytomass. (**b**) *Nymphaea odorata* Aiton. (**c**) *N. nouchali* Burm. f. (**d**) *N. pubescens* Willd.

Fig. 7.24 (**a** and **b**) *Vetiveria zizanioides* and (**c** and **d**) Water lilies (*Nymphaea*) in commercial market

Fig. 7.25 Ornamental *Canna indica* in soil scape filtration for removal of nutrients and colouring material from waste water (Huiping Xiao et al. 2010)

(water hyacinth) (Malik 2007). Similar solutions need to be worked out for the ornamentals proposed for toxic metal celanup.

Ornamental plants have an added advantage of enhancing environmental aesthetics besides cleaning the environment. This approach has several advantages for environmental moderation, cleanup and generation of revenue. Therefore, this approach will add new dimension to the field of phytoremediation of contaminated environment. The compost generated from the phytoremediated ornamental plants serves as a medium for use as growing media for production ornamentals (Page et al. 2014).

"Scent the soil" with aromatic plants is a fascinating proposition. Several potential and promising options exist for environmental management of contaminated soils using medicinal and aromatic plants. Yet certain bottlenecks are to be investigated for wider applications. The regulatory bodies and biosafety issues might complicate this approach. The compost generated from the ornamentals plants used in remediation serves as a compost and can be reused as growing media for production ornamentals. The quantum of biomass generated would be relatively less in view of high water content in several of these ornamentals. Integrated model and appropriate techno-economic feasible options were suggested for the use of *Eichhorinia crassipes* (water hyacinth) (Malik 2007). Similar solutions need to be worked out for the ornamental proposed for toxic metal celanup.

7.3.4 Non-edible Oil Plants for Biofuels on Contaminated Soil

Non-edible vegetable oils or the second generation feed stocks have become more attractive for biodiesel production. These feed stocks are very promising for the sustainable production of biodiesel (Agbogidi and Eruotor 2012; Agbogidi et al. 2013; Ahmadpour et al. 2010; Jamil et al. 2009; Liang et al. 2012; Luhach and Chaudhry 2012; Majid et al. 2012; Mangkoedihardjo and Surahmaida 2008).

Taking the advantage of second generation biodiesel plants and obtaining the biodiesels from these plants as most of these plants naturally grown in highly contaminated with variety of inorganic and organic pollutants. Most of the these plants grow widely in contaminated substrates. Our field work survey reveled that some of the potential plants are *Ricinus communis, Jatropha curcas, Azadiracta indica*. The world's dependence on fossil fuels is a perfect example. Therefore, biodiesel feedstock should be as diversified as possible, depending on geographical locations in the world. Therefore, exploring alternative biodiesel feedstocks like non-edible vegetable oils should be an important objective for biodiesel industries in near future.

In developing countries like India, biofuel program of Government of India has launched alcohol production from sugar/starch based feedstock the *Jatropha curcas* plant has been planted on massive scale on waste/degraded or other lands to open new avenues for producing biodiesel from *Jatropha curcas* oil thereby reducing/saving foreign exchange needed to import the petroleum fuel (Abioye et al. 2010; Acharya et al. 2012; Gao et al. 2009; Ghavri and Singh 2012; Kumar et al. 2008, 2013; Singh et al. 2013, 2014; Wu et al. 2011; Yadav et al. 2009). In biodiesel production, India is on 8th position with 0.03 billion liters of biodiesel production per year.

The above problem can be solved by using cheapest, low cost several potential tree borne oil seeds (TBOs) and non-edible crop source have been identified as suitable feed stock for biodiesel. However, it must be pointed out that global biodiesel feed stocks should not rely on certain sources as it could bring harmful influence in the long run. The worlds' dependence on fossil fuels is a perfect example.

Therefore, biodiesel feed stock should be as diversified as possible, depending on geographical locations in the world. The determined properties beside the engine performance and emission characteristics of non-edible biodiesel covered in this review indicated that there is a huge chance to produce biodiesel from non-edible sources in the future.

Since, India is net importer of edible vegetable oils, these oils are therefore not available for conversion to biodiesel. India has the potential of becoming the world's leading producer of biodiesel, as it can be "harvested," and produced from non-edible oils like *Jatropha curcas, Pongamia pinnata, Madhuca indica* plants etc (Awwokunmi et al. 2012; Bauddh and Singh 2012a, b).

The increasing use of biodiesel in India will provide green cover to wasteland, support the agricultural and rural economy, reduce the dependency on imported crude oil and improve the environmental emissions. Even though, 12 *Jatropha* species are reported by several Indian floras, research has been confined to nine species only. Among all the *Jatropha* species, *J. curcas* is the most primitive form and has the potential for biodiesel and for medicinal (Abd El-Kader et al. 2012).

There are several tree species that are suitable for Biodiesel production like *Jatropha sps., Pongamia pinnata (Millettia pinnata), Moringa, Simarouba glauca, Calophyllum inophyllum, Citrullus colocynthis, Simmondsia chinesis, Helianthus tuberosus, Garcinia indica, Madhuca indica, Azadirachta indica, Linum usitatissimum* etc. (Fig. 7.26).

Advantages of non-edible oil as Biodiesel has the following advantages:

- Mitigate Environmental Global Warming
- Energy Security
- Rural and Urban Economic Development
- Reduce Sulfur/Aromatics
- Clean Air
- Health Effects
- Biodiesel Exhausts reduce Carcinogen Emissions
- High Cetane and Lubricity
- Biodegradable
- Non-Toxic
- The cancer causing potential of diesel exhaust largely a function of:

Amount, size, and composition particulates
Mutagenicity of exhaust gases
High exhaust mutagenicity can cause:
shortened life, birth defects
asthma and respiratory problems
specially in infants or the elders

Fig. 7.26 Cultivation of biodiesel and oil producing crops contaminated soil (**a**) *Ricinus communis* (**b**) *Vetiveria zizanioides* (**c**) *Jatropha curcas* and (**d**) *Moringa oleifera*

7.3.5 Tree Crops

The following are some examples *Casurina equisetifolia*, *Leucaena leucocephala* (Subabul, koobabul, ipil-ipil, lead tree, tan tan, white popinac etc.) *Parkinsonia aculeata* (Jerusalem thorn), *Pithecellobium dulce* (Jangil jailebi), *Bauhinia variegata, Cassia siamea, Prosopis juliflora* (Mesquite), *P. chiliensis* (Paradeshi Babul), *P. cineraria* (Khejri), *Peltophorum pterocarpum* (Copper pod), *Sesbania gradiflora* (Avisa), and *S.bispinosa* (Jeelgu) (Yang et al. 2003; Zalesny et al. 2009). However, only a few like *Eucalyptus, Leucaena* and *Casuarina* are mostly grown (monoculture). In such plantations, wood production is about 20 cu m/ha/year/ to 60 cu m/ha/year. *Eucalyptus* wood has industrial value in pulp, rayon charcol, methanol distilleries (Fig. 7.27).

In the contemporary time energy and environment security are at stake in our situation. Land resources are under immense pressure glocally (globally and locally). The pressure on available land resources is increasing due to land degradation, population explosion, global economic development and urbanization. Land degradation is mainly due to erosion, nutrient depletion, loss of organic matter, structural losses, induced land degradation, faulty irrigation, atmospheric deposition of pollutants, poor agricultural practices. Climate changes increases the inten-

Fig. 7.27 Stabilization of mine tailings with *Cymbopogon citratus* (lemon grass) miracle grass, *Vetiveria zizanioides* and Jatropha curcas (**a**) Nyveli lignite mine (**b**) Mine over burden (**c**) *Jatropha curcas* plantation in mine over burden and (**d**) Jatropha biodiesel

sity of land degradation. Therefore, utilization of contaminated environment (terrestrial and aquatic) following the principles of phytoremediation for biofuel production would be one of the sustainable options (Núñez-López et al. 2008). Although this strategy has immense scope and limitations (Tables 7.3 and 7.4) considerable progress and successful demonstration projects have provided convincing evidence for environmental moderation, cleanup and co-generation of revenue. Therefore, this approach will add new dimension to the field of sustainable development.

Natural vegetation of *Prosopis juliflora* in Patancheru Industrial Development Area contaminated with highly above permissible limits of heavy metals in soil and surface and ground water. *Prosopis juliflora* is an evergreen, fast growing, drought resistant, widely distributed phreatophyte not only in India but also in other arid and semi-arid tropical countries. A valued tree for shade, timber and forage It is a thorny, deciduous, large crowned and deep rooted bush or tree which grows up to 10 m height or more, depending on the variety and climatic conditions. It is widely distributed in the dry tropical and sub-tropical regions of Central America and Northern South America. Also, it is widely propagated in Africa and Asia. It is the only exotic species capable of growing on a wide variety of soils and climatic conditions. It is an ideal species for afforestation and helps in the reclamation of waste lands, stabi-

Table 7.3 Metal accumulation reports with reference to *Helianthus annus* (sun flower) (Ruiz et al. 2007)

Al, Cd, Cr	Gallego et al. (2002)
Al, Cd, Cu, Fe, Mn, Zn	Fauziah et al. (2011)
Al, Cd, Cu, Ni, Pb, Zn	Chakravarty and Srivastava (1992)
As	Baroni et al. (2004)
As, Ca, Cd, Co, Cr, Cu, Mn, Na, Ni, Pb, U, V, Zn	Paun et al. (2012)
As, Cd, Co, Cu, Pb, Zn	Marchiol et al. (2007)
As, Cd, Cr, Fe, Ni,	January et al. (2008), Cutright et al. (2010)
Ca, Cd, Co, Cu, K, La, Li, Mg, Mn, Na, Ni, Zn	Enache et al. (2003)
Cd	Yurekli and Kucukbay (2003), Gallego et al. (2005)
Cd, Cr, Cu, Pb, Zn	Soudek et al. (2010)
Cd, Cr, Ni	Chen and Cutright (2001)
Cd, Cr, Pb,	Ullah et al. (2011)
Cd, Cu, Fe, Mn, Ni, Pb, Zn	Liphadzi et al. (2003)
Cd, Cu, Ni, Pb, Zn	Meers et al. (2005), Jadia and Fulekar (2008)
Cd, Cu, Ni, V, Zn	Lombi et al. (1998)
Cd, Cu, Pb,	Adewole et al. (2010)
Cd, Cu, Pb, Zn	Garcia et al. (2006, 2009), Nathan et al. (2012), Mayora et al. (2012), Angelova et al. (2012)
Cd, Hg	Rai and Kumar (2010)
Cd, Pb	Lotfy et al. (2009) Awotoye et al. (2009)
Cd, Pb, Zn	Nehnevajova et al. (2005, 2007)
Cd, Zn	Xiu-Zhen et al. (2012)
Cr	Fozia et al. (2008)
Cr, Fe, Mn, Zn,	Singh et al. (2004)
Cr, Pb	Araiza-Arvilla et al. (2006)
Cs	Soudek et al. (2004)
Cs, Sr, U	Prasad (2007b)
Cu	Zengin and Kirbag (2007), Herrera-Rodríguez et al. (2007)
Cu, Cd, Pb, Zn,	Lesage et al. (2005)
Cu, Fe, Mn, Si, Sr, Ti, Zn,	Busuioc et al. (2009)
Cu, Fe, Mn, Zn	Sabudak et al. (2007)
Cu, Ni, Zn	Rajkumar et al. (2008)
Cu, Pb, Zn,	Tandy et al. (2006)
Hg	Pedron et al. (2013)
Ni	Szymaska and Matraszek (2005), Najafi et al. (2011)
Pb	Azhar et al. (2006), Sinegani and Khalilikhah (2008), Melo et al. (2009), Azhar et al. (2009), Sinha et al. (2011), Usha et al. (2011), Azad et al. (2011), Chandra et al. (2011), Seth et al. (2012)
Pb, Zn	Solhi et al. (2005), Adesodun et al. (2010)
Ra, U	Tomé et al. (2008)
Zn	Fauziah et al. (2011)

Table 7.4 Medicinal and aromatic plants capable of growing on contaminated soils

Plant name	Common name	Family	Parts used
Abies densa	Silver fir	Pinaceae	Wood
Acorus calamus	Sweet flag	Araceae	Rhizome
Acorus gramineus	Sweetflag	Araceae	Aerial parts
Acorus gramineus	–	Araceae	Rhizome
Adenosma indicum	–	Scrophulariaceae	Aerial parts
Amomum sp.	Cardamom	Zingiberaceae	Fruit
Aquilaria crassna	Eaglewood	Thymelaeaceae	Wood
Artemisia vulgaris	Mugwort	Asteriaceae	Aerial parts
Blumea balsamifera	–	Asteriaceae	Leaf
Chenopodium ambrosioides		Chenopodiaceae	Aerial parts
Cinnamomum camphora	Camphor	Lauraceae	Wood
Cinnamomum cassia	Cassia	Lauraceae	Bark, leaf
Cinnamomum glaucescens	–	Lauraceae	Berry
Cinnamomum iners	Thai cinnamon	Lauraceae	Bark
Cinnamomum loureirii	Vietnamese cassia	Lauraceae	Bark
Cinnamomum obtusifolium	–	Lauraceae	Bark, leaf
Cinnamomum tamala	Indian cinnamon	Lauraceae	Leaf
Citrus hystrix	Leech lime	Rutaceae	Fruit peel
Cunninghamia sinensis	–	Pinaceae	Saw dust
Cymbopogon distans	–	Poaceae	Aerial parts
Elscholtzia cristata	–	Lamiaceae	Aerial parts
Elsholtzia blanda	–	Lamiaceae	Aerial parts
Eucalyptus globulus	Eucalypt	Myrtaceae	Leaf
Gaulteria fragrantissima	Wintergreen	Ericaceae	Leaf
Homalomena aromatica	–	Araceae	Rhizome
Homalomena occulta	–	Araceae	Rhizome
Hyptis suaveolens	–	Lamiaceae	Herb
Jasminum sambac	Arabian jasmine	Oleaceae	Flower
Juniperus indicus	Juniper	Cupressaceae	Berry
Lavandula angustifolia	Lavender	Lamiaceae	Flower
Lavandula officinale	Lavender	Lamiaceae	Flower
Litsea cubeba	Cubeb	Araceae	Fruit
Lonicera japonica	Honeysuckle	Caprifoliaceae	Flower
Michelia alba	Champi	Annonaceae	Flower
Nardostachys grandiflora	Spikenard	Valerianaceae	Rhizome
Ocimum gratissimum	Lemon basil	Lamiaceae	Aerial parts
Ocimum tenuiflorum	Holy basil	Lamiaceae	Aerial parts
Parmelia nepalensis,	Lichens/ Tree moss	Parmeliaceae	Whole plant
Pelargonium fragrans	Nutmeg-scented geranium	Geraniaceae	Leaf
Pelargonium capitatum	Alta of rose geranium	Geraniaceae	Leaf
Pelargonium crispum	Curly-leaved geranium	Geraniaceae	Leaf
Pelargonium graveolens	Pot geranium	Geraniaceae	Leaf
Pelargonium macrorrhizum	Scented geranium	Geraniaceae	Twig
Pelargonium pratense	Scented geranium	Geraniaceae	Twig
Pinus roxburghii	Pine	Pinaceae	Resin
Pinus khasya	Pine	Pinaceae	Resin
Pinus merkusii	Pine	Pinaceae	Resin

(continued)

Table 7.4 (continued)

Plant name	Common name	Family	Parts used
Rhododendron anthopagon	Rhododendron	Ericaceae	Twig
Rosa damascena	Damask rose	Rosaceae	Flowers
Usnea sp. *Ramaliana* spp.	Lichens/Tree moss	Usneaceae	Whole plant
Vetiveria zizanioides	Vetiver	Poaceae	Root
Zanthoxylum armatum	Zanthozylum	Rutaceae	Fruit
Zingiber purpureum	Phlai’	Zingiberaceae	Rhizomes

Table 7.5 Metal accumulation in selected Medicinal and aromatic plants

Plant name	Metals	References
Anethum graveolens	Cd, Pb, Cu, Mn, Zn	Zheljazkov et al. (2008a, b)
Chamomilla recutita		
Coriandrum sativum		
Hyssopus officinalis		
Melissa officinalis		
Mentha x piperita .		
Ocimum basilicum		
Salvia officinalis		
Acorus calamus	Al, Ca, Fe, K, Mg, Na, P, Zn	Ozcan and Akbulut (2007)
Artemisia absinthium		
Brassica alba		
Capparis ovata		
Capsicum frutescens		
Carum copticum		
Cinnamomum zeylanicum		
Cuminum cyminum		
Echinophora tenuifolia		
Foeniculum vulgare ssp. piperitum		
Glycyrrhiza glabra		
Laurusnobilis		
Matricaria chamomilla		
Melissa officinalis		
Mentha piperita		
Myrtus communis		
Nigella sativa		
Ocimum minumum		
Pimpirella anisum.		
Piper nigrum		
Rhus coriaria		
Rosmarinus officinalis		
Salvia aucheri		
Salvia fruticase		
Satureja hortensis		
Sesamum indicum		
Syzygium aromaticum		
Thymbra spicata		
Tilia cordata		

(continued)

Table 7.5 (continued)

Plant name	Metals	References
Ocimum basilicum	Cd, Pb, Zn	Galeş et al. (2009)
Salvia officinalis		
Vetiveria zizanioides	Cd, Pb	Minh and Khoa (2009)
Catharanthus roseus *Hyptis suaveolens*	Cu, Fe, Al, Cr	Deo et al. (2011)
Woodfordia fruiticosa		
Taraxacum officinale	Pb, Cd, Cu, Zn, Hg, Fe, Co, Cr, Mo	Malawska and Wiłkomirski (2001)
Artemisia herba alba,	Al, Ca, Fe, K, Mg, Mn, P, Ba, Cd, Pb, Zn	Imelouane et al. (2011)
Lavandula dentata,		
Rosmarinus tournefortii,		
Thymus vulgaris		
Salvia officinalis	Pb, Cd, Cr, Co, Ni, Zn, Fe, Cu, Mn	Abu-Darwish et al. (2011)
Salvia officinalis	Pb, Cd, Cu, Zn	Blagojević et al. (2009)
Thymus *vulgaris*	Cd, Cr, Pb, Ni, Cu, Mn, Zn, Fe, Co	Abu-Darwish (2009)
Thymus serpyllum		
Salvia officinallis		
Tribulus terrestris	Cd, Pb, Zn	Stancheva et al. (2011)
Salvia officinalis	Cd, Cu, Pb, Zn	Stancheva et al. (2009)
Hyssopus officinalis	Cd, Pb, Cu, Mn, Zn, Fe	Roodi et al. (2012)
Satureja montana		
Hypericum perforatum		
Achillea millefolium		
Mentha piperita		
Mentha arvensis var *piperascens* Malinv.		
Majorana hortensis	Ca, Na, Mg, Fe, Mn, Zn, Cu, Cd, Ni, Pb	Khalifa et al. (2011)
Mentha pipperita		
Pelargonium graveolens		
Foeniculum vulgaris		
Matricaria chamomilla		
Abutilon indicum	V, Cr, Mn, Ni, Co, Cu, Zn, As, Se, Rb, Sr, Mo, Ag, Cd, Sb, Ba, Ti, Pb, U, Na, Mg, Al, Si, K, Ca, Fe	Kumari et al. (2012), Bauddh and Singh (2012a, b)
Achyranthes aspera var.		
Adhatoda vasica Nees,		
Alternanthera sessilis		
Azadirachta indica		
Eucalyptus globulus		
Hyptis pectinata		
Ocimum sanctum,		
perphyristachya		
Ricinus communis		
Tinospora cordifolia		
Vetiveria zizanioides	As, Cd, Cr, Cu, Hg, Ni, Pb, Se, Zn	Danh et al. (2009)
Vetiveria zizanioides	Zn, Cu, Ni, and Cr	Roongtanakiat et al. (2003)

(continued)

Table 7.5 (continued)

Plant name	Metals	References
Rosmarinus officinalis *Origanum majorana*	Fe, Mn, Zn, Ni, Cu, Pb, Cd, Cr, Co	Koc and Sari (2009)
Sideritis congesta		
Mytrus communis		
Hypericum perforatum		
Capsicum annum		
Thymus vulgaris		
Saturage hortensis		
Melisa officinalis		
Lavandula officinalis		
Vitex agnis		
Mentha piperita		
Laurus nobilis		
Chrysopogon zizanioides	Fe, Zn, Mn, Cu	Roongtanakiat et al. (2009)
Chrysopogon nemoralis	Zn, Cd, Pb	Roongtanakiat and Sanoh (2011)
Chrysopogon zizanioides		
Acorus calamus	Pb, Cd, Ni, Cu, Fe, Mn, Co, Zn	Malenčić et al. (2005)
Thymus montanus		
Salvia verticillata		
Ocimum gratissimum	Cd, Zn	Chaiyarat et al. (2011)
Mentha piperita	Co	Aziz et al. (2011)
Mentha piperita	Cd, Pb	Amirmoradi et al. (2012)
Majorana hortensis,	Ca, Mg, Na, Fe, Mn, Zn, Cu, Cd, Ni, Pb	Hussein et al. (2006)
Mentha pipperita		
Pelargonium graveolens,		
Foeniculum vulgaris,		
Matricaria chamomilla,		
Salvia officinalis	Cd, Cu, Pb, Zn	Stancheva et al. (2009)
Azadiractha indica	Zn, Pb, Cd	Princewill-Ogbonna and Ogbonna (2011)
Occimum gratissimum		
Vernonia amygdaline		
Mentha arvensis	Pb, Ni, Cr, Zn, Cu, Mn	Chand et al. (2012)
Catharanthus roseus	Cd, Mn, Ni, Pb	Srivastava and Srivastava (2010)
Rosmarinus officinalis	Zn, Pb, Cd	Gaïda et al. (2013)
Vetiveria nigritana,	Cd, As, Pb	Oshunsanya et al. (2012)
Vetiveria zizanioides		
Matricaria recutita,	Cd, Pb, Ni	Lydakis-simantiris et al. (2012)
Salvia officinalis		
Thymus vulgaris		
Phyllanthus amarus,	Al, Cd, Pb, As	Jadhav et al. (2012), Agamuthu et al. (2010)
Jatropha gossypifolia		
Ruta graveolens		

lization and prevents soil erosion. It has tremendous field potential for reclamation of a variety of mine soils, fly ash land fills and disturbed ecosystems.

P. juliflora is an ideal species for stabilizing the pegmatitic tailings of mica mines in Nellore district of Andhra Pradesh. Research findings revealed that it is helpful for reclamation of copper, tungsten, marble, dolomite mine tailings and is a green solution to heavy metal contaminated soils. This is an appropriate species for rehabilitation of gypsum mine spoil in arid zone restoration of sodic soils. It outperformed all other tree species in sand dune stabilization. Arbuscular mycorrhizal inocula have been isolated from its rhizosphere (low cost agrotechnology) were found to accelerate the growth of their agroforestry and social forestry legumes in perturbed ecosystems (Patrick Audet 2014).

Prosopis juliflora colonized the industrial effluent produced by textile, paper products, tannery, chemical products, basic metal products, machinery parts and transport equipments industry. *P. juliflora* and *Leptochloa fusca* association was successful for revegetating salt laden lands (Singh 1995; Shelef et al. 2012) (Figs. 7.28, 7.29, 7.30, 7.31, and 7.32).

Grass-legume-tree association need to be tested on different sites for remediation, if necessary with biotic and abiotic amendments. Restoration of fly ash landfills with *P. juliflora* following different amendments and *Rhizobium* inoculation

Fig. 7.28 *Prosopis juliflora* in industrial areas contaminated with heavy metals. is the feed stock in biomass based power plants (**a**) *Prosopis juliflora* (**b**) Prosopis wood (**c**) Biomass fired power plant

Fig. 7.29 *Prosopis juliflora* – charcoal production (**a**) Prosopis wood (**b**) Controlled burning to produce charcoal (**c** and **d**) Charcoal

yielded promising results (Dwivedi et al. 2008). Mycorrhizae improved the growth of *P. juliflora* on high pH soils. *P. juliflora* seedlings growing in gypsum mine had high frequency arbuscular mycorrhizal fungal infection. However, *P. juliflora* has some biological characters that foster invasion, hence appropriate management practices needed to be developed for recommending it for phytoremediation.

Industrial and urban activities impact our environment, especially in terms of soil pollution. Large numbers of sites are nowadays contaminated by pollutions of chemical or organic origin. Treating these pollutions represents an economic need, which often remains unanswered by conventional civil engineering methods, due to their inappropriateness, their environmental impact and costs (notably for large sites). During the last two decades, we have witnessed the emergence of gentle soil remediation techniques using various plant species and the combination of microbial biotechnologies. Several phytotechnologies can be considered and applied to polluted soils Conesa et al. (2012): (1) phytostabilisation, which uses perennials able to sorb and immobilize potentially toxic trace elements (PTTE) in the root zone, avoiding their transfer toward groundwater and aerial parts and preventing their bioaccumulation in the food chain as well as dispersion by natural agents (wind erosion, water, etc.) (2) phytoextraction, based on root-to-shoot transfer and storage of PTTE in harvestable plant parts. *P. juliflora* produced phytoproducts are shown in Figs. 7.33–7.40).

Fig. 7.30 *Prosopis juliflora* wood is used as fuel and also for production of charcoal which is also used as a carrier of biofertilizing microbes (**a**) Charcoal production (**b**) Charcoal (**c**) Charcoal is used as carrier for plant growth promoting bacteria (**d**) Application of biofertilizer using charcoal as carrier

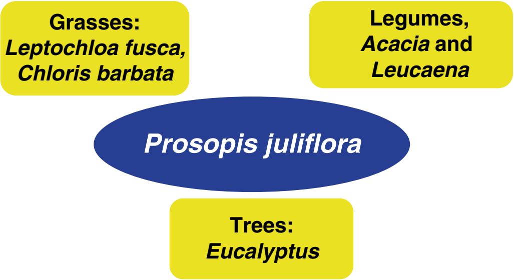


Fig. 7.31 Tree – grass – legume association was found to be the best combination for restoration of mica, copper, tungsten, marble, dolomite, limestone, and mine spoils of Rajasthan State and else where in India

7.3.6 Products from Phytoremediated Fiber Crops

Since ancient times, plants were of considerable help in satisfying man's necessities in respect of food, clothing and shelter. In those days, man also required some form of cordage for his snares, bow-strings, nets, etc. and also for better types of covering

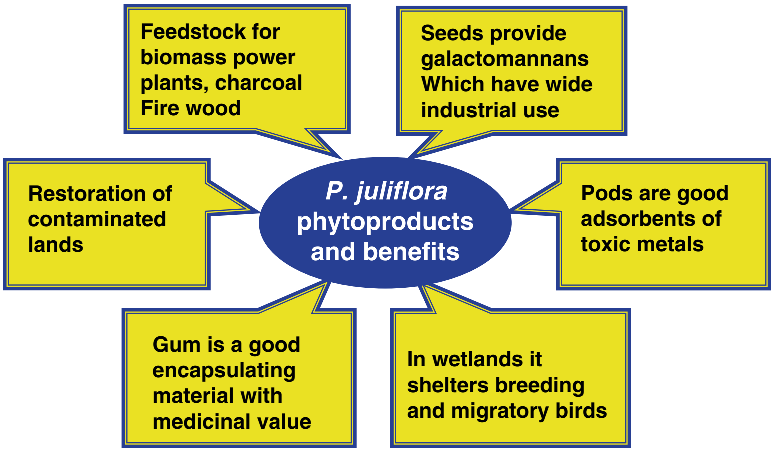


Fig. 7.32 *Prosopis juliflora* benefits and products

Fig. 7.33 Cultivation of *Gossypium arboreum* in polluted (**a** and **b**) (**c**) Cotton ready for hearvest (**d**) Cotton godown

Fig. 7.34 (**a**) Cultivation of *Vetiveria*, (**b**) *Hibiscus cannabinus,* (**c**) *H. sabdariffolia* and (**d**) *Jatropha gossipyfolia* on contaminated lands. Variety of non-edible products are produced from these plants

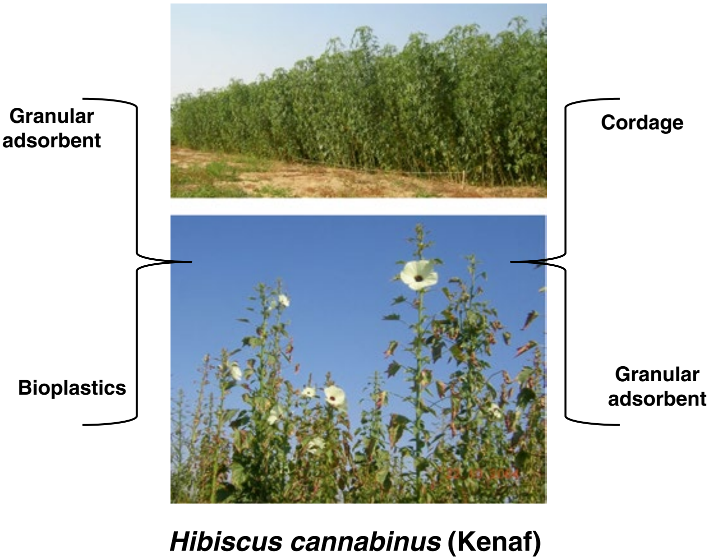


Fig. 7.35 Novel composites containing polyaniline coated short kenaf (*Hibiscus cannabinus*) bast fibers and polyaniline nanowires

Fig. 7.36 Variety of handi crafts made out of vetiver roots (Source: www.vetiver.org/IND_handicrafts.pdf; www.vetiver.org and Dr Paul Truong)

Fig. 7.37 Venetian blinds and door curtains made out of vetiver roots (Source: www.vetiver.org/IND_handicrafts.pdf; www.vetiver.org and Dr Paul Truong)

Fig. 7.38 Variety of household items made out of vetiver roots (Source: www.vetiver.org/IND_handicrafts.pdf; www.vetiver.org and Dr Paul Truong)

Fig. 7.39 Garlands and a wide variety of household items made out of vetiver roots (Source: www.vetiver.org/IND_handicrafts.pdf; www.vetiver.org and Dr Paul Truong)

Fig. 7.40 Soft sandals and wide variety of household items made out of vetiver roots (Source: www.vetiver.org/IND_handicrafts.pdf; www.vetiver.org and Dr Paul Truong)

for his shelter. Tough, flexible fibres obtained from stems, leaves, roots, etc., of various plants served the above purposes very well. With the advancement of civilization, the use of plant fibres has gradually increased and their importance today is very great. Fibre-yielding plants have been of great importance to humans and they rank second only to food plants in their usefulness. Although many different species of plants, roughly about two thousand or more, are now known to yield fibres, commercially important ones are quite small in number (Tables 7.2 and 7.3). Fibers are long narrow tapering cell, dead and hollow at maturity, thick cell wall composed mostly of cellulose and lignin. They are rigid for support, found mainly in vascular tissue. Most importantly natural fibers are biodegradable (Figs. 7.33–7.40).

7.3.7 Dye Yielding Plants

Dye yielding plants are shown is Table 7.12.

7.3.8 Phytoremediation Crops for Carbon Sequestration

Biofuel production, carbon sequestration are the two sides of the coin of the "Phytoremediation crops" (Aggarwal and Goyal 2007). Before the industrialization revolution (1760–1830 A.D), the amount of greenhouse gases (GHGs) such as Carbon dioxide (CO_2), Carbon monoxide (CO), Nitrous oxide (N_2O), Methane (CH_4), Ozone (O_3), Chlorofluorocarbon (CFC) i.e., Hydrofluoro-carbons (HFCs), Perfluorocarbons (PFCs), Sulfur hexafluoride (SF_6) in the atmosphere remained relatively constant. Except for slow changes on a geological time scale, the absorption through photosynthetic process by green plants and release of carbon from various sources was at equilibrium.

The worldwide economic growth and development basically requires energy. Among the many human activities that produce GHGs, the use of energy represents by far the largest source of emissions of GHGs, direct combustion of fossil fuels dominates the GHGs emissions from the energy sector. CO_2 results from the oxidation of carbon in fuels (www.iea.org). According to available data 2011 A.D, total CO_2 emissions from the consumption of energy is 32,578.645 Million metric tonnes (http://www.eia.gov). The world's current data for atmospheric CO_2 is measured at the Mauna Loa Observatory in Hawaii. Measurements are made and reported independently by two scientific institutions: Scripps Institution of Oceanography and the National Oceanic and Atmospheric Administration (NOAA). According to the recent data, the upper safety limit for atmospheric CO_2 is 350 parts per million (ppm) has crossed in 1988 itself and in July 2013 the atmospheric CO_2 raised to 398.58 ppm and projected to cross the 400 ppm mark (http://co2now.org) (Table 7.6).

Although some of the effects of increased CO_2 levels on the global climate are uncertain, most scientists agree that doubling atmospheric CO_2 concentrations may cause serious environmental consequences. The ten indicators of warming world are increasing the humidity, air temperature near surface (Troposphere), temperature over oceans, sea surface temperature, sea levels, temperature over land, ocean heat content, decreasing the glaciers, snow cover, and sea ice. Increasing global temperatures could raise sea levels, change precipitation patterns and affect both weather and climatic conditions. Currently, we are experiencing all the effects of global-warming and in future our next generations have to face.

Anything that removes carbon from the atmosphere is a 'sink'. In order to be effective in combating climate change, the sink must be large and the carbon must stay in the sink. Carbon is continuously exchanged between atmosphere, soil, ocean and life, which is predominately, plants. Since, CO_2 is important GHGs, one strategy that can partially combat global warming and climate change is to increase the amount of carbon stored in plants. By increasing the amount of plant life on earth, or altering it to plant types that store the most carbon, more carbon dioxide may be pulled out of the atmosphere and stored for a period of time through photosynthetic process. It is presumed that only 26 % (9.5 million metric tonnes) of CO_2 is trapped again in the photosynthetic process by green plants. However, real time data reveals the rapid land changing pattern i.e., clearing the forest lands, increasing the

Table 7.6 Ornamental plants capable of accumulating metals

Metal	Metal accumulation values	References
As	0.06–0.58 mg/g	Meera and Agamuthu (2011)
B		Bañuelos et al. (1993)
Cd		Carlson et al. (1982)
		Hiroyuki et al. (2005)
		Hattori et al. (2006)
	1.26 mg/Kg	Subramanian et al. (2012)
		Jyothi et al. (2003)
Cr		Carlson et al. (1982)
Cu		Carlson et al. (1982)
	87.5 mg/Kg	Jyothi et al. (2003)
	65.39 mg/Kg	Subramanian et al. (2012)
Fe		Carlson et al. (1982)
		Meera and Agamuthu (2011)
		Abioye et al. (2012)
		Subramanian et al. (2012)
Hg		Carlson et al. (1982)
Mg	410 mg/Kg	Subramanian et al. (2012)
Mn		Carlson et al. (1982)
		Subramanian et al. (2012)
		Kanchi et al. (2012)
Na	782.42 mg/Kg	Subramanian et al. (2012)
Pb		Ho et al. (2008), Kiliç et al. (2008), Rahi et al. (2013)
		Bada and Kalejaiye (2010)
		Jyothi et al. (2003)

agricultural lands (http://www.iaees.org) and burning fossil fuels more rapidly. Due to shrinking of plant life in due course of time the present percentage of carbon sequestration is still further reduces. This phenomenon forced to increasing the global temperature and rise of sea levels, which are significant effects of GHGs. In the process of human development further, industries are necessary and release of pollutants is obvious end products. Hence to combat and control the GHGs and other pollutants (inorganic and organic), huge plantation programme should be conducted and see that its survival in industrial zones as marginal lands. This helps in carbon sequestration as well as pollutants remediation from those industrial zones. The latest carbon sequestration method is digging the deep wells and release into the injection zone (i.e., 7,000 ft below the surface) (http://www.epa.gov). Taking the advantage of latest carbon sequestration method integrated approach of phytoremediation techniques in the vicinity of industrial zones is both way getting benefited i.e., release of GHGs are significantly reduced and effectively implement the phytoremediation.

Selection and plantation of right choice of plants for effective phytoremediation as well as carbon sequestration is important for obtaining the phyto products in industrial zones and contaminated abandoned lands. Revegetating with right choice of plants on former mining sites can provide phytoremediation services as well as carbon sequestration. Though, the process is cost effective it requires considerable time and should be employed at sites where remediation can occur over a long period of time. Generally, long term carbon sequestration can be achieved when carbon from above ground biomass transfers to the roots and enters the pool of Soil Organic carbon (SOC) or Soil Inorganic Carbon (SIC) which is possible for perennial trees and herbaceous plants with extensive root systems (Jansson et al. 2010) (Fig. 7.41).

Photosynthesis

$$6CO_2 + 6H_2O + 674\ \text{Kcal} \xrightarrow[\text{Solar energy}]{\text{Chlorophyll}} \underset{\text{Carbohydrate}}{C_6H_{12}O_6} + \underset{\text{1 mol}}{6O_2}$$

One of the important limiting factor of solar energy conversion by plants is their photosynthetic efficiency

$$IS \rightarrow P \rightarrow H \rightarrow C \rightarrow TC$$

IS = Insolation (in coming solar radiation)
P = Producer, H = Herbivore, C = Carnivore
TC = Top carnivore
PN = Q.β.ε-R (PN= Net Productivity)
Q = PAR, the quantity of incident light

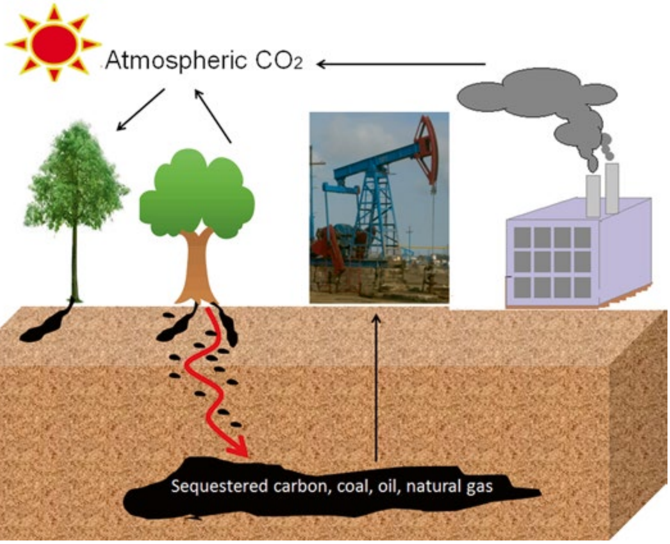


Fig. 7.41 Simplified carbon cycle. Unlike fossil fuels, biomass does not increase atmospheric green house gases when burned. Closed carbon cycle

β = the proportion of that light intercepted by green plant organs (canopy size, structure, pigments)
ε = the efficiency of photosynthetic conversion of the intercepted light into biomass
R = respiration

$$CO_2 + 2H_2O + \text{light}\left(8\,\text{quata}\right) \rightarrow \left(CH_2O\right) + H_2O + O_2 \text{where} CH_2O = 1/6\,\text{glucose molecule}$$

Gibbs free energy stored per glucose is 477 KJ and 8Q of light (400–700 nm monochromatic) of 575 nm is required.

8Q of light have energy content of 1,665 KJ, which gives maximum photosynthetic efficiency of 477/1,665 = 0.286

Maximum photosynthetic efficiency of PAR constitute about 43 %

Canopy absorb only 80 % available PAR

Respiratory losses and energy requirement for life accounts for 1/3 of stored energy = 66.7 %

Hence, over all photosynthetic efficiency of conversion of solar energy into stored chemical energy by terrestrial plants is $0.43 \times 0.8 \times 0.286 \times 0.667 = 6.6\ \%$

Therefore, in view of the above explained limitation, the only way is to use contaminated land for phytoremediation crops and thereby enhance carbon capture.

1. Strategies of wasteland development (NWDB)

   Remediation have been frequently used in the literature.
   Restoration: replication of site conditions prior to disturbance
   Reclamation: rendering a site habitable to indigenous organisms
   Rehabilitation: disturbed land will be returned to a form and productivity in conformity with a prior to land use plan
   Full restoration: Restoration of a site to its pre-damaged condition
   Partial restoration: Restoration of selected ecological attributes of the site and Creation of an alternative ecosystem type the latter though often desirable, is not to be called restoration.

2. Biotic and Abiotic stress factors
3. Species available for sustained yields
4. Ecological constraints/Soil management for

   - nutrient depletion
   - annual crop production
   - pasture livestock production
   - perennial and tree crops

5. Role of biofertilizers in restoring soil fertility, *Azobacter, Azospirillum Rhizobium*, Legume green manure

Also stated that, bioenergy crops (bioethanol, biogas, biodiesel, feedstock for electricity, charcoal) occupy a distinctive position in future terrestrial carbon sequestration and the vast areas of bioenergy cultivation envisioned for sustainable biofuel production (Smith et al. 2013), especially from perennial grasses and woody species, offer the potential for substantial mitigation of GHGs emissions both by displacing fossil fuels and through phyto-sequestration through extensive root systems. It is well known that most of these plants can accumulate pollutants by any of the phytoremediation process (Fig. 7.42).

Promising short rotation woody energy crops (SRWEC) are *Populus* ssp. (Imada et al. 2009; Sebastiani et al. 2004; Wu et al. 2010), *Salix* spp. (Lewandowski et al. 2006), *Liquidambar styraciflua, Platanus occidentalis, Robinia pseudoacacia, Acer saccharinum* L. and *Eucalyptus* can be grown for other uses also such as paper production and the waste can be utilized for energy (Capuana 2011; Claudia et al. 2012; Delplanque et al. 2013). *Hibiscus cannabinus* (Kenaf), *Brassica juncea* (Indian mustard), *Helianthus annus* (Sunflower), *Ricinus communis* (Castor), *Vetiveria zizanioides* (Khus Khus grass) *Prosopis juliflora* (Velvet Mesquite), are potential candidates for phytoremediation and carbon sequestration. Conversion of phytoremediation- borne biomass for (1) green-fine chemistry (catalyst production from

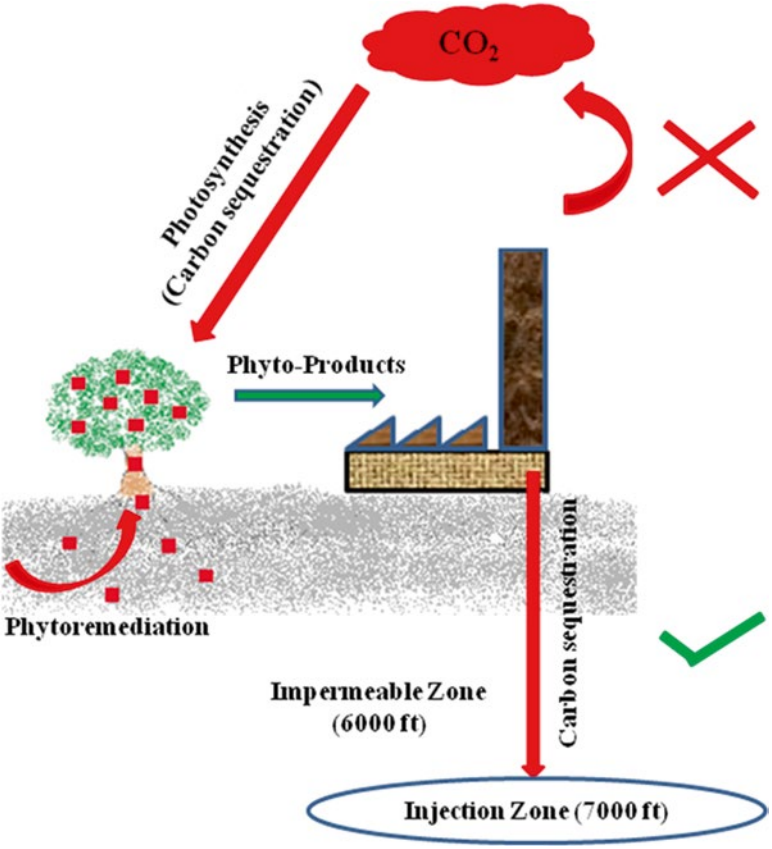


Fig. 7.42 Scheme showing carbon sequestration by phytoremediation crops

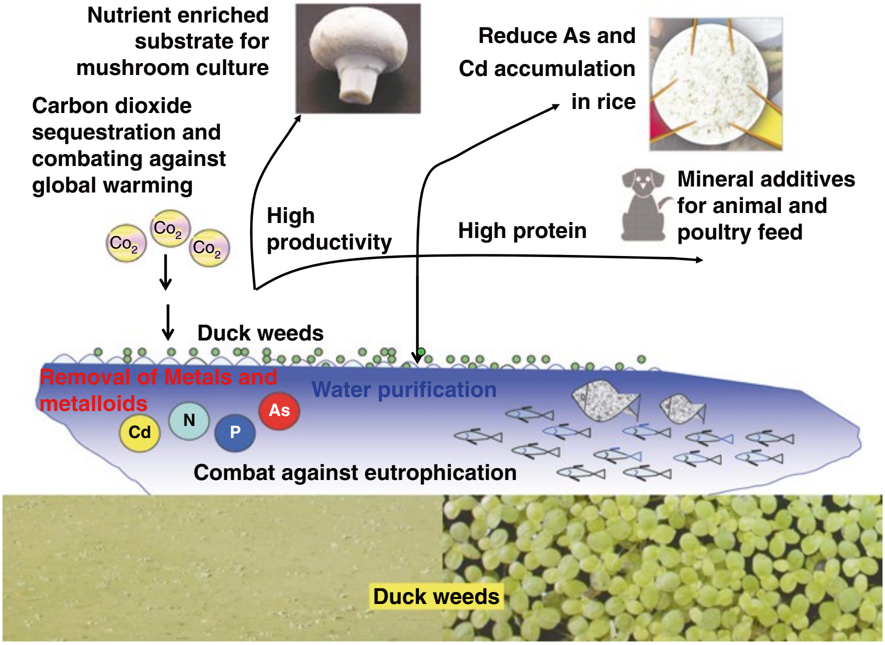


Fig. 7.43 Carbon sequestration by aquatic macrophytes and byproduct generation (Prasad 2012, © Springer Science+Business Media, LLC 2012)

metal accumulating biomass) (2) biorefinery (prehydrolysis and organosolv pretreatment from metal accumulating woody lignocellulosic biomass) and (3) by increasing the panel of plant species cultivated on metal contaminated soils for value chain and value added products enhancing bioeconomy are emerging fields (Fig. 7.43).

7.3.9 Non-edible Oil Plants for Bio-Fuels on Contaminated Soils

Our world runs on energy – it's fundamental to our way of life and growing our economy. Majority of the world's energy needs are supplied through petrochemical sources, coal and natural gases (non-renewable), with the exception of hydroelectricity and nuclear energy. World primary energy consumption grew by 1.8 % in 2012 and oil remains the world's leading fuel, at 33.1 % of global energy consumption (http://www.bp.comstatisticalreview). Today, global transportation sector is almost entirely dependent on petroleum-derived fuels and its escalating supply and consumption is dramatically increasing. While supply and consumption is increasing, its associated problems such as greenhouse gases especially CO_2 emission is also increasing (http://www.eia.gov/). Petroleum-based products are one of the main causes of anthropogenic carbon dioxide (CO_2) emissions to the atmosphere. Moreover, the increase in pollutants emissions from the use of petroleum fuel will affect human health, such as respiratory system, nervous system and skin diseases etc. The conventional source of energy is non-renewable resources and in the recent times the world has been confronted with an energy crisis due to rapid depletion of natural resources, increased social and environmental problems. It is important to develop suitable long-term strategies based on utilization of renewable fuel that would gradually substitute the declining fossil fuel production. Various groups of biomass generated and its uses are shown in Table 7.7.

Biodiesel is considered to be a possible substitute for conventional diesel getting the interest of scientists and workers all over the world. Biodiesel, mixture of fatty acid methyl esters (FAME), is generally produced from a varied range of edible (First generation feedstock) and non-edible (Second generation feedstock) vegetable oils, algae (Third generation feedstock), animal fats, used frying oils, and waste cooking oils and waste soap stocks from the oleo-chemical industries have been identified as a source of biodiesel feed-stock.

The biodiesel is quite similar to conventional diesel fuel in its physical characteristics and can be used as a direct substitute for petrodiesel and is technically called B100. The preferred ratio of mixture ranges between 5 % (B5) and 20 % (B20). Up to 20 % blending of biodiesel with diesel has shown no problems.

There are a great number of advantages as the primary feedstock can grow season after season and it provides a market for excess production of vegetable oils, and animal fats, thus enhancing the rural economies. Also for using biodiesel apart from reduces the country's dependence on imported petroleum and specifically it is biodegradable, non-toxic, renewable and closed carbon cycle. Also it reduces emission

Table 7.7 Metal accumulation capacity in selected high biomass producing ornamentals (Kaiser et al. 2009)

	References
Canna indica	
Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn	Bose et al. (2008)
Co, Cr, Cu, Ni, Zn	Yadav et al. (2012)
Cr, Ni	Yadav et al. (2010)
Ipomoea carnea	
Cd	Ghosh and Singh (2005)
Cd, Cr, Cu, Mn, Ni, Pb,	Pandey (2012a, b)
Alternanthera sessilis	
Cd, Cr, Cu, Fe, Mn, Pb	Rai et al. (1995)
Cd, Cr, Cu, Fe, Mn, Pb	Marchand et al. (2010)
Cd, Cr, Pb	Chandran et al. (2012)
Cd, Cu, Ni, Pb, Zn	Premarathna et al. (2011)
Cr	Sinha et al. (2002)
Cr, Na	Bareen and Tahira (2011)
Cr, Ni, Pb	Moodley et al. (2007)

of CO, CO_2, SO_2, particulate matter, volatile organic compounds and unburned hydrocarbons as compared to conventional diesel. In addition it has higher cetane number and flash point greater than 423 K as compared to 350 K for petroleum based diesel fuel. World production of various sources of vegetable oils in 2012–2013 was 160.22 Million metric tonnes and mostly used for consumption purposes (www.fas.usda.gov). However, in different countries of the world, same vegetable oils resources are used for biodiesel production. The source for biodiesel production is chosen according to physico-chemical properties, production cost, transportation and policy. In USA, Europe, Brazil other parts, 95 % used type of biodiesel fuel is first generation feedstock i.e., edible oils like soybean, rapeseed, sunflower, safflower, canola, palm, Coconut and fish oils are used to reduce air pollution and dependency on fossil fuel, which are limited and localized to specific regions (Jeonng and Park 2008; Darnoko and Cheryman 2000; Vicente et al. 2004; Ramadhs et al. 2004; Cheng et al. 2004; de Oliveira et al. 2005; El Mashad et al. 2008; Sarin and Sharma 2007; Meka et al. 2007).

Although, biodiesel are mainly produced in many regions recently, environmentalists have started to debate on the negative impact of biodiesel production from edible oils (Butler 2006). Recently, the use of edible vegetable oils or the first generation feed stocks has been of great concern and the major obstacle for commercialization of biodiesel is its cost from the feed stocks (Canakci and Van Gerpen 2001). Cost of edible oils is very higher than petroleum diesel and we use edible oils for biodiesel production leads food oil crisis. This is because they raise many concerns such as food versus fuel debate that might cause starvation especially in the developing countries and other environmental problems caused by utilizing much of the available arable land. This problem can create serious ecological imbalances as countries around the world began cutting down forests for plantation purposes and perfect examples is in countries like Malaysia, Indonesia and Brazil. In fact, the real time world land alterations can be glanced at on http://www.iaees.org.

Taking these factors into consideration, the above problem can be solved by using cheapest, low cost non edible oils which are not suitable for human consumption because of the presence of some toxic secondary metabolites in their oils. Non edible oil crops can be grown in waste lands and the cost of cultivation is much lower because these crops can still sustain reasonably high yield without intensive care.

Exploring the availability of non-edible oil seed as alternative biodiesel feedstock in the transportation sector is critical towards achieving higher self-reliance energy security. This situation offers a challenge as well as an opportunity to look for replacement of fossil fuels as well as first generation feedstock of biodiesels for both economic (Food *verses* Fuel) and environmental benefits. The following are the advantages of non-edible oil:

Non-edible vegetable oils are not suitable for human consumption due to the presence of some toxic compounds in their oils. Non-edible oil plants are well adapted to arid, semi-arid, high rain fall zone conditions and require low fertility and moisture and to grow. Moreover, Non-edible biodiesel crops are expected to use lands that are largely unproductive and those that are located in poverty stricken areas and in degraded forests which can fix upto 10 t/ha/year CO_2 emissions. They can also be planted on cultivators' field boundaries, fallow lands, and in public land such as along railways, roads and irrigation canals. They do not compete with existing less farm land and agricultural resources. Hence they eliminate competition for food and feed. Non-edible biodiesel plant cultivation as mentioned above could become a major poverty alleviation program for the rural poor apart from providing energy security. Moreover, they can be propagated through seed or cuttings. Most of the non-edible oils are highly pest and disease resistant. Non-edible feed stock can produce useful by-products during the conversion process, which can be used in other chemical processes or burned for heat and power generation.

7.3.10 Bioenergy from Phytoremediated Phytomass via Gasification

Phytomass gasification is basically the conversion of wood chips and wood waste into a combustible gas mixture called as producer gas (Low Btu gas). This process involves partial combustion of phytomass. Given that phytomass contains carbon, hydrogen and oxygen, complete combustion would produce carbon dioxide and water vapour. Partial combustion produces carbon monoxide and hydrogen both of which are combustible gases. The gas thus generated in a "Gasifier" could be used for captive power generation (a few KWs to several hundred KWs). Fuelwood direct combustion has several disadvantages owing to its limited applications and is of low efficiency. Direct thermal applications for power generation require steam boilers with steam engine or turbine along with necessary equipments. Such a conversion technology is not only capital intensive but is of low conversion efficiency. Conversion of the same phytomass (wood chips/ wood waste) to combustible gases in gasifier and its utilisation for power generation has innumerable advantages. Phytomass gasification (using gasifiers of various capacities) generates electricity, and the gas can be utilised for direct thermal energy and for shaft power (Fig. 7.44).

7.3.10.1 Aquatic Biomass

Biomass of *Eichhornia crassipes* (water hyacinth), *Pistia statoides* (water lettuce) and other aquatic weeds can be used for gasification (Figs. 7.45–7.49). Macrophytes spread rapidly and clog the aquatic systems (Bi et al. 2011). Therefore, utilization of such freely available biomass for bioenergy would be a happy solution. Aquatic weed biomass when subjected to anaerobic digestion optimum yield of gas was recovered when the C/N ration was between 20 and 30. One hectare of water hyacinth grown on sewage can purify the wastewater and produces 0.8 ton of dry matter per day which can be converted to 200 cu m gas that is enough for generating 250 kw power.

It is possible for generating 100 L of biogas from 1 kg of dry matter under controlled conditions. In China and Japan, large scale sea weed farms are under operation. *Macrocystis* (Giant kelp) is grown for fuel production. The kelp yields are represented to be of the tune of 90 tons/ha/year. In USA, California expects an area

Fig. 7.44 (**a–d**) Harvested phytoremediated aquatic weed biomass is used as feed stock for biogas in anaerobic digester

Fig. 7.45 **(a–c)** Profuse growth of water hyacinth (*Eichhornia crassipes*) in polluted water. Harvested biomass is used as feed stock for biogas (please see also Fig. 7.22)

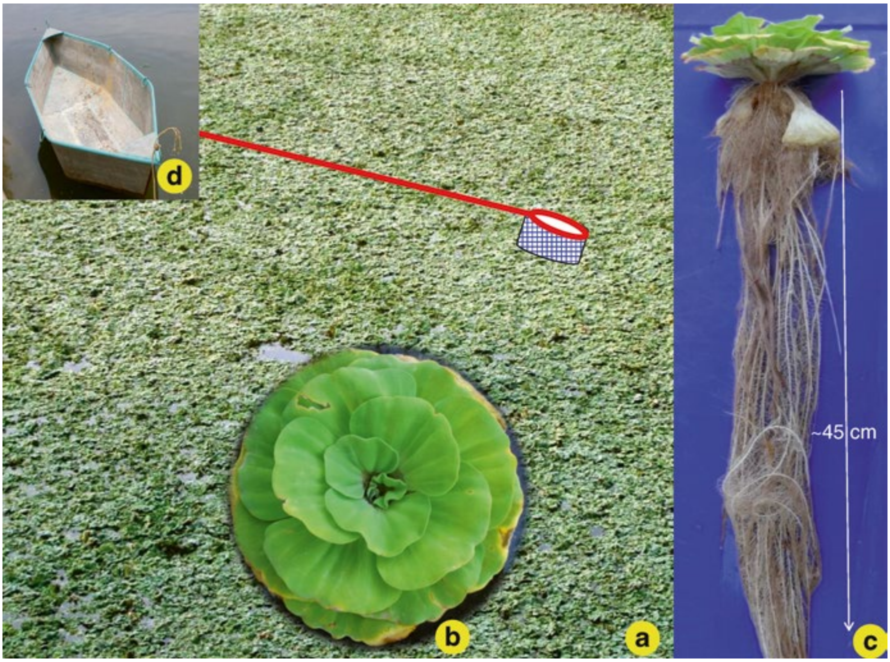


Fig. 7.46 Phytofilteration of toxic metals in aquaculture ponds using *Pistia stratiotes* (Prasad and Prasad 2012, © Walter de Gruyter, Berlin, Boston)

Fig. 7.47 After harvesting *Pistia stratoites* the water body is used for fish culture – *white arrows* show feed bags suspended with the help of rope across the water body

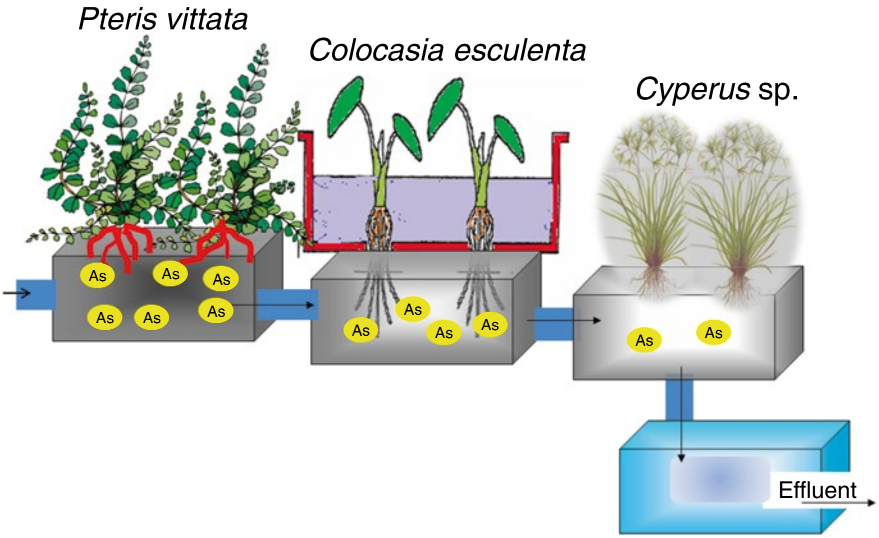


Fig. 7.48 Arsenic accumulating ornamentals are being used for treating arsenic contaminated water e.g. *Pteris vittata, Colocasia esculenta* and *Cyperus* sp.) (Kurosawa et al. 2008; Nakwanit et al. 2011; Prasad and Nakbanpote 2015, © Springer India 2015)

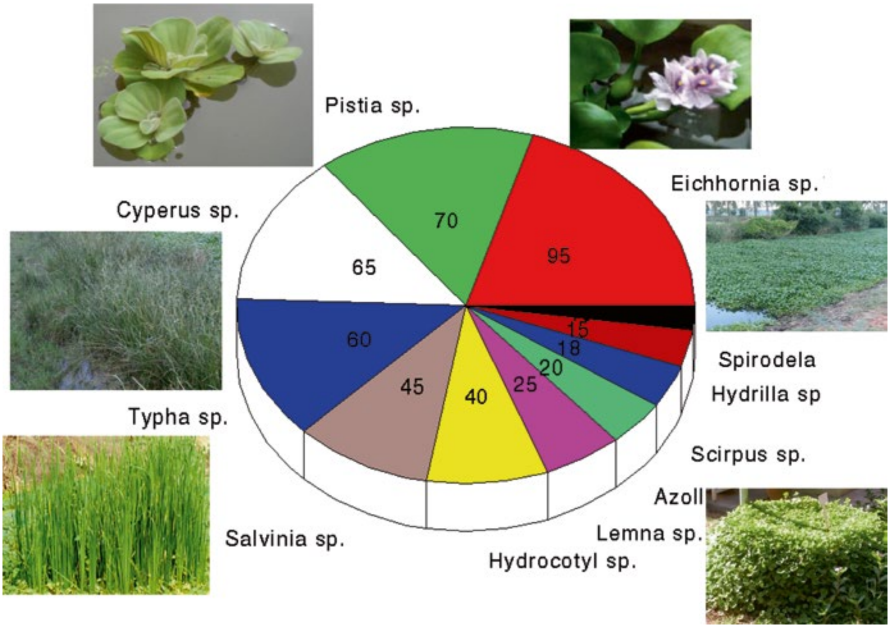


Fig. 7.49 Productivity and relative proximate dry matter production of potential macrophytes being applied for phytoremediation (Prasad et al. 2001)

of 40,000 ha of ocean energy farms by the turn of the century. Each hectare of cultivated kelp would yield about 10 million kilo calories of oil and about a 100 kilo calories of methane energy per year.

Plants endophytes relationships and the microbial communities play a key role in degrading the hazardous contaminants in rhizosphere to varying extents (Reichenauer and Germida 2008; Husain et al. 2009; Scow and Hicks 2005).

Arsenic contamination in Bengal Delta region is prevalent. The first known arsenic hyper accumulating plant is *Pteris vittata.* It is also known as Chinese brake fern, was discovered from an arsenic-contaminated site that was contaminated from pressure-treating lumber using chromated-copper-arsenate (CCA). *P. vittata* is reported to accumulate 22 g kg^{-1} of arsenic in its fronds (Carrier et al. 2011, 2012; Shelmerdine et al. 2009; Ye et al. 2011).

In addition to *P. vittata* and *P. cretica*, several other arsenic hyperaccumulating plants have been reported recently including *Pityrogramma calomelanos, Pteris longifolia* and *Pteris umbrosa.* Pilot-scale demonstration of phytofiltration for treatment of arsenic has been demonstrated in New Mexico for production of drinking water (McCutcheon and Schnoor 2003) (Fig. 7.24).

Bioconcentration factor: Bioconcentration of heavy metal by water weeds is described as the bioconcentration factor (BCF), which is the ratio of heavy metal accumulated by plants to that dissolved in the surrounding medium. For this, two bioconcentration factors were computed from the plant compartment concentrations as

$$\mathrm{BCF_R} = \mathrm{CR_{root}} / \mathrm{C_{water}} \tag{7.1}$$

$$\mathrm{BCF_L} = \mathrm{C_{leaf}} / \mathrm{C_{water}} \tag{7.2}$$

The translocation of heavy metal from the roots to harvestable aerial part is generally expressed as the translocation factor (TF) (Li et al. 2009, 2011, 2014). It was calculated on a dry weight basis by dividing the heavy metal concentration in aerial parts by the heavy metal concentration in root. Based on the above two equations (7.1) and (7.2), the translocation factor can be expressed as:

$$\mathrm{Translocation\,factor}\left[\mathrm{TF}\right] = \mathrm{BCF_{leaf}} / \mathrm{BCF_{root}} \tag{7.3}$$

Plants with efficient phytofiltration of toxic metals are beneficial for cleanup of contaminated fish ponds (*Pistia stratiotes* = Water lettuce/Water cabbage). For metal contaminants, plants with high potential for phytoextraction (uptake and recovery of contaminants into above-ground biomass) are desirable (Cao et al. 2007; Prasad 2007a, b) (Fig. 7.50)

Hazardous wastewater utilization for high rate algal ponds for production of biodiesel is being considered. Algae growing in wastewater treatment, high rate algal ponds [HRAPs] assimilate nutrients and thus subsequent harvest of the algal biomass recovers the nutrients from the wastewater (Figs. 7.51–7.54).

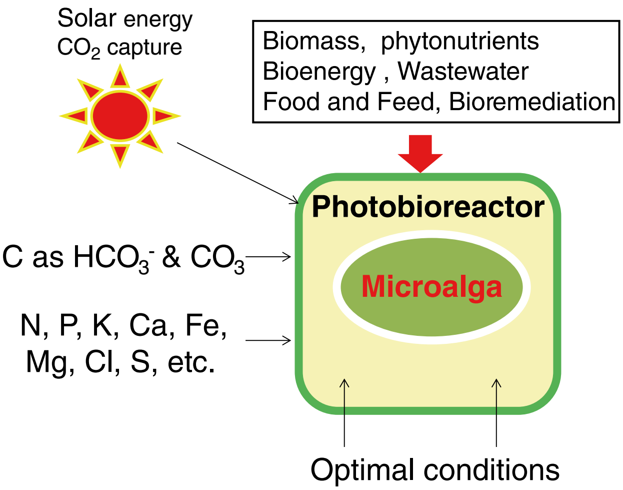


Fig. 7.50 Schematic view of photobioreactor for cultivation of algae in hazardous waste water (Chisti 2008)

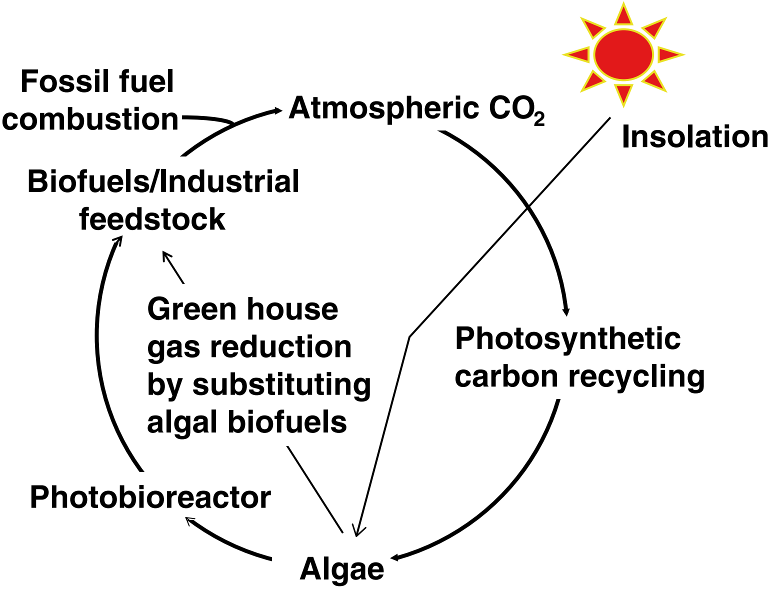


Fig. 7.51 Algae based photobioreactor for cultivation of algae in hazardous waste water for production of bio fuels, industrial feedstock and carbon dioxide sequestration. Leachate from hazardous waste dump sites are being used to establish **High Rate Algal Ponds** [HRAPs] for production of biodiesel (Park et al. 2011). The harvested phytomass of aquatic plants used for bioremediation serves as a valuable feedstock for biogas production (Abbasi et al. 1991) (Fig. 7.53)

Fig. 7.52 Nutrient rich and sewage water treatment in constructed engineered wetland using high biomass produced macrophytes viz. *Typha* and *Phragmites.* Production of low cost roofing material and compost from macrophytes used in nutrient rich and sewage water treatment in constructed engineered wetland (Zhang et al. 2014; Zheng et al. 2013)

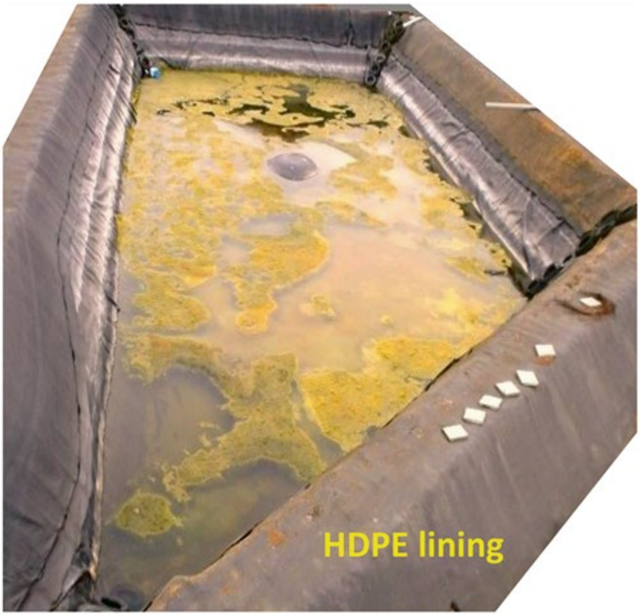


Fig. 7.53 Waste water treatment in High Rate Algal Pond [HRAP] using hazardous waste water (Lim et al. 2013)

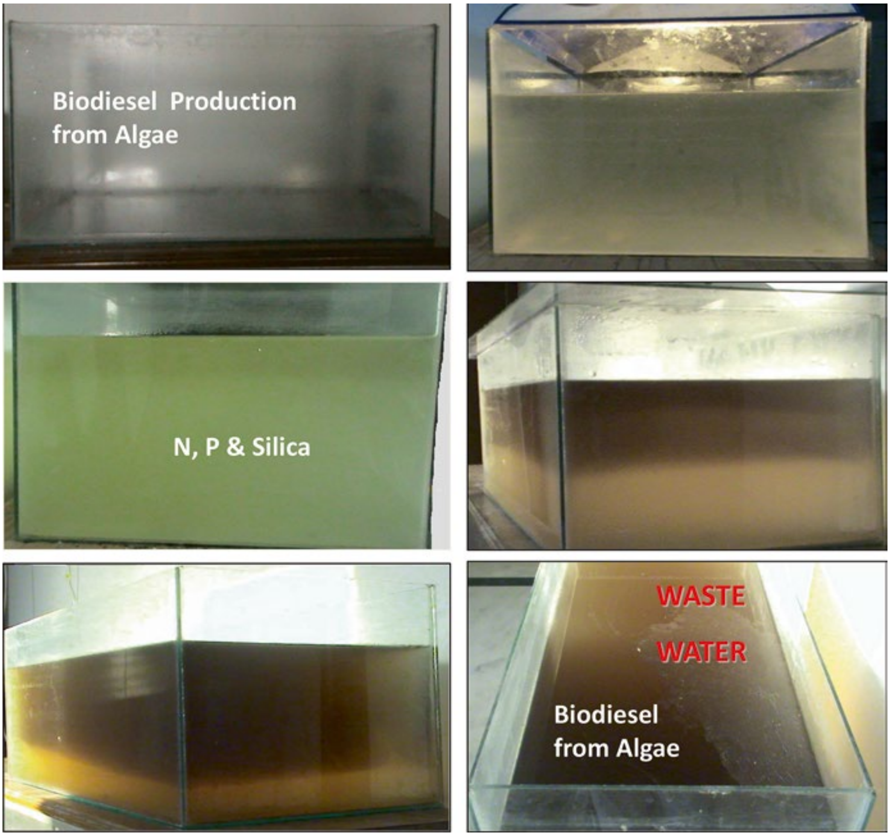


Fig. 7.54 Biodiesel production using algae and waste water at lab scale (Source: Mr M.V. Bhaskar "Kadambari Consultants Pvt Ltd - Nualgi")

7.3.11 Stabilization of Contaminated Lands by Sodding

Mulberry is an economically important tree, used for feeding the silkworm, *Bombyx mori*. Mulberry exhibits spatial localization and serves as sink for Sr, Zn and Cd in leaves along with Ca and Si accumulation. It is the sole food source for the silk worm (Ashfaq et al. 2009; Hegde and Fletcher 1996; Katayama et al. 2013). The productivity of leaf biomass on coal mine over burden is quite high and serves as a resource. An estimate of 40 tons/ha/year (approximately 10 tons of dry matter) has been reported. Based on the yield data, the amount of Sr deposition in leaves is roughly estimated to be 300 kg/ha/year. Mulberry leaves posses not only a high Sr sink but also yield high biomass, indicating that mulberry is one of the most efficient bioaccumulator plants for Sr and can be used in cleaning or rehabilitating soil contaminated by radiostrontium (Fig. 7.55).

Sodding is a bioengineering technique that uses vegetation mats for mine soil stabilization and erosion control. This technique has been used with success with a variety of grasses (Bonanno 2012; Bonanno et al. 2013), Perennial grasses with sturdy adventitious root mat anchor and stabilize mine soils. The following is a list of recommendations for using vegetation mats as bioengineering materials (Fig. 7.56)

- To anchor perennial solid binding grass mats to a slope, mats can be cut to form any shape desired. A shallow, narrow trench built along the contour of a slope and planted with a vegetation mat may become an effective terrace.
- The mat should remain attached to stable vegetation and thus be held in place from the top. The mat can be pegged to prevent ripping and sliding. This technique could be used to stabilize the contaminated soil.
- Vegetation mats can be used as building bricks. Slice the mats into rectangular pieces and use them to construct a very steep, living wall. The bricks can be pegged to each other and to the underlying substrate. This technique may be useful around culverts or sunken walkways and controls erosion.

Tables 7.8–7.17 show various examples of biomass generation in phytoremediation and their possible economic uses.

7.4 Conclusions

Although phytoremediation is environmentally friendly, powerful and low-cost technology, one general belief is that it might take long time to clean-up inorganics in soil. However, it is relatively convenient to clean small water bodies and waste waster. Most of the previous researches have focused only on wild selected species (non-economic crops) that can tolerate and takeup large amounts of inorganic contaminants to increase the efficiency of phytoremediation. Much progress has been

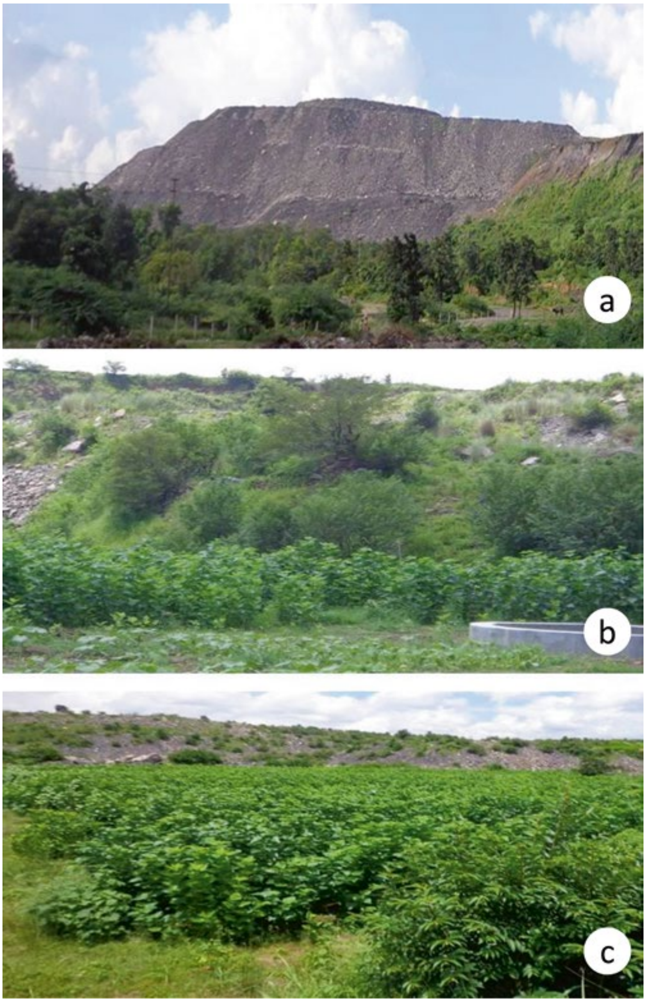


Fig. 7.55 Luxurient growth of *Morus alba* (mulberry) on coal mine over burden of west bokaro coal field

made in countries like UK, USA, Canada, Australia, Japan and many European countries. In developing country like India, it is difficult to convince environmental regulators and local agencies to grow metal accumulators (the data on hyperaccumulators is scanty) in the contaminated areas for the sole purpose of removing pollutants from their environment unless financial renumeration or expenses are subsidized.

Fig. 7.56 Sodding, a bioengineering technique that uses grass mats for soil stabilization and erosion control. Perennial grasses are preferred. Grasses with sturdy adventitious root mat stabilize metalliferous soil. To anchor perennial solid binding grass mats to a slope, mats are cut to desirable sizes (1 × 1 foot). This technique would beneficial to stabilize the contaminated soil (Thangavel and Sridevi 2015, © Springer India 2015) (**a**) Cultivation of Zoysia grass with contaminated substrated (soil and water) (**b**) Harvested grass mats are ready for sale (**c**) and (**d**) road cutting are stabilized with grass mats

Table 7.8 Metal accumulation in *Ricinus communis* (Castor bean)

Ag, Cd, Cu, Pb	Figueroa et al. (2008), de Souza Costa et al. (2012)
As	Santos-Jallath et al. (2012)
As, Cd, Co, Cr, Cu, Mn, Ni, Pb	Varun et al. (2012)
B, Cu, Fe, Mn, Zn	de Abreu et al. (2012)
Ba	Coscione and Berton (2009)
Cd	Shi and Cai (2009), Huang et al. (2011), Prabavathi et al. (2011), Bauddh and Singh (2012a, b)
Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn	Singh et al. (2010)
Cd, Cu, Mn, Ni, Pb, Zn	Olivares et al. (2013)
Cd, Cu, Mn, Pb, Zn	Olivares et al. (2013)
Cd, Cu, Pb, Zn	Chaudhry et al. (1998), Olivares et al. (2013)
Cd, Pb	Zhi-xin et al. (2007), Niu et al. (2009), de Souza Costa et al. (2012)
Cd, Pb, Zn	Sas-Nowosielska et al. (2008)
Cu, Fe, Mn, Zn	Stephan et al. (1994), Schmidke and Stephan (1995), Stephan et al. (1995)
Cu, Pb, Zn	Xiaohai et al. (2008), Nazir et al. (2011)
Cu, Zn	Chaves et al. (2010)
Cu, Zn, Fe	Khanam and Singh (2012)
Hg	Siegel et al. (1984)
Mn, Ni, Pb, V	Vwioko et al. (2006)
Ni	Giordani et al. (2005)
Pb	Romeiro et al. (2006)

Table 7.9 *Prosopis juliflora*, a phreatophyte and its capability for accumulation of heavy metals

A1, As, Au, Ba, Br, C1, Ce, Cs, Cu, Fe, Hf, In, K, La, Mg, Mn, Na, Sb, Sc, Sm, Th, Ti, U, V, W, Yb, Zn,	Gabriel and Patten (1994)
Al, B, Ba, Ca, Cr, Cu, Fe, K, Li, Mg, Mn, Na, Ni, Sr, V, Zn,	Nagaraju and Prasad (1998)
Al, Cr	Jamal et al. (2006)
As	Mokgalaka-Matlala et al. (2008, 2009)
As, Cd, Cr, Cu, Mn, Pb, Zn	Solís-Domínguez et al. (2011)
As, Cd, Cu, Pb, Zn	Al-Farraj and Al-Wabel (2007)
As, Cr, Cu, Mo, Zn	Haque et al. (2009)
B, Ba, Co, Cr, Cu, Fe, Mn, Mo, Ni, Sr, V, Zn	Chaudhary et al. (2009)
Cd	Khan (2007)
Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn	Shukla et al. (2011)
Cd, Cu, Zn	Usha et al. (2009)
Cd, Pb	Varun et al. (2012)
Ce, Zn,	Viezcas (2009)
Co, Fe, Mn, Ni	Naveed et al. (2012)
Cr	Arias et al. (2010)
Cr, Cu, Fe, Mn, Zn	Rai et al. (2004), Sinha and Gupta (2005)
Cr, Cu, Fe, Pb, Zn	Atiq-Ur-Rehman and Iqbal (2008)
Cu, Cd	Senthilkumar et al. (2005)
Cu, Pb, Zn	Iqbal et al. (1999)
F	Saini et al. (2012), Baunthiyal and Sharma (2012)
Pb	Naveed et al. (2010)
Zn	Hernandez-Viezcas et al. (2011)

Table 7.10 Fiber yielding plants that can be grown on contaminated sites (Bjelková et al. 2011; Griga and Bjelkova 2013; Linger et al. 2002; Smykalova et al. 2010)

Plant Source	Description
Seed fiber	Collected from seeds or seed cases (Eg: *Gossypium Sps., Ceiba pentandra.*
Leaf fiber	Collected from leaves (Eg: *Furcraea andina* (introduced in India), *Agave* Sps. *Sansevieria roxburghiana*, *Sansevieria hyacinthoides* (Bowstring Hemp).
Bast fiber (or) Skin fiber	Collected from the skin or bast surrounding the stem of their respective plant. These fibers have higher tensile strength than other fibers. Therefore, these fibers are used for durable yarn, fabric, packaging, and paper. Some examples are Flax (produces linen) *Linum usitatissimum*, Jute (widely used, cheapest fiber after cotton) *Corchorus capsularis, C. olitorius* Kenaf (The interior of the plant stem is also used for fiber.) *Hibiscus cannabinus,* Hemp (A soft, strong fiber, edible seeds.) *Cannabis sativa, Boehmeria nivea* 600 species of palms in the tribe Calameae (rattan) and vine fibers.
Fruit fiber	Collected from the fruit of the plant (Eg: *Cocos nucifera*).
Stalk fiber	Stalks of the plant (Eg: straws of *Triticum* sps. *Oryza sativa Hordeum vulgare* and other crops including bamboo and grass.
Other fibers	Bamboo fiber, Grewia optiva, Himalayan Nettle (*Urtica dioica* L.) Bhabar (*Eulaliopsis binata*).

Table 7.11 Metal accumulation in *Vetiver zizanioides*

Al, As, B, Ba, Ca, Cd, Co, Cu, Fe, Hg, K, Mg, Mn, Mo, Ni, Pb, Rb, Sr, TI, Zn	Martin et al. (2010)
As	Datta et al. (2011)
As, Ca, Co, Cr, Cu, Fe, Hg, Mg, Mn, Na, Ni, Zn	Bhat et al. (2010)
As, Cd, Cr, Cu, Hg, Ni, Pb, Se, Zn	Danh et al. (2009)
As, Cd, Pb	Oshunsanya et al. (2012)
As, Cu, Zn	Chiu et al. (2005)
B, Pb	Angin et al. (2008)
Cd	Chen et al. (2000), Aibibu et al. (2010)
Cd, Cu, Mn, Pb, Zn	Roongtanakiat and Chairoj (2001)
Cd, Cu, Pb	Jayashree et al. (2011)
Cd, Cu, Pb, Zn	Yang et al. (2003), Chena et al. (2004)
Cd, Pb	Minh and Khoa (2009)
Cd, Pb	Xia (2004)
Cd, Pb, Zn	Lai and Chen (2004), Zhuang et al. (2005), Roongtanakiat and Sanoh (2011)
Cr, Cu, Ni, Pb, Zn	Roongtanakiat et al. (2003)
Cr, Cu, Pb, Zn	Antiochia et al. (2007)
Cs, Sr	Singh et al. (2008)
Cu	Liu et al. (2009)
Cu, Fe, Mn, Pb, Zn	Roongtanakiat et al. (2007)
Cu, Fe, Mn, Zn	Roongtanakiat et al. (2008, 2009)
Cu, Pb, Zn	Chiu et al. (2006), Danh et al. (2011), Chen et al. (2012)
Pb	Chantachon et al. (2004), Wilde et al. (2005), Rotkittikhun et al. (2007), Rotkittikhun et al. (2007), Gupta et al. (2008), Andra et al. (2009, 2010, 2011), Punamiya et al. (2010)
Pb, Zn	Pang et al. (2003)

Table 7.12 Dye yielding plants capable of growing on contaminated soils

Plant name	Family	Parts used	Colour obtained
Abrus precatorius	Fabaceae	Seeds	Black
Acacia catechu	Mimosaceae	Bark	Brown/black
Acacia catechu var. *sundra*	Mimosaceae	Wood	Reddish brown
Acacia leucophloea	Mimosaceae	Bark, leaves	Red
Acacia nilotica	Mimosaceae	Bark and pods	Yellowish brown
Acacia nilotica	Mimosaceae	Seeds	Brown/black
Acanthophonax trifoliatum	Araliaceae	Fruit	Black
Achyranthes aspera	Amaranthaceae	Whole plant	Black-brown
Achyranthes bidentata	Amaranthaceae	Whole plant	Black-brown
Actaea acuminate	Ranunculaceae	Seeds	Reddish-green
Adenanthera pavonina	Mimosaceae	Wood	*Red*
Adhatoda vasica Nees	Acanthaceae	Leaves	Yellow
Adhatoda vasica Nees.	Acanthaceae	Leaf	Yellow
Adhatoda zeylanica.	Acanthaceae	Leaves	Yellow-green
Aegle marmelos	Rutaceae	Fruits	Yellow
Aegle marmelos	Rutaceae	Rind of the fruit	Reddish
Aesculus indica	Hippocastanaceae	Bark	Brown
Agrimonia pilosa.	Rosaceae	Roots	Yellow
Alnus glutinosa	Betulaceae	Bark	*Black*
Alnus nepalensis	Betulaceae	Bark	Red
Aloe barbadensis	Liliaceae	Whole plant	Red
Alpinia galanga	Zingiberaceae	Root, stalk	Yellow-brown
Althaea rosea	Malvaceae	Flowers	Red dye
Amaranthus hypocondriacus	Amaranthaceae	Arial parts	Red pigment
Ampelocissus latifolia	Vitaceae	Leaves	Black
Anacardium occidentale	Anacardiaceae	Pericarp	Light red
Annona reticulata.	Annonaceae	Fruit, shoots	Bluish black
Arnebia benthamii	Boraginaceae	Roots	Red
Artemisia japonica	Asteraceae	Leaves	Brown
Artemisia nilagirica	Asteraceae	Leaves	Brown
Artocarpus heterophyllus	Moraceae	Wood/fruits	Yellow
Artocarpus lakoocha	Moraceae	Wood/fruits	Yellow
Averrhoa carambola.	Oxalidaceae	Fruits	Yellow/brown
Azadirachta indica	Meliaceae	Bark	Brown
Bauhinia purpurea	Caesalpiniaceae	Bark	Purple colour
B. racemosa	Caesalpiniaceae	Bark	Light green
Bauhinia variegate.	Caesalpiniaceae	Flowers	Purple
Benthamidia capitata	Cornaceae	Fruits	Red
Berberis aristata	Berberidaceae	Bark roots	Yellow
Berberis asiatata	Berberidaceae	Bark/roots	Yellow
Berberis chitria	Berberidaceae	Bark/roots	Yellow
Beta vulgaris	Amaranthaceae	Roots	Red

(continued)

Table 7.12 (continued)

Plant name	Family	Parts used	Colour obtained
Bischofia javanica	Euphorbiaceae	Bark/seeds	Black
Bixa orellana	Bixaceae	Seeds	Red/pink
Bougainvillea glabra	Nyctaginaceae	Flower with ivory	Yellow brown
Brugmansia suaveolens	Solanaceae	Leaves	Green
Butea monosperma	Fabaceae	Dried flowers	Brilliant yellow dye
Butea superba	Fabaceae	Root	Red
Butea superba	Fabaceae	Root	Yellow
Caesalpinia sappan	Caesalpiniaceae	Wood and pod	Red
Capsicum annuum	Solanaceae	Fruits	Red
Careya arborea	Juglandaceae	Bark	Yellow
Carthamus tinctorious	Asteraceae	Flower	Yellow, red
Carthamus tinctorius.	Asteraceae	Flowers	Red and yellow
Cassia auriculata	Caesalpiniaceae	Flower, seeds	Yellow
Cassia fistula	Caesalpiniaceae	Bark/fruits	Brown
Cassia fistula	Caesalpiniaceae	Bark and sapwood	Red
Cassia tora	Caesalpiniaceae	Seeds	Blue
Casuarina equisetifolia	Casuarinaceae	Bark	Light reddish
Celtis australis	Ulmaceae	Bark	Yellow
Ceriops tagal	Rhizophoraceae	Bark	Black, brown or purple
Chrozophora tinctorial	Euphorbiaceae	Herb	Light green
Cinnamonum tamala	Lauraceae	Leaves	Brown
Cladonia verticullata	Cladoniaceae	Whole plant	Yellow-red
Commelina benghalensis	Commelinaceae	Juice of the flower	blue
Convallaria majalis	Liliaceae	Leaves and stalk	Green
Corylus jacquemontii	Betulaceae	Fruits rind	Camel
Crocus sativus	Iridaceae	Flower	Yellow, orange
Cupressus torulosa	Cupressaceae	Leaves	Green
Curcuma angustifolia	Zingiberaceae	Tubers	Yellow
C. aromatica	Zingiberaceae	Rhizome	Yellow
C. domestica	Zingiberaceae	Rhizome	Yellow
C.longa	Zingiberaceae	Rhizome	Yellow
Curcuma zedoaria	*Zingiberaceae*	Rhizome	Yellow
Cyperus scariosus	Cyperaceae	Roots	Brown
Daphne papyracea.	Thymelaeaceae	Bark/fruits	Red
Datisca cannabina Linn.	Datiscaceae	Roots	Yellowish-red
Dipterocarpus spp.	Diptero-carpaceae	Bark	Light brown
Elaeodendron glaucum	Celastraceae	Bark	Red
Emblica officinalis	Euphorbiaceae	Fruits	Brown
Engelhardtia spicata	Juglandaceae	Bark	Dark brown
Enonymus tingens.	Celastraceae	Bark	Yellow
Erythrina suberosa.	Fabaceae	Flower/bark	Dark brown

(continued)

Table 7.12 (continued)

Plant name	Family	Parts used	Colour obtained
Eugenia jambolana.	Myrtaceae	Bark, leaf	Red
Everniastrum cirrhatum	Parmeliaceae	Whole plant	Red brown
Galium aparine	Rubiaceae	Root	Purple
Garcinia mangostana	Clusiaceae	Fruit	Black
Geranium nepalense	Geraniaceae	Roots	Red
Geranium wallichianum	Geraniaceae	Roots	Red/brown
Grevillea robusta.	Proteaceae	Flowers	Yellow
Grewia optiva	Tiliaceae	Fruits	Yellow/orange
Grewia subinaequalis	Tiliaceae	Fruits	Yellow/orange
Haematoxylon campechianum	Caesalpiniaceae	Heart wood	Yellow
Hedychium spicatum	Zingiberacae	Rhizome	Yellow
Hippophae salicifolia	Elaegnaceae	Fruits	Yellow
Hypericum oblongifolium	Hypericaceae	Flowers	Yellow
Impatiens balsamina	Balsaminaceae	Flowers	Red
Impatiens balsamina	Balsaminaceae	Flower	Brown
Indigofera atropurpurea	Fabaceae	Flowers	Purple
Indigofera cassioides	Fabacae	Leaves/flowers	Blue
Indigofera heterantha	Fabacae	Flowers	Pink
Indigofera tinctoria	Fabacae	Leaves/flowers	Blue
Indigofera tinctoria	Fabaceae	Green crop	Blue
Isatis tinctoria	Brassicaceae	Leaves	Dark blue
Juglans regia	Juglandaceae	Bark/fruits	Camel-brown
Lannea coromandelica	Anacrdiaceae	Bark/resin	Yellow-brown
Largestomia parviflora	Lythraceae	Bark	Black
Lawsonia alba	Lythraceae	Leaves	Brown
Lawsonia inermis	Lythraceae	Leaves	Red/orange
Ligustrum vulgare.	Oleaceae	Mature berries	Blue
Madhuca indica	Sapotaceae	Bark	Reddish-yellow
Madhuca longifolia	Sapotaceae	Bark	Yellow-brown
Mahonia borealis	Berberidaceae	Bark/roots	Yellow
Mallotus philippensis	Euphorbiaceae	Fruits	Red
Mallotus phillippensis	Euphorbiaceae	Fruit capsules	Orange
Mangifera indica	Anacardiaceae	Bark/leaves	Yellow
Michelia champaca	Magnoliaceae	Wood	Yellow
Mimusops elengi	Sapotaceae	Seed	Yellow
Mirabilis jalapa	Nyctaginaceae	Flowers	Pink-red
Morinda citrifolia	Rubiaceae	Root bark	Dull red
Myrica esculenta	Lauraceae	Bark/fruits	Red yellow
Nardostachys grandiflora	Valerianaceae	Inflorescence	Red
Nyctanthes arbor-tristis	Oleaceae	Flower	Yellow
Nyctanthes arbourtritis	Oleaceae	Flowers	Yellow-orange
Nymphaea alba	Nymphaceae	Rhizome	Blue

(continued)

Table 7.12 (continued)

Plant name	Family	Parts used	Colour obtained
Onosma hispidum	Boraginaceae	Roots	Red
Oroxylum indicum	Bignoniaceae	Bark/fruits	Black
Osbeckia stellata	Melastomaceae	Fruits	Brown
Peristrophe piniculata	Acanthaceae	Whole plant	Greenish
Phlogacanthus thyrsiformis	Acanthaceae	Flowers	Orange-yellow
Pinus wallichiana	Pinaceae	Bark	Black
Pistacia khinjuk	Anacrdiaceae	Stem galls	Brown
Prinsepia utilis	Rosaceae	Fruits	Blue
Prunus cerasoides	Rosaceae	Fruits	Yellow
Prunus persica	Rosaceae	Leaves, root bark	Light yellow
Psidium guajava	Myrtaceae	Fruits	Black-brown
Pterocarpus marsupium	Cesalpiniaceae	Bark	Red
Pterocarpus santalinus	Cesalpiniaceae	Wood	Red
Punica granatum.	Punicaceae	Flowers/fruits	Yellow-red
Quercus infectoria	Fagaceae	Gall nuts	Light yellow
Rheum moorcroftianum	Polygonaceae	Roots	Yellow
Rheum webbianum	Polygonaceae	Roots	Yellow
Rhododendron arboretum	Ericaeace	Flower	Red
Rhododendron lepidotum	Ericaeace	Leaves/flowers	Pink-red
Rimelia reticulate	Parmeliaceae	Whole plants	Orange-yellow
Rubia cordifolia	Rubiaceae	Whole plant	Red-brown
Rubia cordifolia	Rubiaceae	Stem, root	Light Brown
Rubia tinctorum	Rubiaceae	Wood, root	red, pink
Rubus fructicosus.	Rosaceae	Berries	Brown
Rumex hastatus	Polygonaceae	Roots	Yellow-green
Rumex nepalensis	Polygonaceae	Roots	Yellow-green
Semecarpus anacardium	Anacardiaceae	Fruits	Black
Solanum lycopersicum	Solanaceae	Fruits	Red
Sophora mollis	Fabaceae	Roots/flowers	Brown/yellow
Symplocos paniculata	Symplocaceae	Bark/leaves	Yello
Symplocos ramosissima	Symplocaceae	Bark/Leaves	Yellow
Syzygium cuminii	Apiaceae	Bark and Leaves	Red
Tagetes erecta.	Asteraceae	Flowers	Yellow
Tagetes erecta.	Asteraceae	Flower	Yellow
Tamarindus indica.	Caesalpiniaceae	Leaves	Reddish-yellow
Taxus baccata Linn. *ssp. wallichiana*	Taxaceae	Bark	Red
Tectona grandis	Verbenaceae	Leaf/bark	Reddish
Terminalia alata	Combretaceae	Bark	Red/brown
Terminalia arjuna	Combretaceae	Bark	Red
Terminalia bellirica	Combretaceae	Fruits	Black
Terminalia chebula.	Combretaceae	Fruits	Yellow/black

(continued)

Table 7.12 (continued)

Plant name	Family	Parts used	Colour obtained
Toona hexandra var. gambleri	Meliaceae	Flowers/seeds	Yellow-brown
Toona serrata	Meliaceae	Flowers/seeds	Yellow
Usnia verticillata	Parmeliaceae	Whole plant	Red brown
Utrica dioica	Urticaceae	Roots	Brown-black
Ventilago denticulate	Rhamnaceae	Bark and roots	Violet
Woodfordia fruiticosa	Lythraceae	Flowers	Red Yellow
Wrightia arborea	Apocynaceae	Bark/leaves	Yellow-pal
Wrightia tinctoria	Apocynaceae	Seeds	Blue
Zanthoxylum armatnum	Rutaceae	Bark	Brown
Ziziphus mauritiana	Rhamnaceae	Leaves/bark	Pink/red

Table 7.13 Various groups of biomass resources and their possible scope for utilization as energy sources.

Biomass category	Products	Uses
Energy crops Industrial residues	Methyl esters, alcohol	Energy
	Fibrous waste from pulp, including black liquor	Energy, composite material
	Wet cellulosic industrial residues	Electricity and heat
Industrial products	Pellets, bio-oil (pyrolysis oil), ethanol, biodiesel	Electricity
High biomass Producing grasses	Biohydrogen	Electricity and heat, Proton exchange membrane fuel cell
Contaminated waste	Biodegradable waste Sewage sludge	Biogas

Table 7.14 Metal accumulation and adsorption capacity of *Eichornia crassipes* (Water hyacinth)

Eichornia crassipes	References
Ag, Al, As, Ba, Ca, Cd, Ce, Co, Cu, Dy, Er, Eu, Fe, Ga, Gd, Ge, Hg, Ho, K, La, Mg, Mn, Mo, Na, Nb, Nd, Ni, Pb, Pr, Rb, Sm, Sr, Tb, Th, TI, Tm, U, Y, Yb, Zn, Zr	Valitutto et al. (2006)
Ag, Cd, Cr, Cu, Hg, Ni, Pb, Zn	Odjegba and Fasidi (2006, 2007)
Al, As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Zn	Marchand et al. (2010)
Al, Cr, Cu,	Klumpp et al. (2002)
As	Alvarado et al. (2008), Rahman and Hasegawa (2011), Giri and Patel (2012)
As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, V, Zn	Agunbiade et al. (2009)
Br, Ca, Cr, Cu, Fe, K, Mn, Ni, Pb, Rb, S, Sr, Ti, Zn	Tejeda et al. (2010)
Ca, Co, Cu, Fe, K, Mg, Mn	Cooley and Martin (1979)

(continued)

Table 7.14 (continued)

Eichornia crassipes	References
Cd	Wolverton and McDonald (1978), Cooley and Martin (1979), O'Keeffe et al. (1984), El-Enany and Mazen (1996), Das and Jana (1999), Maine et al. (2001), Das and jana (2004), di Toppi et al. (2007), de oliveira et al. (2009), Rana et al. (2011)
Cd, Co, Cr, Cu, Mn, Ni, Pb, Zn	Soltan and Rashed (2003)
Cd, Co, Cu, Hg, Pb, Zn	Buta et al. (2011)
Cd, Co, Pb	Oseni (2004)
Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn	Singh and Kalamdhad (2013)
Cd, Cr, Cu, Fe, Ni, Pb	Khan et al. (2009)
Cd, Cr, Cu, Fe, Ni, Zn	Mishra et al. (2008)
Cd, Cr, Cu, Fe, Zn	Mishra and Tripathi (2008)
Cd, Cr, Cu, Ni, Pb, Zn	Schorin et al. (1991)
Cd, Cr, Zn	Delgado et al. (1993)
Cd, Cu, Hg, Pb, Zn	Núñez et al. (2011)
Cd, Cu, Pb, Zn	Fayed and Abd-El-Shafy (1985), Yang (1997), Smolyakov (2012)
Cd, Cu, Zn	Smolyakov et al. (2010)
Cd, Mn, Cu, Hg, Pb	Mishra et al. (2008)
Cd, Pb, Zn	Mahamadi and Nharingo (2010)
Cd, Zn	Hardy and O'Keeffe (1985), Lu et al. (2004)
Ce	Chua (1998)
Co, Cs	Saleh (2012)
Co, Cr, Cu, Fe, Ni, Pb, Zn	Zaranyika et al. (1994)
Cr	Rulangaranga and Mugasha (2003), Faisal and Hasnain (2003), Mangabeira et al. (2004), Paivaa et al. (2009), Espinoza-Quiñones et al. (2009), Mangabeira et al. (2011)
Cr, Cu, Mn, Pb, Zn	Tiwari et al. (2007)
Cr, Hg	Jana (1988)
Cr, Ni, Zn	Maine et al. (2006), Maine et al. (2007), Maine et al. (2009)
Cu	Mokhtar et al. (2011), Abdelraheem et al. (2012)
Cu, Hg	Mishra et al. (2012)
Cu, Pb	Vesk and Allaway (1997)
Fe	Jayaweera et al. (2008)
Hg	Panda et al. (1988), Lenka et al. (1992), Ramlal et al. (2003), Skinner et al. (2007), Caldelas et al. (2009)
Ir, Os, Pd, Pt, Rh, Ru,	Farago and Parsons (1994)
Ni	Bres et al. (2012)
Pb	Hameed et al. (1997), Singh et al. (2012), Baruah et al. (2012)
Pb, Zn	Verma et al. (2005)
Se	Mane et al. (2011)

Table 7.15 Metal accumulation in *Alternanthera philoxeroides* (Alligator weed)

As	Li et al. (2011)
Ca, Cr, Cu, Fe, Mg, Mn, Na, Ni, Pb, Zn	Zuo et al. (2012)
Cd	Souza et al. (2009)
Cd, Cr, Cu, Mn, Pb, Zn	Zhi Zhong et al. (2011)
Cd, Cr, Cu, Fe, Ni, Pb, Zn	Lokeshwari and Chandrappa (2007)
Cd, Cr, Cu, Pb, Zn	Gu et al. (2004)
Cd, Cu, Pb, Zn,	Bi et al. (2007)
Cd, Pb, Zn	Liu et al. (2007a, b)
Cr	Mangabeira et al. (2010), Mangabeira et al. (2011)
Cr, Cu	Naqvi and Rizvi (2000)
Cs	Pinder et al. (2005, 2006)
Cu	Guo and Hu (2012)
Cu, Cr, Ni	Jian-Guo et al. (2010)
Cu, Pb, Zn	Li et al. (2010)
Cu, Zn	Tang et al. (2002)
Fe, Pb, Zn	Deng et al. (2009)
Hg	Hong-Wei et al. (2003)
Pb	Shabani et al. (2010)
Pb, Zn	Deng et al. (2006)
Zn	Yuan et al. (2009)

The present study highlights the potential of ornamentals, fiber and energy crops for phytoremediation, because they are non-edible and income generators. Further studies should focus on combining phytoremediation with enhancing soil fertility and maximizing pest management, together with investigation of additional species for phytoremediation which may also enhance economic benefits. The management of plant biomass applied in phytoremediation should be also studied. Use of phytoremediated phytomass for phytoproducts and boosting bioeconomy via cogeneration of value additions and value chain products has tremendous scope and should be a priority area of research.

Grison (2015) pioneered in turning metalliferous waste from plants into a resource through innovative technologies, processes and services. She and her team discovered an unprecedented concept in chemistry, namely ‘ecocatalysis’. The development of this new concept created a paradigm shift in sustainable and green chemistry i.e. the metallic wastes are becoming new ecofriendly and efficient catalytic systems. Grison feels that combining phytoextraction and ecocatalysis has opened up a new vistas (E4) in greener chemistry i.e. Environmental, Ecological, Ethic and Economic (E4) opportunity.

Table 7.16 Metal accumulation in *Pistia stratiotes* (Water lettuce/Water cabbage)

Pistia stratiotes + Metals	References
Ag, Al, As, Ba, Ca, Cd, Ce, Co, Cu, Dy, Er, Eu, Fe, Ga, Gd, Ge, Hg, Ho, K, La, Mg, Mn, Mo, Na, Nb, Nd, Ni, Pb, Pr, Rb, Sm, Sr, Tb, Th, TI, Tm, U, Y, Yb, Zn, Zr	Valitutto et al. (2006)
Ag, Cd, Cr, Cu, Hg, Ni, Pb, Zn	Odjegba and Fasidi (2004)
Al, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, Zn	Lu et al. (2011)
As	Rahman and Hasegawa (2011)
Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, Zn	Sridhar (1986)
Cd	Maine et al. (2001), di Toppi et al. (2007), Bhakta and Munekage (2008), Li et al. (2013)
Cd, Cr	Suñe et al. (2007)
Cd, Cr, Cu, Fe, Ni, Pb	Khan et al. (2009)
Cd, Cr, Cu, Fe, Ni, Zn	Upadhyay et al. (2007)
Cd, Cr, Cu, Fe, Zn	Mishra and Tripathi (2008)
Cd, Cu, Hg, Mn, Pb,	Mishra et al. (2008)
Cd, Cu, Hg, Pb, Zn	Núñez et al. (2011)
Cd, Cu, Ni, Pb, Zn	Miretzky et al. (2006)
Cr	Satyakala and Jamil (1992), Mainea et al. (2004), Sinha and Gupta (2005), Ganesh et al. (2008), Espinoza-Quiñones et al. (2008), Sinha et al. (2009), Sundaramoorthy et al. (2010)
Cr, Cu, Fe, Mn, Pb, Zn	Miretzky et al. (2004)
Cr, Cu, Mn, Ni, Pb, Zn	Tewari et al. (2008)
Cr, Ni, Zn	Mufarrege et al. (2010)
Cu	Upadhyay and Panda (2009)
Cu, Hg	Mishra et al. (2012)
Fe, Mn, Pb, Zn	Ndzomo et al. (1994)
Hg	Mhatre and Chaphekar (1985), De et al. (1985), Lenka et al. (1992), Mishra et al. (2009), Skinner et al. (2007)
Pb	Espinoza-Quiñones et al. (2009), Vesely et al. (2012)
Th, U	Cecal et al. (2003)

Table 7.17 Advantages and limitations of bioremediation (Prasad 2011)

Advantages	Limitations
In- situ	Limited to shallow soils, streams, and groundwater.
Passive	High concentrations of hazardous materials can be toxic to plants.
Solar driven/	Mass transfer limitations associated with other biotreatments.
Costs 10–20 % of mechanical treatments	Slower than mechanical treatments.
Transfer is faster than natural attenuation	Only effective for moderately hydrophobic contaminants.
High public acceptance	Toxicity and bioavailability of degradation products is not known.
Fewer air and water emissions	Contaminants may be mobilized into the groundwater.
Generate less secondary wastes	Potential contaminants enter food chain through animal consumption.
Soils remain in place and are usable following treatment	Unfamiliar to many regulators.
(i) Phytovolatilized contaminants could be transformed to less toxic forms (e.g. elemental mercury and dimethyl selenite gas) (ii) phytovolatilization accelerates degradation processes	The contaminant or a hazardous metabolite might accumulate in vegetation and be passed on in later products such as fruit or lumber. Low levels of metabolites have been found in plant.
(i) Phytostabilization it circumvents the removal of soil, (ii) It has a lower cost and is less disruptive than other more-vigorous soil remedial technologies, (iii) Revegetation enhances ecosystem restoration.	(i) The contaminants remain in place. (ii) The vegetation and soil may require long-term maintenance to prevent re-release of the contaminants and future leaching, (iii) require extensive fertilization or application of soil amendments (Zhu et al. 2004). (iv) Plant uptake of metals and translocation to the aboveground portion must be avoided, (v) The root zone must be monitored to prevent metal leaching.
In phytoextraction, the plant biomass containing the extracted contaminant can be a resource (phytoextraction). For example, biomass that contains selenium (Se), an essential nutrient, has been transported to areas that are deficient in Se and used for animal feed. In green house experiments, gold was harvested from plants.	(i) Metal hyper accumulators are generally s66 with a small biomass and shallow root systems, (ii) Plants harvested must be properly disposal. (iii) Phytoextraction studies conducted using hydroponically grown plants, with the contaminant added in solution, may not reflect actual conditions and results occurring in soil. (iv) Phytoextraction coefficients measured under field conditions are likely to be less than those determined in the laboratory.
(i) Rhizofiltration using terrestrial plants removes contaminants more efficiently than aquatic plants, (ii) This system can be either *in-situ* (floating rafts on ponds) or *ex situ* (an engineered tank system), (iii) An *ex situ* system can be placed anywhere because the treatment does not have to be at the original location of contamination.	(i) The pH of the influent solution may have to be continually adjusted to obtain optimum metals uptake, (ii) The chemical speciation and interaction of all species in the influent have to be understood and accounted for, (iii) A well-engineered system is required to control influent concentration and flow rate, (iv) The plants (especially terrestrial plants) may have to be grown in a greenhouse or nursery and then placed in the rhizofiltration system, (v) Periodic harvesting and plant disposal are required, (vi) Metal immobilization and uptake results from laboratory and greenhouse studies might not be achievable in the field.

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