Tech Science Press

Utilization of Multi-Tasking Non-Edible Plants for Phytoremediation and Bioenergy Source-A Review

Ibrahim M. Abdelsalam[1], Mostafa Elshobary[1,3,*], Mohamed M. Eladawy[1] and Mohammed Nagah[2]

[1]Botany Department, Faculty of Science, Tanta University, Tanta, 31527, Egypt.

[2]Microbial Chemistry Department, National Research Centre, Dokki, Cairo, 12622, Egypt.

[3]School of Food & Biological Engineering, Jiangsu University, China.

[*]Corresponding Author: Mostafa Elshobary. Email: mostafa_elshobary@science.tanta.edu.eg; mostafaelshobary@ujs.edu.cn.

Abstract: Heavy metal contamination of land and freshwater resources is a serious concern worldwide. It adversely affects the health of animals, plants and humans. Therefore, remediation of toxic heavy metals must be highly considered. Unlike other techniques, phytoremediation is a holistic technology and can be used in large scale for soil remediation as it is costless, novel, environmentally-safe and solar-driven technology. Utilization of non-edible plants in phytoremediation is an ingenious technique as they are used to generate new bioenergy resources along with the remediation of contaminated soils. Some nonfood bioenergy crops such as Salix species, Miscanthus species, Populus species, Eucalyptus species, and Ricinus communis exhibit high capability to accumulate various metals and to grow in contaminated lands. However, there are still sustainable challenges facing coupling phytoremediation with bioenergy production from polluted lands. Therefore, there has long been a need for developing different strategies to resolve such challenges. In this article review, we will discuss the phytoremediation mechanism, the technique of phytoremediation coupling with bioenergy production, sustainable problems facing linking phytoremediation with energy production as well as possible strategies to enhance the efficiency of bioenergy plants for soil decontamination by improving their characteristics such as metal uptake, transport, accumulation, and tolerance.

Keywords: Bioenergy plants; heavy metals; phytoremediation; non-edible plants; mechanism

1 Introduction

Due to rapid industrial development, toxic chemical and metal accumulation indiscreetly increase in the environment posing risks to public health, natural habitat, and ecosystem as a whole [1-3]. Contamination of soil with heavy metals is a serious global problem. More than one-third of the worldwide land resources are heavily contaminated due to anthropogenic activities [4]. Moreover, there are around 200,000 areas in Sweden, France, Hungary, Slovakia, and Austria polluted with heavy metals. Meanwhile, in Greece and Poland, 10,000 sites are listed as heavy metal contaminated areas [5]. Leakage of polluted water into the soil, leading to impurity of surface and benthic water resources [6,7]. Heavy metals decrease stomatal conductance, transpiration rate and leaf water content causing water stress in some plants by decreasing the number and size of xylem vessels and chloroplasts [8]. These metals can accumulate in edible parts of the plant and thus enter into the food chain. Hence, it is requisite to remediate these contaminated sites to reduce health-related risks and conserve available soil for food production.

The traditional physicochemical techniques to decontaminate the polluted soil such as soil washing, soil vapor extraction, solidification, stabilization, vitrification, electro kinetic, etc. have hazardous effects including irretrievably soil quality and biodiversity destruction [9]. Hence, there are strong demands of

DOI:10.32604/phyton.2019.06831

effective, economical, and eco-friendly techniques for soil remediation without affecting soil quality and fertility. Phytoremediation could be more accepted technique than others that can be applied to contaminated sites without any noteworthy destruction to the ecosystem. Involvement of non-edible dedicated energy crops in the remediation of heavy metal-impacted soils is a promising approach as these plants can be used to furnish some benefits of ecosystem facilities such as carbon sequestration, biodiversity augmentation, salinity reduction as well as soil and water quality amelioration along with their exploitation for phytoremediation and energy production [10,11]. Potential of bioenergy plants can be developed through different biological and genetic engineering techniques to enhance their ability to remove heavy metals from contaminated sites. In this review, we will comprehensively discuss promising and dedicated non-edible bioenergy plants for phytoremediation and bioenergy production, perspective issues of involvement of such bioenergy plants in phytoremediation as well as the scope of biological and genetic engineering tools to develop efficient bioenergy plants with high potential for phytoremediation of hazardous metals.

2 Heavy Metals: Definition, Origin, and Toxicity

Heavy metals are natural constituents of the earth's crust [12,13]. Some heavy metals are classified as essential such as Fe, Mn, Co, Zn, and Mo as they are required tremendously for carrying out different biological processes [14]. Others including Hg, Pu, Cd, and Pb are classified as non-essential as they do not have any biological function. They are deleterious to the biological system even at lower concentrations [15,16]. Heavy metals originate typically in the soil and water from the natural process of the earth's crust. However, many anthropogenic activities have immensely increased their discharge into the ecosystem such as mining, deposition of industrial wastes urbanization, smelting of ores, and agricultural activities including application of pesticides, sewage sludge, and fertilizers containing heavy metals [17,18].

In contrast to other pollutants, heavy metals cannot be degraded chemically or biologically and are ultimately persistent. Continuous accumulation of toxic metals in food causing oxidative stress which is a critical threat to human health due to over-production of ROS, upper gastrointestinal cancer and many immunological syndromes including carcinogenic effects, teratogenesis, and mutagenesis [19]. Other human health diseases caused by heavy metal contamination include cardiovascular disease, chronic anemia and cognitive impairment [20], nervous system, brain [21], skin, teeth, bone [22], and much more. Some heavy metals and their negative effects have been compiled in Tab. 1. Therefore, it is important to develop efficacious approaches to remove these toxic metals from impacted soils. Different physical, chemical and biological methods utilized for heavy metal remediation are still suffering from many limitations like high cost, long time application, and mechanical complexity. Phytoremediation, meanwhile, is a holistic, promising and universally accepted technology as it is cost-effective, novel and environmentally-friendly approach [2].

Table 1: Some heavy metals and their negative impacts

Heavy metal	Atomic number	Source	Remarks	Negative impacts
Arsenic (As)	33	Industrial activity is the main source of Arsenic that can be transferred by air [23].	As is a very toxic element that presents in different forms such as organic arsenic species, inorganic arsenic compounds, and arsine gas.	As affects crop production and creates human health risks and even death. It can cause DNA breakdown [24,25].
Lead (Pb)	82	Natural sources, industrial sites, leaded fuels and orchards [26].	Pb is a highly toxic element. It is non-biodegradable and remains in the environment for a very	It is harmful to humans, animals, plants, and microbes and causes mental retardation and brain damage [27].

			long time.	
Mercury (Hg)	80	Mining, petrochemical, painting industries, fertilizers, medical instruments, etc. [28].	Hg is a toxic element with a high bioaccumulation potential in living organisms.	Mercury conflicts with electron transport in organelles causing disorder in oxidation reactions and photosynthesis process. In human beings, toxic effects of mercury include neurological and renal disorders [29].
Antimony (Sb)	51	Mining and smelting of metalliferous ores, municipal wastes, fertilizers, pesticides and sewage [30].	Sb is a toxic metal contamination of soil and groundwater poses major environmental and human health problem [31].	Antimony is a toxic trace element of growing interest due to the increased anthropogenic input into the environment [32]. It is known to provoke DNA damage [33], disturb the hematic and gastrointestinal systems [34].
Chromium (Cr)	24	The main source of Cr in leather industry as it can escape in large quantity into the effluent [35].	Cr compounds are highly toxic. They pose serious threats to biological and ecological systems [36].	Cr has a negative effect on growth, development, and reproduction of vascular plants. Cr is responsible for different diseases in human beings such as respiratory disorders, lung Infection, diarrhea/dysentery, and typhoid [37,38].
Nickel (Ni)	28	Industrialization, sewage, chemical fertilizer and pesticide utilization [39].	Nickel is naturally occurring in the soil and water in small amounts.	High concentration of Ni inhibits mitotic activities, reduces plant growth, and nitrogen metabolism [40]. In addition, it has haematotoxic, immunotoxic, neurotoxic, pulmonary toxic, nephrotoxic, hepatotoxic and carcinogenic effects on humans and animals [41].

3 Phytoremediation

Phytoremediation is an emerging technique involves utilization of plants for decontamination of soil and/or water depending on their natural ability to absorb, accumulate and degrade contaminants from the media of interest. Such plants can be used for mineralization and immobilization of toxic compounds in the root zone, and for accumulation and concentration of metals and other inorganic compounds extracted from the soil into their aerial portions as well [16,42]. Generally, plants take up the contaminants without harming topsoil. They are found to conserve its utility and improve its fertility with inputs of organic matter [43]. Phytoremediation approach has emerged recently with research studies carried out, particularly during the last two decades. The idea of phytoremediation is aesthetically appealing and gains public acceptance. It can be applied at large field sites where other remediation techniques are expensive and impractical. Additionally, phytoremediation of contaminated soils has economic importance as it can be used for decreasing risk containments (phytostabilization), phytoextraction of valuable metals such as Hg, Ag and Ni, and efficacious land management [44]. The establishment of green plants for heavy metal remediation is a generally accepted approach as green remediation of hazardous metals and metalloids a convenient of physical and chemical remedial strategies [44].

Mechanism of Phytoremediation

Phytoremediation comprises seven major techniques which are phytoextraction, phytostabilization, phytovolatilization, rhizofiltration, Phytofiltration, Phytodesalination, and phytodegradation.

In general, plant uptake metals according to the bioavailability of heavy metals and plant nutrients in soil solution. Such bioavailability is influenced by several factors such as plant species, root zone, environmental condition, root structure, as well as physical, chemical and biological properties of soil [5]. Absorption of essential and non-essential elements from the soil occurs in response to concentration gradient and selective uptake of ions or by diffusion [45]. Plant root surface adsorbs metals in cationic form as the cell wall contains cellulose, pectins, and glycoproteins that act as specific ion exchangers [46]. Uptake of heavy metal ions from contaminated environments is dominated by specialized transporters such as Zinc Iron Protein (ZIP) family, natural resistance-associated macrophage protein (NRAMP) family and copper transporter (CTR) family. Heavy metals such as Fe, Mn, and Zn are reported to be accumulated by ZIP family [47]. Meanwhile, NRAMP is responsible for the transportation of Cd, Ni, Zn, Fe, Cu inside the root [48,49], and CTR family is specialized for the accumulation of Cu, Co, Ni and many other metals [50,51]. In plant roots, heavy metals may either accumulate in root tissues (phytoimmobilization) or translocated to the shoot via symplastic and/or apoplastic pathways where they are generally accumulated in vacuoles. It is necessary for plants to adopt a tolerance mechanism to keep hazardous metals away from cellular metabolic processes. There are five processes involved in phytorextraction mechanism; metal mobilization in soil and water resources, uptake of metal ions by plant roots, translocation towards aerial plant parts, storage of metals in plant tissues and heavy metal tolerance [44]. Plant tolerance mechanism involves (1) biosynthesis of reactive oxygen scavenger enzymes such as ascorbate peroxidase, catalase, superoxide dismutase, glutathione S-transferase, glutathione reductase, and proline [52-57], (2) biosynthesis of phytochelatins [58,59], (3) biosynthesis of metallothioneins [60,61], and (4) biosynthesis of ferritins [62]. These mechanisms enhance plant tolerance and improve the metal-accumulating ability of plants even at high contamination levels. A brief sketch of the mechanism of phytoremediation of heavy metals is given in Fig. 1.

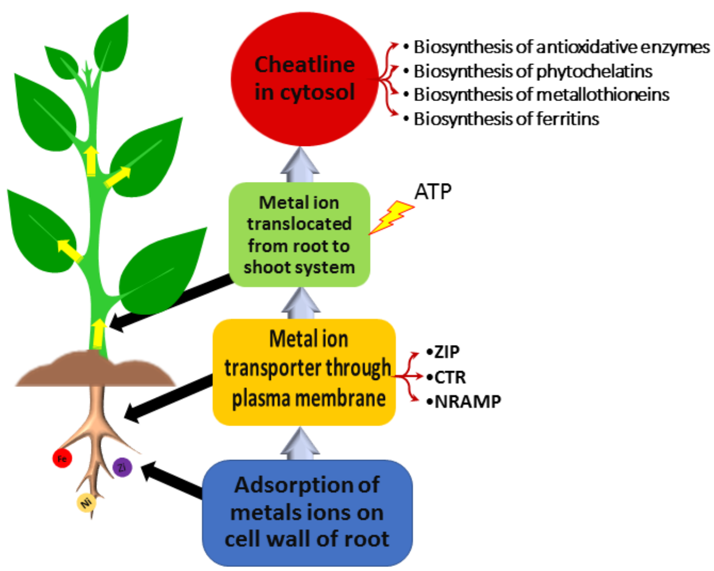

Figure 1: Mechanism of phytoremediation

4 Utilization of Phytoremediation Biomass for Bioenergy Generation

Fossil fuel depletion and fast growth of the global population have led to a rapid increase in energy demand. With present consumption rate, earth oil resources may run out by 2050 [63,64]. In the search for sustainable, biodegradable, and zero-carbon emission fuel, utilization of bioenergy plants in phytoremediation programs is an innovative approach to produce new economically, and eco-friendly bioenergy resources along with the remediation of metal impacted soils and groundwater [4]. One major problem facing the commercial application of phytoremediation is the disposal of contaminated biomass. After each harvesting, the plant is transformed from the site loaded with huge quantity of contaminants. These contaminants should be stored or disposed safely in order not to cause any risk to our system. In this regard, biomass derived from bioenergy plants can be utilized to produce environmentally safer and more sustainable energy sources of economic value compared to fossil fuels. Bioenergy produced from plants is affected by biomass feedstock and land use that can interfere with food production causing food scarcity. Therefore, it should be noted that land use for bioremediation cannot be used at the same time for edible crop production to ensure food safety. Moreover, large biomass produced from plants during phytoremediation has plenty amounts of high caloric molecules such as hemicellulose, cellulose, lignin and minor amounts of other organic compounds that can be used to produce different types of biofuels when treated thermochemically through gasification or pyrolysis [5,65] (Tab. 2). Some non-edible plants that are cultivated in heavy metal contaminated soils have higher ability to produce oil under heavy metal stress than control that is suitable for biodiesel production.

Besides its utilization as an oil source for biofuel production, these plants can provide other benefits such as prevention of erosion (anti-erosion), and establishment of wildlife habitats [66].

On the other hand, it was observed that the metal(loid) content in pretreated ash recovered from the thermochemical process is more concentrated compared to that in the untreated biomass, due to effective substrate reduction during the thermo-chemical process leading to more easily and cost-less retrieval of these metal(loid). This help avoids the cost of disposal for large quantities of biomass and saves the environment [67]. Consequently, phytoremediation technology satisfies both requirements for cost-less land reclamation, biofuel production and element recovery from biomass tissues. Fig. 2 summarized the integrated phytoremediation concept coupling remediation with bioenergy production from biomass and metal(loid)s recovery.

5 Potential Non-Edible Plants for Phytoremediation and Bioenergy

Non-edible bioenergy plants utilized for bioremediation of contaminated soils are highly diverse. Therefore, current reviews tended to focus on identifying the most potential and dedicated non-edible bioenergy crops that show great ability to remediate metal-impacted soils. This is because utilization of edible crops for soil remediation along with energy production has three main disadvantages. Firstly, they affect food security and increase the cost of food products. Secondly, the edible parts (e.g., grains) are the main accumulators for heavy metals lead to several detrimental effects on human and animal health. Finally, cultivation of edible plants for bioenergy production and bioremediation limits arable land and decreases water availability. Non-edible plants, meanwhile, can be cultivated in unproductive, non-arable lands and degraded forests using waste water. These three disadvantages diminish edible plant potential for phytoremediation. However, these problems can be overcome by cultivating nonedible bioenergy plants that provide high energetic biomass content in short-rotation period. This review takes a closer look at 5 of best nonfood bioenergy plants utilized for phytoremediation and bioenergy production. Other potential non-edible bioenergy plants utilized for such dual purposes are summarized in Tab. 3.

Table 2: Some techniques for contaminated biomass treatment, remarks, and example of non-edible plants

Biomass treatment	Description	Remarks	Examples	Refrences
Anaerobic digestion	This method is depending on anaerobic microorganisms to break down organic complex compounds to simple ones while simultaneously generating biogas as a final product.	Economical technique with low-cost requirement [68].	*Salix viminalis, poplar* spp., *Miscanthus* spp.	[69,70]
Pyrolysis	Pyrolysis is an innovative method of contaminated plant material and waste treatment [71]. It depends on exposing the biomass to high temperatures (< 430°C) under anaerobic and pressurized conditions [72].	Pyrolysis is one of the fastest and most effective methods for the disposal of contaminated biomass [65]. Pyrolysis temperature improves the bioavailability of heavy metals by converting them into more stable oxide forms [73].	*Eucalyptus occidentalis, Populus deltoids, Salix schwerinii*	[74-76]
Hydrothermal liquefaction	Hydrothermal liquefaction is a thermochemical conversion of wet biomass into bio-oil and gaseous products under the sub-/super-critical water system, high pressure and moderate temperature [77].	It is an effective technique to convert biomass into biofuels with less energy consumption compared to pyrolysis and gasification [78,79].	*Poplar* spp.	[80]
Gasification	Gasification is the process concluded that biomass feedstock can be subjected to a series of chemical changes to generate clean and combustive gas at high thermal efficiencies [81].	Suitable for recycling wet biomass to produce synthesis gas with a higher percentage of hydrogen [72].	*Poplar* spp.	[82]

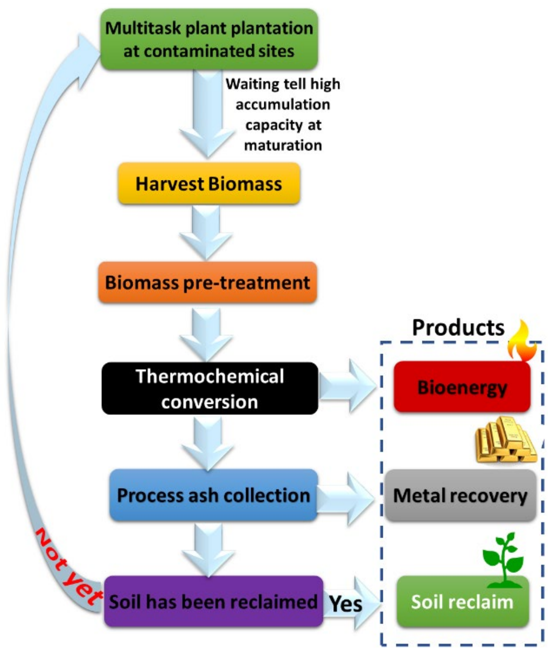

Figure 2: Coupling phytoremediation with bioenergy production from biomass and metal(loid)s recovery

Table 3: Other potential non-edible bioenergy plants utilized for phytoremediation and bio energy production

Bioenergy plants	Metal(s)	Remarks	Plant parts	References
Jatropha curcas	Fe, Al, Cr, Cu, Mn	The plant shows high ability to accumulate Fe and Mn in its root and Cu, Al, and Cr in its shoot.	Shoots and roots	[83]
Helianthus annuus	Cd, Cr, As	*H. annuus* can be used to remediate soils contaminated with Cd, Cr, and As.	Biomass	[84]
Panicum virgatum	Cd, Cr, Ni, As, Fe	Efficient plant for phytoremediation of metal-polluted sites.	Biomass	[85,86]
Pisum sativum	Pb	*P. sativum* is a good accumulator of Pb.	Shoots	[87]
Salix matsudana	Pb	*Salix matsudana* could accumulate a high concentration of Pb.	Roots	[88]
Phragmites australis	Zn, Pb	Moderately accumulator and tolerant species to Zn and Pb.	Roots	[89]
Phalari arundinacea	Cr, Ni, Pb	Phytoremediation of soil contaminated with different heavy metals	Aerial parts and roots	[90,91]
***Hibiscus cannabinus* L.**	Cd, Zn	The plant shows high potential for accumulation of Cd and Zn when grown in lysimetres containing dredging sludge	Shoots	[92]
***Linum usitatissimum* L.**	Cd, Ni, Cu, Fe, Zn	The plant is used for phytoremediation of soil contaminated with Cd, Ni, and	Stems	[93-95]

		other heavy metals.		
Arundo donax	Zn, Cr, Pb, Ni	*A. donax* is suitable for Zn and Ni phytoextraction.	Roots	[96,97]
Azadiractha indica	Zn, Pb, Cd	*A. indica* accumulates large concentrations of Zn, Pb and Cd especially in leaves.	Leaves and Stems	[98]
Acacia nilotica	Fe, Zn, Mg, Cu, Mn	*A. nilotica* can be used for accumulation of various heavy metals.	Barks	[99]
Sapiam sebiferum	Pb, Zn	*S. sebiferum* is a good candidate for phytostabilization of Pb and Zn.	Roots	[100]
Pennisetum purpureum	Cd	*P. purpureum* has high biomass production and remediation potential.	Roots and Leaves	[101]
Cannabis sativa	Ni, Pb, Zn, Cr, Cd	*Cannabis sativa* is effectively used for phytoremediation of sites contaminated with Cd, Ni, Pb, Zn, and Cr.	Leaves and Roots	[102,103, 104,105]

5.1 Salix Species

Salix is a diversified genus with respect to biomass productivity and ability to absorb and tolerate heavy metal ions [106-108]. *Salix* species are fast-growing plants that produce high biomass content [108,109,110], and sequester more carbon compared to softwoods during the growing season. Hence, they are considered one of the most promising biofuels in many countries [111]. Erect stems, capability of rapid growth, and extensive root development are the main characteristics that make *Salix* species suitable for biomass coppice [112]. *Salix* species not only have high biomass content but also exhibit significant ability to remediate various metals from contaminated soils. They are considered as efficient bioindicators of heavy metal pollution. They have the potency for high Cd and Zn accumulation when cultivated in sites of low metal content [113]. Kuzovkina & Quigley [114] grew five different *Salix* species under Cu and Cd to estimate their phytoremediation efficiency and concluded that these species could highly tolerate Cu and Cd, and *S. nigra* was the most tolerable to both metals. Additionally, it was reported that *Salix alba, S. viminalis,* and *S. schwerinii* are potential species used for phytoextraction of Zn, Cd, Cu, Hg, Pb, Cd from contaminated soils [115,116]. *Salix petsusu* accumulated high concentrations of Cd in its leaves and bark that accounted for 50-80% of absorbed Cd [108], and showed maximum proficiency of Cd accumulation when harvested every two years. *Salix subfragilis* is used as a bioindicator for Cd, Pb, Mn, Cu, and Zn. Cd, Pb, and Mn were observed in the leaves, whereas Cd, Pb, and Zn were generally higher in stems than in leaves [113]. These findings suggest the potential role of *Salix* species for the remediation of numerous heavy metals from contaminated soils and groundwater.

5.2 Miscanthus Species

Miscanthus is a C4-perennial rhizomatous grass. The genus *Miscanthus* is known to originate in the tropics and subtropics, while other species are found throughout a wide climatic range in East Asia [117,118]. The genus *Miscanthus* includes around 17 species of perennial rhizomatous tall grasses native to subtropical and tropical regions originating from Asia. Among them, *M. tinctorius, M. sinensis* and *M. sacchrisfl* are key biomass energy crops [117,119]. *Miscanthus* species are characterized by high biomass production with relatively low maintenance and high yield/energy content. Therefore, they are considered as excellent candidates for the production of renewable fuels and chemical materials via thermochemical conversion processes [120,121]. In addition, it has been believed that by 2050 *M. giganteus* may supply up to 12% of the European Union's energy demand [122]. One key aspect of research is the management of *Miscanthus* to stabilize or remove heavy metals and other pollutants at excellent levels besides its high biofuel productivity. *Miscanthus* species have proven to be excellent phytoremediators for different heavy metals such as As, Cu, Pb, Ni, Cd, and Zn from polluted soils and water [123]. They exhibit a complete accumulation capacity for Cd, Pb, and Zn from polluted water samples. In case of the soil, meanwhile, maximum absorption around 97.7% has been reported.

The most common species of *Miscanthus* is *Miscanthus giganteus* L. This grass is well suited for phytoremediation of soils contaminated with Cr [124,125], and Zn [126]. Korzeniowska & Stanislawska-Glubiak [127] reported that *M. giganteus* is a tolerant plant to soils contaminated with Cu, Ni, and Zn. Recently, it has been reported that *M. giganteus* can also successfully stabilize the soil near closed coal, Pb, Zn and Cd mines [128].

5.3 Populus Species

Populus L. (*Salicaceae*) comprises about 30 species [129] widely dispersed in the forests of temperate and cold regions of the Northern Hemisphere. *Populus* species are distinguished by high yield production, high rates of transpiration, extensive roots, and easy propagation [130]. Therefore, they are widely used for remediating metal-impacted sites. Kubátová et al. [131] tested the ability of *Populus* clones for the phytoextraction process using *Populus maximowiczii* × and *Populus nigra* and revealed that these plants are capable of accumulating high amounts of Cd, Pb and Zn when cultivated in contaminated sites especially during Summer harvesting. Recently, *Populus alba* has proven successfully its phytoremediation potential for As, Cd, Cu, and Zn [132]. *Populus* species not only open up new possibilities for phytoextraction but also for stabilizing contaminated sites to limit the release of toxic metals into the soil profile (i.e., phytostabilization) [133,134]. Furthermore, *Populus* species derived from phytoremediation systems are environmentally accepted biomass sources for bioenergy and wood production [107,135]. Hybrid poplar can produce up to 22 Mg ha^{-1} yr^{-1} of above ground biomass at certain sites [136]. Recently, sequencing of *poplar* genome has been proven to be a promising technique for tailoring new clones optimized for biofuels production [137].

5.4 Eucalyptus Species

Eucalyptus is an aromatic plant belongs to *Myrtaceae* Family and of more than 700 species widely distributed throughout the world. *Eucalyptus* species are capable of providing foresters and farmers with a resource of fast-growing species able to grow under a wide range of climatic factors according to the type of species being used [138,139]. Several features including rapid growth rate, propagation by stem and tolerance to adverse environmental conditions have contributed to the success of *Eucalyptus* in phytoremediation programs [140]. In this regard, *E. camadulensis* shows high tendency to concentrate lead (Pb) in its shoots and to dissolve metals in the soil [141]. In addition, *E. camaldulenses* is known to tolerate high soluble Cd concentrations that were affected by changes in both anatomical and physiological features of this plant [142,143]. Moreover, Arriagada et al. [140] found that *Eucalyptus globulus* assimilates 9.9 mg kg^{-1} Cd in its shoots, suggesting that it can be a promising candidate for phytoremediation. [143] concluded that *Eucalyptus globulus* is suitable for phytoremediation of Fe, Cr, Mn, Ni, Cd, Pb, Zn and Cu from contaminated sites. In fact, *Eucalyptus* species can also be utilized as a source for energy production. According to Green [144], Lemon or lemon-scented *Eucalyptus* (*E. citriodora*), Tasmanian blue gum (*E. globulus*), blue mallee (*E. polybractea*), and River red gum (*E. camaldulensis*) are considered as the most common *Eucalyptus* oil yielding species. Additionally, several indirect services can be obtained from *Eucalyptus* species such as fuel production as well as reduction of atmospheric carbon dioxide levels [145,146].

5.5 Ricinus Communis

Ricinus communis (castor oil plant) (*Euphorbiaceae*) is a flowering plant grown in sandy soils, creek banks, and gullies. *Ricinus communis* is characterized by growth under salinity and drought stress and is able to produce twelve-fold higher biomass [147]. It can be utilized for phytoremediation and bioenergy production as it has an excellent ability to grow on heavily polluted soils together with its high capacity for metal ion accumulation and fast growth rate [54,102,147]. Also, castor plant has other multiple uses such as utilization for the production of industrial, pharmaceutical and cosmetic commodities [147]. *R. communis* can remediate area polluted with high concentrations of Cu, Zn, Mn, Pb and Cd [148]. It is reported that *R. communis* has a good phytoremediation potential for soils contaminated with Cd, Co, Ni and Pb [149]. In addition, castor bean seedlings are able to accumulate high amounts of Cu, Cd, and Pb in their roots and shoots [150-152]. Other studies have documented that *R. communis* plant has the ability to extract various heavy metals such as Cd, Zn, Cr, CU, Pb, Mn and Fe when cultivated in fly ash contaminated lands [153,154]. Regarding bioenergy, *R. communis* is used for bioethanol and biogas production due to its rapid growth and high cellulosic biomass yield. In addition, *R. communis* is considered as a promising source for biodiesel production [155]. Castor oil has high concentrations of ricinoleic acid (12-hydroxy-9-octadecenoic acid) that constitutes 89% of oil used for biodiesel production [156], as it has a double bond close to OH group that enhances its physical and chemical properties [157].

6 Strategy for Enhancing Phytoremediation Potential of Bioenergy Plants

There are two feasible strategies for enhancing the phytoremediation potential of bioenergy plants.

6.1 Genetic Engineering

Genetic engineering of plants is a promising technique to improve the adsorption capability of metals via the formation of metal chelators as various genes are required for metal uptake, translocation or even sequestration into plant parts. Gene transfer into candidate plants results in improved metal update, translocation, and sequestration. Therefore, it could be a possible technique to develop genetically engineered plants with improved phytoremediation traits [5,158,159]. Genetic engineering technique has been effectively applied to alter biological functions of plants through modifications of primary and secondary metabolism and by adding new traits of different phenotypes and genotypes to enhance the phytoremediation properties of these plants [159]. Several genes can be used for developing transgenic plants with a higher ability to accumulate various heavy metals such as CAD1, CAX-2, GshI, GshII, PCS, Gst, AtPcrs and AtNramps [160,161]. These genes can also be applied to bioenergy crops to improve their phytoremediation capability. An example of transgenic plants is *Arabidopsis thaliana* that overexpresses AtSAP13 in tolerance response to various toxic metals including As, Cd, and Zn [162]. DNA-protein interaction assays are used to analyze the mode of action of AtSAP13 proteins and their roles in response to multiple abiotic stresses [162]. Furthermore, Shim et al. [163] transformed a sterile line of poplar *Populus alba* X *P. tremula var. glandulosa* with a heavy metal resistance gene, ScYCF1 (yeast cadmium factor 1), and found that the transgenic plants accumulated increased amounts of Cd, Zn, and Pb in their roots. Also, bacterial merC gene has been introduced from the Tn 21- encoded mer-operon into *Arabidopsis*. This transgenic *Arabidopsis* has proven greater ability to extract more Cd than the wild-type [164]. Attention has been given to enhance the capability of plants to detoxify heavy metal ions in the cytoplasm through their inactivation via compartmentalization, chelation, or conversion of toxic ions into less toxic molecules. Heavy metal tolerance and phytoremediation potential of plants could be enhanced via modification or overexpression of enzymes involved in GSH and PCs synthesis in these plants. Bioenergy crops to be utilized in phytoremediation, should exhibit high biomass productivity along with high ability for metal accumulation. Scientists have utilized numerous molecular biology technologies to identify factors affecting biomass production such as genetic variation, canopy architecture and carbon allocation patterns. Poplar plants can display improved biomass (6%), increased amount of chlorophylls, proteins, and total sugars, and improved nitrogen utilization efficiency, especially in young leaves compared to non-transformed controls via overexpression of cytosolic glutamine synthetase (GS1) under elevated nitrogen levels [165]. In general, transgenic plants are arisen either to enhance immobilization or increase plant tolerance against heavy metals to facilitate more translocation and accumulation in aboveground plant parts, which lead to developed metal remediation potential of plants. However, numerous obstacles are still there to overcome. One of them is that the majority of research has not been carried out in the field [166,167]. Therefore, application of risk assessment is necessary before utilizing genetically engineered plants in phytoremediation [168]. There are other risks including humans and wildlife exposure to metals, biotransformation of metals into more bioavailable forms, and unlimited prevalence of genetically engineered plants and restrained genetic diversity in native plants due to cross-pollination or interbreeding [169]. The public acceptance with the use of genetically engineered plants for phytoremediation is another issue. Societal consideration opposing genetically altered organisms is the hypothetical danger to human health and the possible dispersal of the transgene in the environment. Numerous governmental regulations are needed for releasing the genetically modified organism into the environment. Recently, modern approaches have been developed to produce transgenic plants free of marker-genes [170], thus ensure the safety of genetically modified crops and a wider range for their use [5].

6.2 Plant Growth Promoting Microorganisms (PGPMS)

The beneficial flora of microorganisms includes various fungi (arbuscular mycorrhiza fungi-AMF) and bacteria, usually referred to plant growth promoting bacteria (PGPB). PGPMs are beneficial for sustainable environmental conservation since they support plants by providing essential elements and being more tolerant to numerous biotic and abiotic stresses [171]. They also play a vital role in soil protection, biomass and biofuel production, and contaminant uptake [172]. PGPRs produce indole-3-acetic acid (IAA) and ACC deaminase, phosphate solubilizers, siderophore producers, and nitrogen fixers that promote plant tolerance to heavy metals mostly via modifying the bioavailability of these metals in the soil [42]. It is found that *R. communis* inoculated with *Pseudomonas* sp. produced high IAA content and showed an improved accumulation capacity for Ni, Cu, and Zn [173]. It was reported that *Brassica juncea* species grown on Pb-Zn mine tailings promote high rates of growth and biomass production upon inoculation with PGPR consortium containing N2-fixing *Azotobacter chroococcum* HKN5, P-solubilising Bacillus megaterium HKP-1, and K-solubilising Bacillus mucilaginosus HKK-1 [174]. Arbuscular mycorrhizal fungi (AMF) can also be utilized to enhance the process of phytoremediation and the growth of plants in metal-polluted soils. Sarkar et al. [175] demonstrated that inoculating *Miscanthus sacchariflorus* with AM fungi can improve Zn uptake from Zn-deficient soils and prevent extreme Zn accumulation in contaminated soils. Also, it is revealed that Miscanthus × giganteus treated with mycorrhizal inoculum (Solrize) shows enhanced efficiency to phytoremediate soils polluted with Cd-, Pb- and Zn [176,177]. Inoculating *Eucalyptus* species with two AF fungi (*Glomus deserticola* and *Trichoderma koningii*) improved their response to Cd (50 mg L-1 Cd) [178]. Additionally, it is reported that AMF play other vital roles including salinity stress response, CO^2 utilization and plant growth promotion [179,180]. Research is continuing to develop the utilization of fungi and bacteria for the detoxification of polluted sites and for the optimization of the bioremediation and phytoremediation procedures worldwide.

7 Problems Facing the Involvement of Bioenergy Plants in Phytoremediation Approach

There is no doubt that remediation initiatives can improve stakeholder involvement (especially those who are living close to the contaminated and polluted environment). Developmental activities of highly growing population create soils contaminated with heavy metals and thus increase the pressure on the soil. This creates potential irreconcilable situations among the stakeholders [181]. Accordingly, there will be massive pressure on contaminated lands for human habitation due to the restriction of usable land. To avoid these issues, proper participation of respective stakeholders is pivotal for the success of multi-purpose clean-up processes such as site owners, local peoples, farmers, technology providers and consultants, remediation experts and sustainability assessors, regulatory agencies and certification bodies, bio-refineries and financial sponsors, NGOs, and other voluntary organizations [4].

Another problem concerns biomass utilization for bioenergy production due to the issue of contamination transfer and the content of heavy metals in the biomass. Contamination of the crop can cause serious problems in subsequent stages of biofuel production, and the decision on whether crop capture of heavy metal should be fostered on a case-by-case basis. There must be an administration of crops or crop selections and clones can be performed to block capture of pollutants using excluders instead of hyperaccumulators [182]. Climatic factors affect the accumulation capacity of some plants and in some cases, pests and disease can prohibit the phytoremediation mechanism [183]. Moreover, the safety of phytoproducts should be taken into our consideration as previous research findings reported that these phytoproducts are easily contaminated by heavy metals causing human health issues [181,184-187]. Hence, coupling a strength, weakness, opportunities and threat analysis (SWOT analysis) with a detailed cost-benefit analysis (CBA) and social impact assessment (SIA) must be applied to ensure the sustainability of bioenergy production from polluted lands. These initiatives are necessary for the success of bioenergy production form polluted lands [4]. Other possible problems facing the involvement of bioenergy plants in phytoremediation approach are summarized in Tab. 4.

Table 4: Constraints and problems facing the involvement of bioenergy plants in phytoremediation approach

Constraints and problems	Drawbacks	The bright side
Loss of biodiversity	Anthropogenic activity has a serious impact on species diversity causing several species to be exposed to the danger of extinction. Large scale monoculture for bioenergy and bioremediation also increases this dangerous [188,189], especially if these species have high propagation rate that allows them to be highly invasive [10,188].	Perennial coculturing provides a low-impact, less polluting, and more effectual substitute to annual single-species cultivation. Furthermore, using diverse native perennial grasses such as *Miscanthus* may be a probable option instead of monoculture [190,191].
Land use change	Land use change is a major disadvantage of the large-scale plantation [191-193]. Changing land use has serious effects on the ecosystem [188,194], and the scarcity of food and fodder [195].	Contaminated lands are inappropriate for agricultural purpose, so it may be used for energy crop production without affecting food production.
Nutrient loss from the soil	Energy crops require large quantity of nutrients such as nitrogen and phosphorus for propagation leading to nutrient loss from the soil [188,189,196].	Firewood combustion residue that contains both micro- and macro-nutrients required for plant growth and development, can be used to minimize nutrient loss from the soil and improve crop yields and soil properties [197].
Seed poisoning	Seeds are the main storage organ for the contaminants in seed oil producing energy crops. Contaminated seeds are highly toxic for wildlife as well as human beings [198].	Using non-edible plants is a good option to reduce this risk, especially if non-edible seedless bioenergy plants.
Much water requirement	Water shortage in agriculture sector reduces productivity in many countries. Most of energy plants require high water content for their propagation [196,199].	In such condition of rainfed agriculture or water scarcity region, it is not acceptable to cultivate high water requiring energy crops [200].

8 Conclusion

Some interesting facts concerning non-edible plants utilized for bioenergy production along with phytoremediation of heavy metal-impacted soils are revealed in this review.

- There is no doubt that phytoremediation is an appropriate approach for the decontamination of metal-impacted sites. Not only this method decreases the pollutants, but also produces biomass and byproduct, which can be utilized for biofuel production.
- Non-edible plants are the most promising multi-tasking species as they exhibit a wide range of advantages such as fast propagation, low competition for arable lands and source for animal and/or human food.
- Deriving biofuel from phytoremediation not only helps in fulfilling the global energy demand but also offers a path for encouraging a biobased economy for feasible development.
- Selection of the non edible plant is a characteristic key for efficient phytoremediation and bioenergy production process.
- As the biomass of such plants consists of noticeable amounts of hazard contaminants, the fate of these toxins should be considered prior to their utilization for various aspects.
- Research is being conducted to develop genetically modified plants with improved phytoremediation potential for heavy metals and other xenobiotics.

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