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Phytoremediation by Bio-Energy and Aromatic Plants: A Multidimensional and Ecologically Feasible Method of Remediation

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ABSTRACT

Heavy metals have been considered to be a serious environmental threat that has adverse impacts on human health as well. To reduce its risk, a new integrated phytoremediation-bioenergy approach could be a viable solution. These crops offer double advantage of phytoremediation as well as the production of valuable by-products like essential oil and this approach contributes to the circular bioeconomy. The growth of aromatic and bioenergy plants keeps heavy metals out of the food chain. It allows for the long-term use of contaminated land, which creates new approaches to addressing pollution problems. This review article mainly highlights how phytoremediation is coupled with bioenergy and essential oil production, along with managing post harvested biomass. The current review also offers a thorough summary of these plants' utilization in years to address pollution issues and their potential to produce essential oil and bioenergy to meet future energy needs.

Keywords: Phytoremediation; Heavy metal; Bio-energy plants; Bio-ethanol; Biodiesel

1. INTRODUCTION

In the present scenario, utilisation of fossil fuels mainly accounts for the majority of global energy consumption, but total dependence on them for energy may not be a long-term solution. As a result, there should be less reliance on the production and utilisation of fossil fuels, but the generation of renewable energy should be effectively utilised at a global scale. Over the last two centuries, contaminations of soil and water have now become a considerable environmental issue due to the large mining, industrial manufacturing, and urban development[1]. Heavy metals, wastewater contaminants, pharmaceutical waste, micro plastics, persistent organic pollutants, and mining activities are the major concerns. Though heavy metals are mainly found in the soil surface due to leaching and erosion, these heavy metals can be also responsible for the contamination in nearby water areas and land degradation[2]. Moreover, land degradation is mainly due to physical methods such as surface soil erosion, loss of organic carbon, compaction, and crusting and chemical methods like acidification, leaching process, and loss of micro and macronutrients, presence of excess heavy metals, and agrochemicals utilization[3,4]. Biological degradation is primarily caused by large deforestation, biodiversity loss, etc. Some bacteria, microorganisms, and fungi also inhibit the function of helpful soil microbes, decreasing soil fertility and impacting soil productivity[5].

Moreover, the yield production of lands at the global scale has degraded by 50 % due to soil erosion and desertification. The amount of soil lost globally each year is estimated to be 75 billion tonnes, with a corresponding cost of about $400 billion. Only 3 % of the world's surface area has been estimated to be Class I non-degraded land6. As we all know soil remediation is a very expensive, time, and technically complex procedure that includes soil washing, solidification/stabilisation, verification, chemical oxidation, excavation of soil, and incineration[7,8]. These conventional methods are not sustainable and non cost effective; therefore, we need sustainable, cost-effective, and long-term solutions such as phytoremediation. Phytoremediation is an eco-friendly and sustainable technology that employs plants for soil and water remediation by utilising their innate capacity to accumulate and degrade contaminants. Moreover, these plants can be used to accumulate metals and other organic compounds extracted from the earth in their aerial parts, as well as to mineralize harmful substances. In this process, plants can absorb contaminants without harming the ecosystem of topsoil and improve the fertility of soil with organic matter inputs. Additionally, Phytoremediation can be used in large contaminated sites where other types of remediation methods are very expensive or impractical also[9,10].

Moreover, phytoremediation when combined with biomass production provides intensive farming techniques with sustainable solutions[10]. The use of phytoremediation for heavy metal extraction has advanced significantly during the previous 20

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years. However, the translation of phytoremediation from laboratory settings to field conditions remains hard. Although the United States and some regions of Europe have used short-rotation woody crops for phytoremediation, efforts are being made to integrate this technology with the production of valuable biomass and the control of pollutants[11]. Despite these advancements, several obstacles still prevent the widespread application of phytoremediation. As an example, Brassica species have demonstrated significant differences in heavy metal accumulation between field and laboratory settings, which Brunetti *et al.* (2011) attributed to regional and meteorological variations[11]. Moreover, Faubert *et al.* (2021) reported that Salix miyabeana growing in contaminated land revealed an unexpected rise in contaminant concentrations in the soil surface layer[12]. Under intense short rotation woody crop circumstances, this impact was associated with the inter root pumping effect of willow, a phenomenon that was not predictable in laboratory settings. Significant technical obstacles arise from worries about pollutant transmission risks and inadequate field research, in addition to financing and governmental constraints. Furthermore, it is more difficult to correlate plant growth with remediation outcomes for assessing phytoremediation effectiveness. This restriction makes it more difficult to optimise phytoremediation and keeps the use of traditional remediation techniques alive. To fully utilize phytoremediation for environmental restoration, these issues must be resolved. Therefore, the primary goal of this review article is to present the concept of phytoremediation, its methods, and the use of aromatic plants and bioenergy for both remediation and energy production. The use of these plants over the past ten years is also summarised in this article, highlighting their successful application and offering recommendations for future environmental research that identify knowledge gaps.

2. METHOD OF PHYTOREMEDIATION

Phytoremediation is defined as the utilisation of the plant to make the water and soil harmless by accumulating environmental contaminants. Phytoremediation is regarded as an environmentally friendly technique because it avoids the excavation of contaminated sites, maintaining the original ecotype and reducing the chance of contaminant dispersion. Additionally, previous research has demonstrated the economic advantages of phytoremediation on land because, when soil quality is improved through phytoextraction, higher-value crops can be grown. The main mechanisms of phytoremediation are phytoextraction, phytostabilisation, phytovolatilisation, hemofiltration, rhizodegradation etc[13]. The mechanism of phytoremediation is presented in Figure 1.

2.1 Phytoextraction

In this process, contaminants are absorbed and transported by the plant roots and accumulate in the aboveground biomass, such as the plant's leaves and shoots. This process is known as phytoextraction. The plant utilized for phytoextraction needs to be highly capable of generating large amounts of biomass or accumulating pollutants. According to Cristaldi *et al.* (2017), hyperaccumulator species are the ideal plants to use for phytoextraction because of their high capacity to accumulate contaminants[14]. Moreover, phytoextraction can also be carried out with plant species that have a high biomass production capacity. The ratio of metal concentrations in the soil to the plant indicates how successful a particular plant species is at metal phytoextraction. After that, the plants that perform phytoextraction are harvested and burned. The pollutants in the soil are eliminated since the ash from the incineration will be disposed of in a landfill. However, the effectiveness of phytoextraction will be restricted by the low bioavailability and low rate of metal absorption in soil. Furthermore, when the metals are stored in the roots rather than being transferred to the shoots and leaves, the efficiency of phytoextraction will also decrease[13].

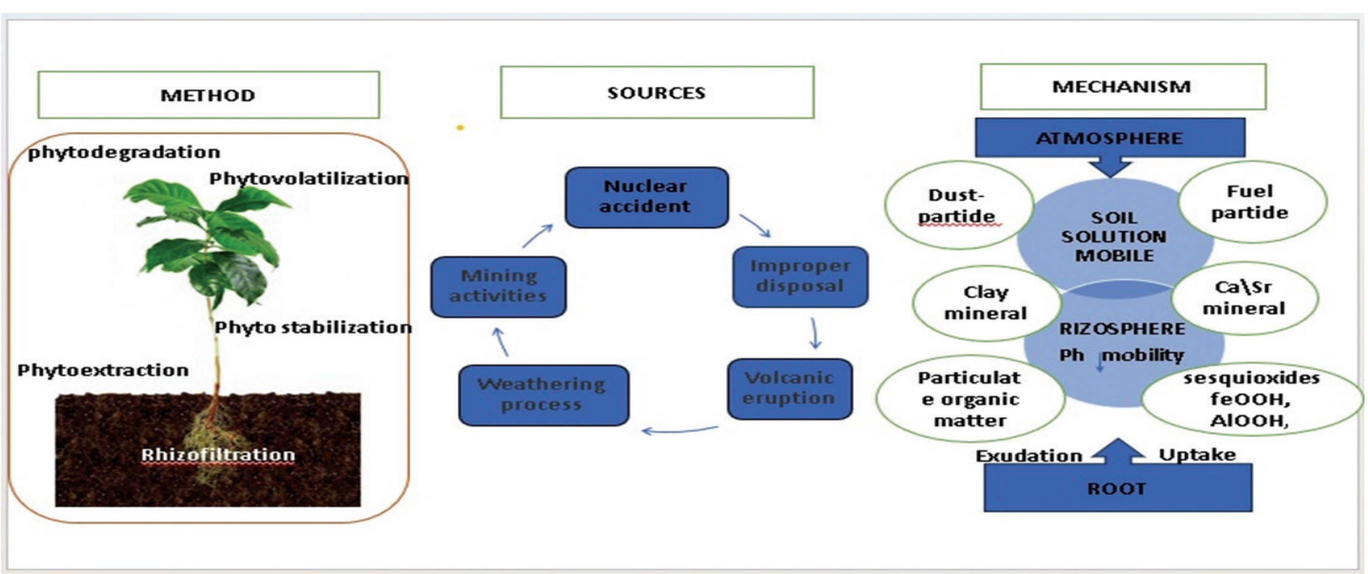

Figure 1. Mechanism of phytoremediation.

2.2 Phytostabilisation

Phytostabilisation is the process by which heavy metals are absorbed by roots or precipitate within the rhizosphere, restricting the mobility of contaminants in the soil. The plant being used for phytostabilisation changes the chemistry of the soil, which makes it easier for heavy metals to be absorbed and precipitated in the soil. Furthermore, in this process, plants release unique redox enzymes that change the heavy metals in the soil into a less harmful form. This method was widely used at the metal-contaminated site. By preventing additional metal contaminant percolation and mobilisation, phytostabilisation protects groundwater contamination. Though it does not remove the heavy metals from the soil or water, this method only inactivates and stabilizes them, making it a management strategy[13].

2.3 Phyotovolatisation

The process that accumulates toxins moves them through the xylem, changes them into less volatile and toxic forms, and then releases the altered forms into the atmosphere is known as phytovolatilisation. The removal of mercury and selenium through phytovolatilisation has been widely used due to their high volatility. According to earlier research, Astragalus racemosus can use a phytovolatilisation to change selenium into dimethyl diselenide, while Arabidopsis thaliana can change Hg^{2+} into Hg^0, increasing the volatility of mercury. Nonetheless, the temperature and amount of light present can affect the leaf tissues' capacity to release mercury into the atmosphere. However, due to accumulation and translocation during phytovolatisation, the plant's edible products, like fruit, may also contain the contaminants. One drawback of phytovolatilisation is that pollutants are not eliminated; rather, they are just changed into less harmful forms and moved from the soil to the atmosphere[13].

2.4 Rhizifiltration

Rhizofiltration is the process by which plants absorb contaminants on their roots to remove them from contaminated water, groundwater, and wastewater. Rhizofiltration-suitable plants are selected primarily based on their large absorption surface area, metal tolerance, and hypoxia tolerance. Terrestrial plants are preferred for in situ or ex-situ hemofiltration over aquatic ones because of their more fibrous systems and developed roots, which offer greater surface areas for absorption. The removal of uranium from contaminated groundwater using *Phaseolus vulgaris* and *Helium annuus* is a successful example of hemofiltration with 90 % of the removal. The drawbacks of this mechanism include the pH adjustment and initial cultivation in a greenhouse. Moreover, once the root adsorption capacity reaches its maximum, the plants utilised for hemofiltration must be harvested and disposed of[13].

2.5 Rhizodegradation

Rhizodegradation is the process by which the organic contaminants in the soil are broken down by the microorganisms in the rhizosphere. Yeasts, bacteria, and fungi are a few examples that perform rhizodegradation. The microorganisms in the rhizosphere receive nitrogen and carbon from the nutrient-containing exudates, which increases their metabolic activity by ten to one hundred times. Then, the nutrient-rich environment makes the extraction and removal of contaminants more effective. Plants also release enzymes that help break down organic pollutants in the soil and promote the growth of soil microbes. Moreover, the plant's large surface area of roots helps to promote microbial growth by supplying more oxygen. However, in deep soil that is at least 20 cm below the surface, photodegradation efficiency is reduced. Furthermore, the roots' ability to grow into deeper soil will be constrained by the physical makeup of the soil[13].

3. MICROALGAE-ASSISTED REMEDIATION

Algae play a significant and vital role in the biological treatment of wastewater in "phytoremediation." Organic, inorganic, and radioactive materials can easily build up in the cells of algae after remediation. Although some algae are terrestrial, the majority of algae are autotrophic chlorophyllous organisms found in water. Moreover, the majority of microalgae species can thrive under all cultivation conditions, making them a superior choice over other microbes particularly for environmental remediation. Microalgae can be photoautotrophic, heterotrophic, or mixotrophic9. Microalgae plays a significant role can breaking down complex organic compounds into non-toxic substances without releasing secondary pollutants. Therefore, the microalgae based treatment system can be selected as an efficient remediation method over other conventional techniques due to its affordability, efficiency, and environmental friendliness. It is reported that, for the breakdown of pollutants, the most widely used microalgal species are *Synechococcus, Botrycoccus, Chlamydomonas, Arthrospira, Spirulina, Porphyridium, Anabaena,* and *Chlorella.* Numerous factors, including the physicochemical characteristics of the wastewater, the kind of pollutants, and the species of algae, can affect how well microalgae absorb a wide range of pollutants. In appropriate conditions, microalgae can eliminate very high metal concentrations and can also produce a large amount of biomass including bio based high-value compounds, alcohols, bio hydrogen, hydrocarbons, and health supplements. Moreover, a variety of mechanisms, such as precipitation, ion exchange, surface complexation, electrostatic contact, absorption, and adsorption, are the main accumulation processes. Furthermore, bioaccumulation is the second process in which cells are utilized to detoxify pollutants where they absorb substances and subsequently metabolise or accumulate them. Moreover, biodegradation is another process where bioremediation involves the breakdown of target pollutants either through the complete mineralisation of parent molecules to CO_2 and H_2O or through biotransformation, which contains a series of enzymatic reactions to produce different metabolic intermediates. Microorganisms act as biological filters to concentrate pollutants and separate them from the surrounding water. Furthermore, Cristaldi *et al.* (2017) also stated that the microalgal biomass obtained from wastewater treatment plants can be processed further to produce biofuels, biofertilisers, cosmetics, pigments, bioplastics, and other products[14]. Therefore this is an urgent need to explore the phytoremediation potential of microalgae for several contaminants with the production of biofuels on a large industrial scale.

4. THE ECONOMIC AND ENVIRONMENTAL BENEFITS OF COMBINING BIOENERGY WITH PHYTOREMEDIATION

Energy from the organic matter of plants is one of the most important and sustainable sources of renewable energy[15]. The reliance on plant biomass for bioenergy production necessitates a large amount of land, which can potentially reduce the amount of land available for growing food[15]. In these circumstances, we can cultivate bioenergy crops on contaminated soil which is subjected to various types of abiotic stresses such as heavy metal toxicity, pesticides, and pharmaceutical waste and poses a serious threat to the environment[15]. However, apart from the remediation potential, and production of plant biomass, economic outcomes like high-value chemical compounds, bioenergy production, and formation of compost are also the most important criteria for selecting plants for phytoremediation and bioenergy production. Farmers and indigenous populations can also think about the transition from traditional cropping patterns to taking phytoremediator plants[16]. There are several plants reported with heavy metal accumulating capacity, such as *Miscanthus* species, *Panicum virgatum, Brassica juncea, Jatropha curcas, Ricinus communis, Arundo donax,* and *Salix* species[16]. Moreover, the biomass generated by these plants cultivated in contaminated lands can be also used to generate large amounts of bioenergy with good economic return[17,18].

5. BIO-ENERGY PLANTS: A SAFE OPTION FOR PHYTOREMEDIATION AND BIOENERGY PRODUCTION

Bioenergy plants are any plants used to produce bioenergy. The organic matter produced from plants might be utilised as a solid material (biomass) for combustion, or as a liquid for the manufacturing of biofuels. Organic matter and biomass energy can both be produced from biomass feedstocks, agricultural byproducts, or waste materials as well. The organic substance of plants is generally made of sugars, water, cellulose, starches, hemicelluloses, lignin, proteins, lipids, and other compounds and has the potential to be thermally oxidised and generate energy. In this context, bioenergy plants such as Willow (*Salix spp.),* switchgrass (*Panicum virgatum L.),* poplar (*Populus spp.),* mesquite (*Prosopis spp*.), elephant grass (*Pennisetum purpureum Schum.*) and other crops have been promoted as having the greatest potential for biomass production. Apart from producing bioenergy, these plants have the potential to thrive in polluted environments also[19]. Recently Rheay *et al.* (2020) reported that the hemp plant is an extremely potent species for providing benefits of phytoremediation and production of high-value fuels like biodiesel, bioethanol, and biogas[20]. Similarly, Chen *et al.* (2020) recently reported that crop varieties from Lamiaceae, Pteridaceae, Crassulaceae, Solanaceae Asteraceae, and Phytolaccaceae families are very strong phytoremediators and the production of bioenergy[20]. They also stated that bioenergy plants such as *E. haichowensis* produced around 259.2 ± 2.9 mL/g amount of bioenergy, S. Alfred produced around 238.7 ± 4.2, *S. nigrum* generated approximately 135.9 ± 0.9 of biofuels, *P. americana* produced around 129.5 ± 2.9, and *P. vittate* produced around 106.8 ± 2.1 mL/g, of biofuels. In addition to that, some positive impacts related to metals and crops were also observed in their study; for instance, the 1000 mg/kg concentrations of Cu enhanced the total biogas production by the plants whereas *S. alfredii,* in the presence of ≥500 mg/kg concentration of Zn, resulted in a very less impact on the production of methane and biogas. Moreover, Jiang *et al.* (2015), reported that the threshold limit of heavy metal in dry biomass of plants for hyperaccumulator plant species reported to be around >10,000 µg/g for Mn and Zn, and for heavy metals such as As, Co, Cu, Ni, Se is reported around >1000 µg/g and around >100 µg/g is also reported for Cd[21].

Moreover, in this context, Van *et al.* (2015) also started the concept of a gromining as an innovative technology[22]. In this method metal accumulator plant is used as a phytoremediator crop and after phytoremediation plant biomass is processed till ashing to recover the maximum amount of heavy metals[23]. Therefore, hyperaccumulator bioenergy crops are a viable and sustainable approach for phytoremediation and production of energy. Furthermore, eight energy crops, which include *Arachis hypogea* (peanut), *Brassica rapa* (rapeseed), *Cannabis sativa* (hemp), *Carthamus tinctorius* (saflower), *Glycine max* (soybean), *Helianthus annuus* (sunflower), *Linum usitatissimum* (flax), and *Ricinus communis,* were also studied for remediation of cadmium and zinc. After experiments, these crops have shown excellent potential for phytoremediation and bioenergy production[24,25]. Details of bioenergy crops used for phytoremediation in past years are listed in Table 1.

6. AROMATIC CROPS SUITABLE FOR PHYTOREMEDIATION

Along with the bioenergy plants, several aromatic plants have been reported for their phytoremediation potential. Aromatic plants such as vetiver (*Chrysopogon zizanioides*), Citronella (*Cymbopogon winterianus Jowitt*.), Basil (*Ocimum basilicum*) lavender (*Lavandula*), lemon grass (*Cymbopogon citratus*), rosemary (*Rosmarinus officinalis L*) are widely reported for the remediation with high economic return. In contrast to phytoremediation by aromatic plants, vetiver grass which belongs to the family – Poaceae, is widely reported for its excellent phytoremediation capability[35]. Vetiver grass is an Indian native grass that is economically very beneficial because it contains large amounts of aromatic oil content in its aerial parts. Because of its diverse inherent capabilities, this particular species is best suited as a model species for phytoremediation and production of essential oils. Furthermore, lemon grass is also a natural aromatic species that belongs to the family Poaceae. Lemon grass is also reported to contain a high potential for phytoremediation and has a high capacity to produce essential oils[36]. Similarly, the plant Citronella belongs to the family of Poaceae and is reported for phytoremediation and production of essential oil. Furthermore, Basil (*Ocimum basilicum*) is also an aromatic plant belonging to the family Lamiaceae. This plant is widely reported for phytoremediation of heavy metals and has a high capacity to produce essential oil. Basil can operate as a photo stabilizer, but plants cultivated for phytoremediation should not be utilised for food purposes to prevent food chain contamination. Loannidou *et al.* (2015) reported the Phytoremediation capability of basil for cadmium and zinc toxicity[37]. Similarly, Pirzadah *et al.* (2019) also reported its remediation potential against cadmium[38]. Several recent studies have found that the presence of heavy metals can enhance the essential oil content in their aerial parts[39]. Angelova *et al.* (2016) reported the phytoremediation capability of aromatic plants with Pb, Cd, and Zn[18]. Similarly, Zheljazkov and Nielsen (2008) also used these plants for the remediation of Cd, Pb, Cu, Mn, Zn, and Fe and found a great potential for accumulation[40]. Zheljazkov and Astatkie (2011) performed their research work on the production of the essential oil of lavender and its phytoremediation potential and found that the essential oil of lavender was not contaminated with heavy metal contamination[41,42]. Details of aromatic crops used for phytoremediation in past years are listed in Table 2.

Table 1. An update on the use of bioenergy crops for remediation

S. NO.	Plants name	Common name and family	Heavy metals	Remarks	References
1.	*Arundo donax*	Giant reed, Poaceae	Cu and Zn	*Arundo donax* was found to remediate Cu and Zn in significant concentrations.	25
2.	*P. purpureum*	Napier grass, Poaceae	Organic compound	A high impact of organic compounds was observed.	26
3.	*Carthamus tinctorius*	Asteraceae, Saffower	Zn	Accumulation found in root and shoots.	29
4.	*Ricinus communis*	Euphorbiaceae, Saffower	Cr	Accumulation found in root and shoots.	28
5.	Vetiver zizinoides & Cannabis sativa	Vetive r grass, Poaceae *&* Cannabaceae*,* Hemp	Multi metals	Both are potential candidate.	29
6.	*Helianthus annuus*	Sun flower, Asteraceae	As, Cr, Cd	*Helianthus annuus* act as a potential hytostabilizer of As, Cr, Cd.	30
7.	*Chlorella vulgaris*	Chinese Chlorella, Chlorellaceae	Multi metals such as chromium (Cr), cadmium (Cd), copper (Cu), and lead (Pb)	79%, 93%, 72%, 79% decrease of chromium (Cr), cadmium (Cd), copper (Cu), and lead (Pb) was observed by *Chlorella vulgaris*.	31
8.	*Arundo donax L.*	Gramineae, Giant cane	Multi metals	A potential candidate for phytoremediation and high capability to produce biomass.	32
9.	*Chlorella sorokiniana*	*Chlorella vulgaris, Chlorellaceae*	Cd, Cr, and Pb	Chlorella was observed to remediate heavy metals with efficiency > 95% for Cd.	33
10.	*Chlorella vulgaris*	*Chlorella vulgaris, Chlorellaceae*	Multi metals and hydrocarbons	Phytoremediation efficiency of *Chlorella vulgaris* of heavy metals (70%–97%) and hydrocarbons (48.59 %). High production of biomass approximately 1.69 g L^{-1} grown in water.	34

Table 2. An update on the use of Aromatic crops for remediation

S. NO.	Plant names	Common name and family	Heavy metals	Remarks	References
1.	*C.zizanioides* and *C. nigritana*	Vetiver and khus, Poaceae	Pb, Cd, Zn	Vetiver can act as phytoextractant of heavy metal.	43
2.	*Cymbopogon flexuosus*	lemongrass, Poaceae	Multi-metals	*Cymbopogon flexuosus* was found to be remediating Cr (VI) and As (III) in significant concentrations.	29
3.	*Ocimum basilicum*	Tulsi, Lamiaceae	Cd: ionic and nanoparticle	Cd is mainly accumulated in the roots.	44
4.	*Ocimum basilicum*	Tulsi, Lamiaceae	Amoxicillin	Accumulation is mainly done in root and shoot.	45
5.	*Ocimum basilicum*	Tulsi, Lamiaceae	Tetracycline	Accumulated in root and shoot	46
6.	*Coriandrum sativum*	Chinese parsley, Apiaceae	Cd, Pb and Zn	Metals accumulated in root and shoot	47
7.	*Ocimum gratissimum*	Tulsi, Lamiaceae	Zn	Metals accumulated in root and shoot	48
8.	*Mentha piperita* L.	Mint, Lamiaceae	phenanthrene (Phe)	Metals accumulated in root and shoot	49
9.	Vetiver grass	Vetiver, Poaceae	Cd	Metals accumulated in root and shoot	50
10.	*Acacia mangium*, *Jatropha curcas* and *Manihot esculenta*	Acacia (Fabaceae), Jatropha (Jatropha) and Cassava (Euphorbiaceae)	Cd	Acacia accumulated up to 5.1 mg kg^{-1} whereas *cassava and jatropha* accumulated about 2.2–3.9 and 2.7–4.1 mg kg^{-1}.	51

7. POST-HARVESTING OF CONTAMINATED BIOMASS

We all know, that phytoremediation performs the bioaccumulation of contaminants within the plant biomass. So, if these plants are harvested improperly, plants' biowastes could be extremely toxic and result in secondary contamination. As a result, it is very important to develop appropriate post treatment of bio-waste handling and production of bioenergy. Various post treatment methods are available and these are very economical and eco-friendly to improve the production of biofuel from lignocellulosic biomass or biowaste via conversion processes. Moreover, the common biochemicals such as acetic acids, lactic acid, and microbe-based enzymes such as cellulase, amylase, and pectinase, and bioactive substances, such as phenylpropanoids and phenolic compounds can be also used to produce bioenergy by using a variety of bioprocesses like hydrolysis, fermentation, and anaerobic decomposition[52]. Moreover, there are several other methods for treating plant biomass such as incineration, gasification, pyrolysis, and hydrothermal modification. Meanwhile, the main byproducts of fermentation and anaerobic decomposition are liquid biofuels like ethanol and diesel, as well as biogas like methane. This process includes different types of techniques for dealing with heavy metal-containing post-phytoremediation plant waste, such as heat treatment method, extraction of contaminants, composting, and compaction of plant-derived biowaste, nanomaterial synthesis, and phytomining also. The future use of remaining biomass has been an ongoing research issue from the start of phytoremediation research which is an integrated and comprehensive biotechnology-based research field. Nowadays, these methods are challenged by various new technologies in the consolidation of reducing biomass waste procedures that incorporate circular economy approaches resulting from decades of research (Fig. 2). The circular economy is a new and innovative approach that minimises huge consumption of raw materials, redesigns materials, and services to be less resource intensive, and considers "waste" as a resource for the production of new materials.

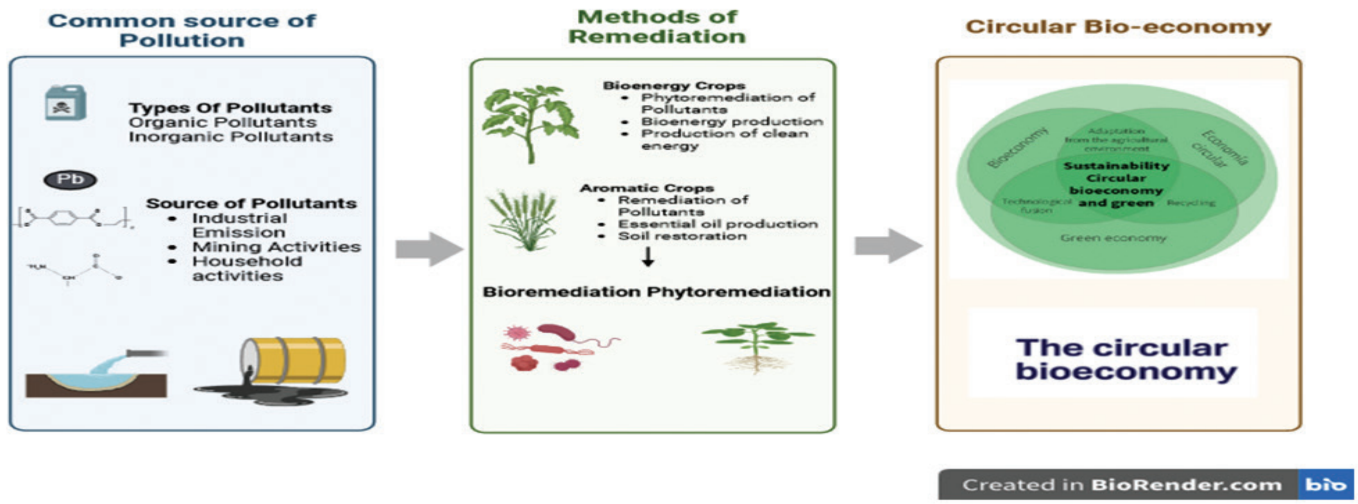

Figure 2. Coupling of phytoremediation with bio-energy production.

7.1 Thermochemical Conversion

Thermochemical conversion refers to chemical conversion facilitated by heat which includes incineration process, pyro-gasication, and pyrolysis[53]. Moreover, biochemical conversion, such as anaerobic digestion or fermentation, occurs when the transformation of plant biomass is powered by bacteria rather than heat. When lignocellulosic biomass present in the plants is burned in the oxidation process, the carbon, hydrogen, oxygen, combustible sulfur, and nitrogen react with the oxygen to create energy. The common meaning of biomass conversion is to use heat energy by combustion, which includes approximately 90 % of energy generated from biomass that contributes 97 % of bioenergy production at the worldwide scale. The biomass of plants contains high amounts of moisture content and oxygen level, which is one of the most disadvantageous characteristics and results in low heating values of biomass. In addition, the tiny number of toxic metals should ideally be controlled and predictable in their concentration in these products. Low concentrations may make the product usable for additional processing, whereas high concentrations will hinder downstream processing. The future use of the product is determined by the metal separation in the various streams[54].

7.2 Pyrolysis

The anaerobic breakdown of plant material at a high temperature is known as pyrolysis. Bio-oil, biochar, and pyrolysis gases (combinations of H_2, CO_2, and CO) are the byproducts of biomass pyrolysis. The thermochemical processes involve processes like pyrolysis and gasification in which carbon material can be decomposed[55]. As compared to incineration, in which the biomass is fully oxidised into gasses, pyrolysis is mainly performed without any oxygen (pyrolysis) or gasification is mainly done in the presence of substoichiometric air. There are currently four different kinds of pyrolysis: slow, intermediate, and fast. Typically, slow pyrolysis produces biochar at temperatures between 300 and 700 °C with lengthy heating times of 5 to 720 minutes. Fast pyrolysis occurs at a much higher temperature (between 400 and 800 °C) and results in a high amount of bio-oil production with a residence time of only 5 seconds.

7.3 Gasification

In this process, solid materials are heated to a specific temperature in which plant biomass transforms into syngas (a combination of hydrogen and carbon monoxide gas). Typically, gasification takes place between 550 and 900 °C, but after the addition of gasifying substances like air or carbon dioxide, the temperature can increase to between 1000 and 1600 °C. After being gasified, plant material loses more weight[56]. When the post-phytoremediation plant is gasified, the Boudouard reaction (gasification and conversion of biochar into carbon dioxide) is thermodynamically advantageous at 710 °C temperature and it may result in a significant weight loss. Therefore, temperatures above 750 °C are typically used for the gasi□cation procedure. The syngas produced during the gasification process are typically used to create electricity using fuel cells or gas turbines[56].

7.4 Biochemical Conversion of Biomass

Biochemical conversion of biomass refers to the plant biomass conversion into various products by physical method, chemical method, and biological pretreatments also[57]. In biochemical conversion techniques, the conversion of biomass is done properly without any waste generation as compared to other techniques. In this technique, biomass will be converted into various products, such as mannitol, organic acids, xylitol, hydrogen, biogas, ethanol, 1,4-butanediol, butanol, (pyruvate, oxalic acid, levulinic acid, lactate, citric acid), 2,3-butanediol, isobutanol, and xanthan gum by taking various bacteria and microorganisms via biochemical conversion. Biochemical conversion also includes the use of bacteria and microorganisms to convert plant biomass into biofuel. These methods require a very low amount of energy consumption. The process of biochemical conversion processes such as fermentation and anaerobic digestion[58, 59].

7.5 Incineration

The process of incinerating involves both high-pressure oxidation and the combustion of heavy metal-containing plant biomass. There are three steps in incineration such as pretreatment of biomass, combustion of biomass, and energy recovery. The plants' water will fully evaporate during the first phase, which takes place at 185 °C temperatures. In the second section, the weight of the plants is reduced greatly as a result of the cellulose and hemicelluloses decomposing at very high temperatures between 185 and 400 °C. The carbon in the plants continues to break down in the concluding phase at temperatures between 400 and 697 °C but weight loss begins to be started at the initial steps. Additionally, the heat produced during the incineration procedure can be used again for different purposes, like power generation. Fly ash would be produced as the post-phytoremediation plant material was burned[60]. Inappropriate handling of fly ash releases that contain hazardous heavy metals could result in secondary pollution.

8. FUTURE PROSPECTS

Though, phytoremediation offers a very eco-friendly, highly economical technology, widely used and commendable power of contaminated and degraded sites reclamation this technology has some challenges as well such as remediation takes a very long time, poor biomass, slow growth rate, contamination of food chain, etc. Moreover, genetic engineering by introducing novel genes from plants used as bio-scavengers will play a major role in the future for enhancing the phytoextraction ability of chosen plants. Moreover, hyperaccumulators carry excellent capability of resistance against heavy metals, extremely high metal accumulation, and translocation, therefore, may be also employed in the field of phytomining to recover several commercially important metals from contaminated biomass[60]. Moreover, Phytoremediation can be also performed with the help of a variety of chemical and biological things, such as chelating agents (EDTA, tartrate, glutamate, etc.) and microbial association (bacterial or mycorrhizal fungi) and it will be also an emerging field in the environmental research. However, there are still some changes that could be made to increase the effectiveness and efficiency of the various methods in the field of environmental research. Moreover, shortly the best practice could be a deep study to better understand plant selection for remediation, plant uptake processes inner elemental interferences, and their chemical properties such as oxidation states. Furthermore, by making the right choices when choosing hyper accumulating plant species, the method can overcome its time consuming shortcomings and become more promising. Genetic engineering already opens a path toward the generation of more tolerant plant varieties with stronger xenobiotic and heavy metal phytoremediation potential. It is reported that to know the biological processes in phytoremediation we can either formulate appropriate protocols or we can use cutting-edge genetic editing technology such as (CRISPR)-Cas9 (clustered regularly interspaced short palindromic repeats) by which scientists can quickly change DNA sequences and specify how genes work. Therefore, CRISPR can be also used for plants in phytoremediation, so that we can perform genome editing on them and know which gene can perform well in case of contamination.

In addition to bioinformatics techniques, the phytoremediation method must incorporate some special sensing techniques, such as RGB, LiDAR, UV, multispectral, hyperspectral, infrared thermal imaging, and RGB sensors. Along with that, several measurement techniques, such as X-Ray Computed Tomography (XRCT), MRI, SAR, near-infrared (NIR), NIR hyperspectral imaging, RGB, and vis-NIR also need to be explored. The application of AI to phytoremediation, including heavy metal sequestration in plants, the impact of climate change on food security, carbon capture, etc., requires a thorough investigation. Future studies in this field are encouraged to examine the following suggestions, as they may eventually contribute to improved toxicity of pollutants in the environment, food security, and plant growth.

9. CONCLUSION

The rapid growth of the world's population and the depletion of fossil fuels have led to an increase in the large energy demand. Earth's oil resources may be depleted by 2050 if current consumption rates continue. Utilisation of bioenergy plants in Phytoremediation is a recent and innovative strategy to create new and affordable, eco-friendly energy resources. After phytoremediation of heavily contaminated site plants will be harvested and these contaminants should be safely stored or disposed of. Energy generated from plant biomass can be an environmentally safer option with a high economic return value as compared to fossil fuels. Bioenergy generated from plant feedstock cultivated in contaminated land can interfere with food production. Therefore, it should be noted that land used for Phytoremediation cannot be used for edible crop production at a similar point in time to ensure food safety. Some other aromatic plants cultivated in the presence of high levels of heavy metal in soils showed a great potential to generate essential oil which will be further beneficial for phytoremediation as well.

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