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Biomass-Based Phytoremediation: A Dual Approach for Heavy Metal Removal and Resource Recovery

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Abstract**—***Heavy metal contamination of soils, mainly caused by municipal solid waste leachate, is a long-term environmental hazard with severe ecological and health impacts. Conventional remediation technologies are often beset by high cost, technical complexity, and secondary pollution. This review addresses phytoremediation as a green, low-cost alternative for mitigating heavy metal contamination in leachate-polluted soils. Emphasis is placed on phytoextraction using two fast-growing biomass crops, Gliricidia sepium and Leucaena leucocephala, which are easily accessible and well adapted to Sri Lankan agroclimatic conditions. These crops show encouraging metal uptake while simultaneously producing biomass that is suitable for bioenergy applications. Biomass management options after harvest, including composting, incineration, and phytomining, are discussed in detail to promote process sustainability as a whole. This dual approach offers a new potential pathway for environmental remediation and renewable energy generation, allowing long-term recovery of ecosystems and resource rebound in polluted environments.*

Keywords**—***Bioenergy crops, Heavy metal contamination, Leachate-polluted soil, Phytoremediation, Phytoextraction.*

I. INTRODUCTION

Heavy metal pollution is a crucial problem that is common in almost every country in the world. The extraction from ores and the use of those with diverse uses result in the mobilization of heavy metals. The release of these compounds into the environment has resulted from this. As industrialization increases and natural biogeochemical cycles change, heavy metals become more of an issue [1]. The non-biodegradable nature of heavy metals leads to this accumulation in the environment. The contamination of soil and water is the source of this pollution. Then, these elements accumulate in the body tissues of living organisms, and their concentration increases as they pass through to the upper trophic levels [1].

Open dumping of solid waste is a common but significant problem, especially in developing countries [2],[3]. The leachate generation occurs when a considerable amount of solid waste has been dumped for a specific time due to biodegradation, which is characteristic of putrescible materials [2]. Weather conditions such as rain can enhance the leachate generation from a solid waste dump. High levels of organics, nutrients, and heavy metals are frequently present in leachates. Out of these, heavy metals are the most alarming contaminant that can contaminate the soil up to a hazardous level [2]. The primary sources of heavy metals are municipal solid waste, batteries, paintings, plastic, electronic waste, paper, ceramics, and cosmetics [4].

Remediation of heavy metals in the leachate-contaminated soil is imperative to reduce the impact on the ecosystem and food chain. However, heavy metal removal/remediation is one of the costliest and technically complex scenarios, making it complicated. Some conventional physical and chemical techniques include in situ vitrification, soil flushing, soil incineration, soil washing, solidification, excavation and landfill, and stabilization of electrokinetic systems [1]. Several key factors, including disturbance of native soil microflora, irreversible changes in soil properties, high cost, and intensive labor, limit these methods. Some chemical methods can also lead to secondary pollution [1].

To overcome such limitations, there is a need to develop cost-effective, efficient, and environmentally friendly remediation technology to eliminate heavy metal contamination [5]. Phytoremediation is a strategy that employs plants and their associated microorganisms to reduce the harmful concentration of pollutants in the environment. Phytoremediation comprises a variety of methods, such as rhizofiltration, phytoextraction, phytostabilization, and phytovolatilization. The methods are differentiated based on the plant's role in phytoremediation. Phytoextraction involves accumulating toxic elements in plants and concentrating them in the aerial parts (i.e., Shoots), which are then harvested and either eliminated or processed and stored [6]. This is the most efficient and beneficial technique out of all phytoremediation technologies [7]. However, crop disposal after the phytoextraction process is a problem with this technique. By using fast-growing biomass crops for phytoextraction, the harvested crops can produce bioenergy through combustion. The solution is sustainable because the plant is growing while absorbing the contaminants, and the grown upper biomass can be used as biomass for combustion or incineration [8]. However, the raw contaminated biomass contains high volatile matter constituents, moisture, and low bulk density, and calorific value [9]. Therefore, a volume reduction method such as composting or compaction should be used before proceeding to thermochemical processes. After the

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combustion process, the remaining ashes have several alternatives, including use as permanent building structures (e.g., bricks) and a modern metal extraction concept named phytomining, which can generate revenue by extracting salable heavy metals produced by biomass ash, also known as bio-ore [9].

In summary, there is a need to analyze and identify the phytoextraction capability of fast-growing biomass crops in Sri Lanka to remediate heavy metal-contaminated soil. That creates an eco-friendly and sustainable way to gradually remediate areas with contaminated soil due to solid waste leachate. Additionally, it can provide biomass for energy generation. This review focuses on bridging the knowledge gap on using fast-growing biomass crops for both phytoremediation and sustainable bioenergy production in leachate-affected soils.

II. Heavy Metal Pollution And Soil Contamination

Metals and metalloids that possess a specific gravity greater than five and an atomic mass greater than 20 are considered heavy metals. Examples of such metals are cadmium (Cd), copper (Cu), mercury (Hg), lead (Pb), arsenic (As), nickel (Ni), chromium (Cr), Zinc (Zn), and nickel (Ni) [10]. From a biological perspective, heavy metals are a series of metalloids and metals that can be toxic to animals and plants even in low concentrations [11]. Rapid development in industry and agriculture, as well as disruption of the natural environment because of the increasing world population, has caused heavy metals to become a severe threat to food security [12]. The covert, persistent, and irreversible nature of heavy metals leads to the degradation of the quality of water bodies, food crops, and the atmosphere. Also, heavy metals pose a significant threat to the well-being and health of human beings and organisms via accumulation in the food chain [13].

A few examples in literature emphasize the threat of several toxic heavy metals. Cadmium (Cd) toxicity has been shown to induce a range of harmful effects on cellular components, primarily by disrupting the balance between oxidants and antioxidants. Moreover, Cd has been associated with the development of numerous health conditions, including various forms of cancer, itai-itai disease, kidney disease, heart attacks, peripheral vascular disease, and high blood pressure related to diabetes [14]. Long-term exposure to arsenic (As) can lead to a range of health issues, like neurological disorders, complications during pregnancy, hypertension, diabetes, vascular and respiratory diseases, as well as skin conditions like melanosis, leucomelanosis, and keratosis [15]. Furthermore, lead (Pb) is not a necessary component for the human body, and overconsumption of Pb can negatively affect the nervous, skeletal, enzymatic, endocrine, immune, and circulatory systems [13].

As the worldwide economy expands, human activities have led to a gradual rise in the quantity and variety of heavy metals in the soil. This has significantly contributed to environmental degradation over the years [16]. Prior to now, soil contamination was thought to be less severe than air and water pollution. This is because soil pollution spans a large geographical area, and it is hard to control and regulate. However, the escalating severity of soil pollution in industrialized nations in recent years has drawn increasing attention.

Consequently, it has emerged as a critical issue in global environmental conservation efforts [17]. Heavy metal contamination of soils has several characteristics that make it a more formidable threat to the ecosystem and health. A wide distribution of heavy metal contamination of soils can be seen with the development of the economy and society. That makes the issue an increasingly common and significant threat to almost every country [17]. Heavy metal contamination, being both invisible and odorless, presents a challenge in terms of detection. Its impact on the environment cannot be easily detected, thus routinely deceiving observers into underestimating its potential for harm. However, when the concentration of these heavy metals goes beyond the environmental tolerance threshold or when the environmental conditions shift, such dormant pollutants become active. This activation can lead to severe ecological damage. Hence, the phenomenon of heavy metal contamination is frequently compared to latent chemical time bombs (CTBs), silently ticking away [18]. Heavy metals are hard to remove from the soil through dilution or natural degradation. Some soils with heavy metal pollution may take centuries to recover. Hence, the cost and time of restoring such soils are pretty high [18].

Many factors contribute to the accumulation of excess heavy metals in the soil, such as the deposition of pollutants from the air, the irrigation with sewage water, the improper disposal of industrial solid waste, the activities of mining industries, and the application of pesticides and fertilizers [19]. The primary sources of airborne heavy metal contamination are the emissions and dust from energy, transport, metallurgy, and construction materials industries. Except for mercury, heavy metals are primarily present in the air as aerosol particles and settle to the ground through natural processes and precipitation [17]. One of the reasons for heavy metal contamination in the soil is the wastewater produced by irrigation. This leads to the accumulation of heavy metals (such as Hg, Cd, Pb, Cr, etc.) in the soil over time. Wastewater irrigation is a practical solution for crop watering in dry regions. However, the risk of heavy metal contamination from wastewater irrigation should not be ignored [17]. Solid waste contamination from mining and industry is a significant issue due to the complex composition of these wastes. Exposure to sunlight, rain, and erosion during storage or treatment makes heavy metals more mobile. These metals can then leach into nearby water and soil sources, creating a funnel and radiation pattern of pollution [17]. A common problem of using too many pesticides for a long time is that they pollute the soil with heavy metals. Most pesticides are composed of organic substances, but some contain a mix of organic and inorganic substances or pure minerals, including heavy metals such as Hg, As, Cu, and Zn [20].

According to the literature, heavy metal contamination of soil has several impacts on living organisms. According to Barajas Aceves et al. (1999), the level of soil contamination can be assessed by measuring the microbial biomass of the soil. The soil's concentration of heavy metals, like Cu, Zn, Pb, and others, severely affects microbial activity [21]. Kandeler et al. 1996 reported that the soil contaminated by these heavy metals had a significant reduction in microbial biomass. Also, plants can tolerate a specific range of soil heavy metal levels, whether they are essential or non-essential for their growth. When the levels of heavy metals in the soil exceed a certain threshold, plants tend to accumulate an excessive amount of heavy metals beyond their tolerance capacity [22]. This accumulation leads to toxicity in the plants, ultimately resulting in their demise [17]. According to Tiancai et al. (1994), Cd concentration of 30 μ mol/ L hurt the development of cabbage and bean seedlings: it reduced the root length, plant height, and leaf area [23]. Cd may affect crop processes such as photosynthesis and protein synthesis and may also cause membrane damage, among other effects [24], [25]. Several alarming impacts have been found on human health through the heavy metal contamination of soil. Urban soils contain heavy metals that can enter the human body through various pathways, such as dust inhalation and skin contact, and pose a direct threat to human health, especially for children.

Moreover, these heavy metals would also degrade the urban environment and result in indirect harm to human health by contaminating food, water, and air. Yabe et al. (2010) conducted a study on blood Pb concentration among children. They determined that soil dust contamination in the city was a contributory factor to human health [26]. The study revealed that about 30% of Chinese children had blood Pb levels above the domestic standard (100 μg/ L), and this proportion was more than 60% in urban areas. Another study showed a strong exponential relationship between the level of Pb in urban children's blood and the level of Pb in the city soil [27]. Excessive intake of Cd can interfere with the normal functioning of calcium in the body, leading to low levels of calcium and problems with the joints and bones, such as fractures. In terms of health risks, the Agency for Toxic Substances Management Committee rates cadmium as the sixth worst material. Pb can enter the human body through the mouth or nose and then circulate in the blood in different forms, such as soluble salts, protein complexes, or ions. Most of the insoluble phosphate lead is stored in the bones. Pb has a strong affinity for tissues and can affect and damage various organs and systems in the body, such as the kidney, reproductive system, immune system, liver, nervous system, urinary system, and cellular and genetic processes. Cu, Zn, and Ni are necessary trace metals for the human body, but excessive amounts of Cu, Zn, and Ni from external sources can harm human health. Ni and Cu are factors that promote tumor growth, and their potential to cause cancer has been a global concern [17].

III. Heavy Metal Contamination At Open Dumpsites

One of the main challenges for many large urban areas in various countries is how to deal with solid waste management (SWM). This is primarily a pressing issue for many developing countries with high population density [28], [29], [30]. A common practice for disposing of MSW in many countries with low or lower-middle income levels, such as those in Sub-Saharan Africa and South Asia, is to dump it without treatment or selective collection. This open dumping method of waste management is widely used, according to Salvia et al. (2021) and Wijesekara et al. (2014). These countries produce various kinds of MSW, such as e-waste, plastics, industrial and biomedical wastes, glass, batteries, paper, and the organic fraction that contains harmful substances like toxic metals and organic pollutants. These wastes are disposed of by the open dumping method without sorting, which causes high pollution that can threaten the environment (soil, water, and sediment), living beings, and human health in direct or indirect ways [30]-[34].

According to estimates, urban areas in Sri Lanka are home to over 260 municipal landfills. Most of these landfills are unregulated open dumpsites, except for the ones in Dompe and Aruwakkalu [35], [36]. Many of these sites were constructed without proper EIA, and therefore, they pose a threat to the nearby ecosystems, such as wetlands and major rivers in Sri Lanka. Some examples of these sites are Karadiyana, Muthurajawela, Gohagoda, and Ginthota [37]. To minimize environmental harm done by landfills receiving municipal solid waste (MSW), the United States has established policies that manage where and how they should be located. Among these policies are the avoidance of wetlands and floodplains, as landfills can damage ecosystems and water resources. Furthermore, they mandate the implementation of a leachate collection and removal system to safeguard against groundwater and soil contamination in the absence of proper treatment [38]. A serious risk of soil pollution is posed by the leachate that is produced by the chemical and biological breakdown of organic and inorganic pollutants [39], [40].

The quantity and quality of such leachates are affected by a number of variables, including the waste type and composition, the structure of the landfill, seasonal weather variations, landfilling technique, and the method of piling and compacting. Especially the age of the landfill causes a significant variation in the composition of landfill leachates [41]. A variety of substances are present in the liquid that seeps from landfills, including organic matter that can be broken down or not, nitrogen compounds, compounds with chlorine, salts, and heavy metals [42]. When rainwater infiltrates through the garbage, it creates leachate, which can contaminate the groundwater with harmful substances [43]. The soil can also be affected by heavy metals such as lead, copper, manganese, iron, chromium, zinc, and cadmium that come from various sources of waste, such as industrial waste, incinerator ash, mine waste, and household items like batteries, paints, dyes, inks, etc [44]. Heavy metals are a significant concern for soil pollution in areas where there is a lot of industrial and urban waste disposal [45]. Heavy metals are difficult to decompose and have a tendency to collect in soil [46]. The chemical forms of hazardous metals such as Pb, Zn, and Cd are more critical than their total element concentration for their mobility in the biogeochemical cycles [47]. Therefore, heavy metals in leachate can move away from the landfill boundaries and pose a serious risk of pollution for the soil and the water table around the disposal site [48], [49].

IV. Heavy Metal Remediation Methods For Soil

Heavy metal pollution in soils poses a serious threat to human and environmental health. It requires the application of effective and site-specific remediation technologies that can safely and efficiently restore soil quality [50]. Various soil remediation technologies have been developed and applied in the past few decades [51]-[53]. These methods aim to reduce the total and bio-accessible concentrations of heavy metals in the soil and their potential pathways to the food chain [54], [55]. Traditional techniques for removing heavy metals from contaminated soils involve physical, chemical, and biological processes that can be combined to achieve better results. However, most of these methods have drawbacks such as high cost, environmental damage, and long duration [56].

Various forms of heavy metals result from their entry into the environment. The longer they remain in the soil, the less accessible they become [57]. Plants can utilize exchangeable metal forms and aqueous solvents in soil remediation to detoxify heavy metals [58]. Fig. 1 presents an overview of soil heavy metal remediation methods.

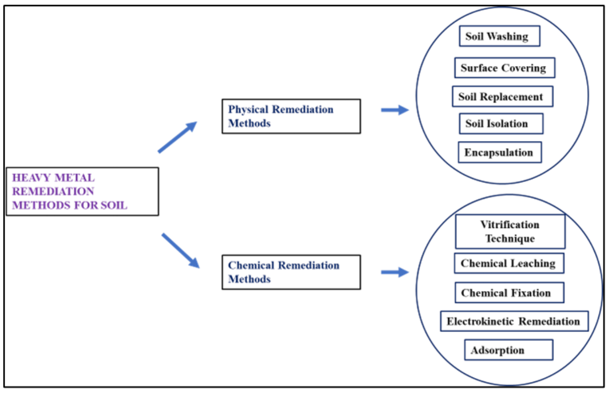

Fig. 1. Overview of heavy metal remediation methods for contaminated soil.

A. Physical Remediation Methods

Different physical strategies were employed to remediate the soil contamination, such as soil washing, surface capping, soil replacement, soil isolation, electro- kinetic remediation, and encapsulation. The process of physical remediation combines soil replacement and hot desorption [59]. The goal of soil substitution is to remove and replace contaminated soil with clean soil to lower the levels of chemical compounds in a particular area [60], [61].

- Soil Washing: A widely employed method for the removal of organic and inorganic contaminants from soils is soil washing. This technique involves the application of an extraction fluid to separate contaminants from the soil matrix. The water is then reclaimed, reused, treated, and disposed of accordingly. Soil washing works best with soils of coarse texture and uniform permeability [62].
- Surface Covering: A surface cover is a type of containment technology that applies a layer of a material that does not al-low water or air to pass through it over a contaminated site. This creates a safe barrier that prevents direct contact with the polluted soil. This technique does not restore the soil quality, as it does not reduce or eliminate the heavy metal ions that are present in the soil [63]. However, it reduces the exposure risk from industrial emissions or accidental ingestion. By blocking the infiltration of surface water, the surface cover also prevents soil pollutants from reaching the surface water and groundwater. The covered soil, however, loses its natural ability to support plant growth [64].
- Soil Replacement: One way to deal with contaminated soil is to replace it partially or fully with soils that are not contaminated. Since 1984, the most common method for managing polluted land has been to dig up, reclaim off-site, and restore the soil. A soil replacement system lowers the heavy metal concentration in the soil, which improves soil durability. The replaced soil can be used to extract heavy metals or dispose of them elsewhere [61].
- Soil Isolation: A technique for separating soils that are contaminated by heavy metals from those that are not known as soil isolation. However, this technique also involves several additional technological steps to complete the remediation. Isolation methods aim to restrict the spread of heavy metals and other pollutants beyond a defined area by confining contaminants within that area only [65]. Soil isolation is often applied to prevent heavy metals from contaminating groundwater when other remediation methods are not viable commercially or technically [59].
- Encapsulation: A standard method for dealing with contaminated areas is to use encapsulation, which can either prevent emissions or remediate the contamination [66]. Environmental studies often employ development trenches that are sealed with watertight encryption, which incorporate various encapsulation techniques. The main idea is to create a barrier that prevents gases and liquids from passing through by building it underground around the perimeter of the site. Different construction methods have been devised, such as thin walls made of slurry cut-off, slurry mixtures of cement-bentonite-water, walls of sheet piles, jet grouting curtains, injection wells, cut-off walls of bored-pile, and frozen barriers [67].

B. Chemical Remediation Methods

A chemical approach can decrease the bioavailability of heavy metals to plant organisms. This is done by changing the pH of the soil in such a way that the metals dissolve or precipitate and permit the contaminated materials to be withdrawn [59].

- Vitrification Technique: A new vitrification process involves increased paste intensity at a temperature of between 1400 and 2000°C, leading to natural breakdown or dissolution of the harmful chemicals. The treatment produces steam and leads to pyrolysis byproducts derived from the fumed gas emitted by the treatment system [63]. For ex-situ recovery, energy can be supplied by using fossil fuels or by directly applying microwaves or plasma. For in-situ remediation with direct heat application, electrodes can be inserted directly into the polluted soil. This technique provides high efficiency, eliminating heavy metals. However, this technique is complex and requires more integrated resources, making it more expensive and less feasible for large-scale applications [68].

- Chemical Leaching: A technique for cleaning contaminated soil with solvents, reagents, or various liquids or toxic gases that can remove dirt impurities is artificial discharge [69]. The leachate can receive heavy metals from the soil through processes such as precipitation, particle exchange, chelation, and adsorption, and then be evaluated afterward. The penetration mainly involves surfactants, common inorganic compounds, and chelating agents [70]. Metals extracted from the improperly sulfurized soil were examined as extracting agents to eliminate toxins from the soil using different types of nitric acids, hydrofluoric acids, sulfuric acids, phosphoric acids, and hydrochloric acids [71].
- Chemical Fixation: Chemical fixation is just one technique of reducing the environmental impact of pollutants in contaminated soil by transforming the impurities into less soluble forms and minimizing their mobility into groundwater, crops, and other environments. Chemical fixation does not eliminate the pollutants from the ground but integrates them into a stable matrix. For instance, some studies have evaluated the potential of fine-grained, glassy-like hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$) to immobilize metals in polluted soil by forming metal phosphates [72]- [74].
- Electrokinetic Remediation: Another way to remediate contaminated soil is to apply very high voltage and generate an electric field gradient between the two sides [75]. This method causes the charged pollutants to move toward the poles by electro-migration, electro-osmotic flow, and electrophoresis process [76]. This method is suitable for soil with low permeability and has the benefits of low cost, easy installation, and operation [77], [78]. Moreover, this method preserves the original composition of the soil [79] and protects the ecotype [75]. However, a drawback of this method is that it cannot control the soil pH [70]. Some recent techniques try to overcome this limitation by adding a buffer solution or using an ion exchange membrane to regulate the soil pH and enhance migration [63].
- Adsorption: One of the most widely used methods for soil remediation of heavy metals and organic compounds is adsorption [80]. For this, a variety of adsorbents have been created and evaluated. Because of their high soil metal removal effectiveness, agricultural wastes and biomass-based activated carbon sources are superior to the others. These adsorbents have also shown potential for other adsorption-related applications [81].

C. Bioremediation

One area of biotechnology called bioremediation uses microorgan-isms, such as fungi, bacteria, and plants [82], [83], to degrade or remove contaminants and toxins from soil and water. It is a natural way of restoring the environment from pollution, preserving the original ecosystems, and preventing further damage [73]. Bioremediation is cheaper than chemical and physical remediation techniques. Bioremediation usually involves in-situ treatment of metal-contaminated sites, which dispenses with the need for transport or excavation, thus reducing the costs of site remediation. Moreover, in some cases, bioremediation allows for heavy metal containment or removal without human intervention, which translates into significant cost savings. Furthermore, phytoremediation, which uses plants for remediation, is about ten times cheaper than other technologies and therefore represents the most eco-nomically friendly option on the market [75]. Various microorganisms, such as Pseudomonas, Bacillus, Asper-gillus, etc., participate in the remediation process, and the efficiency of waste degradation depends on their metabolic activity. According to the place where remediation activities are carried out, there are two types of bioremediation activities: in-situ and ex-situ.

- In-situ Bioremediation Techniques: One of the advantages of in-situ remediation is that it avoids the extraction and transportation of contaminated soil to other locations for treatment, which can reduce soil disturbance, exposure of workers and residents to pollutants, and treatment expenses. However, in-situ remediation requires careful evaluation of the field conditions, such as temperature, depth of pollution, soil permeability, and potential chemical migration to deeper layers [70].

1) Bio-sparging: Bio-sparging pressurizes air beneath the groundwater table to promote more oxygen in the groundwater to increase biodegradation of organic pollutants by indigenous microorganisms [84]. The technique encourages aerobic as well as volatilization degradation. Effectiveness of bio-sparging depends on two key factors: soil permeability and contaminant biodegradability. Pressure management is essential to prevent the escape of volatile substances into the air during oxygen delivery at the impacted area. Bio-sparging is commonly applied at sites with medium-weight petroleum products, such as gasoline or jet fuel [85].

2) Bioventing: Bioventing is one of the most well-liked in situ technologies that induces the growth of indigenous bacteria through the provision of air and nutrients to contaminated soils through wells [67]. The technique is significant in the overall treatment of groundwater and soil. The process entails low airflow but sufficient oxygen to enhance biodegradation and minimize the volatilization of contaminants into the air. The removal rate of contaminants may differ depending on the site, as the soil texture and hydrocarbon structure influence the outcome [85]. The method is very effective for remediating hydrocarbons and can be applied to deep subsurface contamination [59].

3) Remediation using bacteria: The remediation mechanism involves various processes such as extracellular complex formation, intracellular accumulation, and precipitation or redox reactions that alter the physicochemical properties of the heavy metals without degrading them. Microorganisms do not break down substantial metals themselves [59]. According to Galal et al. (2017), low-grade minerals can be effectively leached using microbial methods [86]. Moreover, microorganisms can help in the bioremediation of various environmental pollutants, such as heavy metals in sewage sludge, industrial waste, sediments, and soils [87]. According to Priya & Nagan (2015), some microorganisms, such as Bacillus sp, Pseudomonas sp, Desulfuromonas palmitatis, Torulopsis bombicola, etc, can degrade sewage sludge, industrial waste, and restore soils and residues polluted with heavy metals. These microorganisms can perform Bioremediation of various environmental contaminants [88].

4) Remediation with fungi: Fungal cells, both living and dead, have been shown to have a high affinity for binding inorganic substances [89]. Fungi are, therefore, widely employed as biosorbents to remove and recover toxic metals from various sources [90]-[92]. This is a promising technique for the remediation of metal-contaminated environments. Some biosorbents, such as Phanerochaete chrysosporium, Aspergillus sp, Coprinopsis atramentaria, and others, exhibit remarkable capacities for adsorbing and recovering metals, which can be helpful in the elimination of toxic metals [93].

5) Remediation with Plants (Phytoremediation): Using different plant species to reduce the environmental toxins from human activities is the main idea of phytoremediation, which consists of various techniques to lower, immobilize, and degrade the pollutants in contaminated areas [94]. The phytoremediation processes use specific plants to extract metals from polluted sites. The uptake of metals by plants and bioavailability can be enhanced by adding chelating agents, fertilizers, organic amendments, and adjusting pH. Phytoremediation is a promising method for remediating soil contamination [95].

6) Remediation with chelates and plant species: Plants can extract foreign substances from water or soil through their roots, which can be used for separation purposes. Moreover, chelating agents can enhance the storage capacity of plants for these materials, and they can also help in the remediation of metal-contaminated soils [63], [70].. The chelating agents form soluble metal complexes that increase the solubility of the metals. Then, the metals can be either removed or immobilized from visible soil fractions or specific surfaces, and the extent of heavy metal uptake and the related stress tolerance can be assessed [59].

- Ex-situ Bioremediation Techniques: Ex-situ soil remediation is a process that consists of three steps: removing the soil from the site where it is polluted, taking it to a plant where it is treated away from the site, and getting rid of the treated soil at locations that are approved. This process is more costly than in-situ remediation, which treats the soil on-site because it requires more activities such as excavation, transportation, disposal, and refilling of the soil. Still, it also offers benefits such as faster results and more management [70].

1) Composting: One of the most eco-friendly methods to transform natural waste into a valuable soil amendment is soil fertilization, which is regarded as a fundamental and remedial strategy [63]. The natural matter in wastes stimulates the growth of microorganisms that are involved in degradation processes. Different microorganisms thrive at different stages depending on the temperature patterns [59]. The stages include mesophilic and thermophilic. Mesophiles are aerobic microorganisms that decompose organic matter at low temperatures (the mesophilic range). Mesophilic bacteria can survive between 20°C and 40°C, and most of them are also found in topsoil (Mukhopadhyay & Maiti, 2010). Thermophilic microorganisms are very active and produce a significant amount of heat. This stage can last until about 70°C, but such high temperatures are not typical or desirable in backyard compost [94].

2) Land farming: Land cultivation is a simple method that requires minimal equipment and can remove almost all the components of wastewater. The soil with contaminants is extracted and laid on the ground, where the native microorganisms degrade the constituents [59]. The aerobic degradation process is enhanced by stimulating the growth and activity of the biodegradative organisms that are naturally present [85].

3) Bio-piling: Bio-piling is a technique that combines soil remediation and farming. It involves creating a large pile of contaminated soil and setting up a system for aeration and leachate collection. By promoting the process of biodegradation, it is expected to lower the content of petroleum compounds in the soil. The primary aim of biopiling is the remediation of surface topsoil, which has been oil- and hydrocarbon-contaminated. Through the creation of a good environment, biopiling allows native anaerobic and aerobic bacteria to break down the pollutants [96].

V. Phytoremediation Methods

Using plants and their associated microbes to absorb and clean up environmental contamination through engineered constructed wetland systems is a potential plant-based technology called phytoremediation. The main goal is to either extract the pollutant from the contaminated media or to change the chemical and physical nature of the pollutant so that it no longer poses a threat to human health and the environment [97]. A variety of contaminants, such as metals (Pb, Zn, Cd, Cu, Ni, Mn), metalloids (As, Sb), and inorganic compounds (Nitrate, Ammonium, phosphate), can be effectively removed by phytoremediation from low to medium-contaminated media. A technique called phytoremediation employs plants to break down or immobilize harmful substances in the environment [98]. Some phytoremediation strategies can be applied to treat soils contaminated by heavy metals, such as

- Phytostabilization—reducing the bioavailability of heavy metals in soil by using plants,
- Phytoextraction—removing and extracting heavy metals from the soil by using plants,

- Phytovolatilization—absorbing heavy metals from the soil by using plants and releasing them into the air as volatile compounds and
- Phytofiltration—using plants grown hydroponically to absorb or adsorb heavy metal ions from groundwater and liquid waste [99]-[101].

Other phytoremediation strategies are phytodegradation and biodegradation, which are used to degrade organic pollutants [5].

A. Phytostabilization

The mechanisms of phytostabilization include precipitation or reduction of metal ions in the rhizosphere, uptake, and sequestration by root tissues, or adsorption on root cell walls [102]-[104]. Phytostabilization involves planting species that can resist metal toxicity and bind heavy metals in the soil, reducing their bioavailability and preventing their transfer to the ecosystem and the food chain [100], [105]. Phytostabilization also helps to maintain soil health in areas contaminated by heavy metals. The plants can not only immobilize heavy metals in the soil and limit their leaching to groundwater but also reduce the dispersion of contaminated soil particles from wind [106], [107]. A benefit of phytostabilization is that it does not generate hazardous biomass that needs to be disposed of, unlike Phytoextraction [108].

B. Phytoextraction

Phytoextraction is one of the phytoremediation techniques that can remove contaminants from soil or water, which involves the uptake and accumulation of those contaminants in the aboveground biomass of plants [109], [101]. Phytoextraction is preferable to phytostabilization for commercial application, as it offers a permanent solution by eliminating heavy metals from polluted soil, while phytostabilization only immobilizes them below ground. The phytoextraction process consists of several steps:

1. Mobilization of heavy metals in the rhizosphere,
2. Uptake of heavy metals by plant roots,
3. Translocation of heavy metal ions from roots to aerial parts of the plant,
4. Sequestration and compartmentation of heavy metal ions in plant tissues [1].

The factors that influence the efficiency of phytoextraction include plant selection, plant performance, heavy metal bioavailability, soil, and rhizosphere properties [5].

C. Phytovolatilization

By their transpiration process through the leaves or foliar system, plants may take up contaminants from the soil, turn them into less harmful volatile chemicals, and release them into the atmosphere. This is called phytovolatilization, a type of phytoremediation. This method can be used to remove organic pollutants and some heavy metals such as Se, Hg, and As from contaminated soils [110]. One of the drawbacks of phytovolatilization is that it does not eliminate the contaminant; instead, it transfers it from the soil to the atmosphere, where it may be redeposited elsewhere. This makes phytovolatilization the most disputed among the phytoremediation technologies [111].

D. Phytofiltration

Phytofiltration is a process that involves using different parts of plants, such as roots (rhizofiltration), stems (caulofiltration), or young plants (blastofiltration), to remove pollutants from water sources that are contaminated [112]. During rhizofiltration, heavy metals may be absorbed by the roots or may adhere to the root surface. The pH of the rhizosphere can be altered by root exudates, which causes heavy metals to precipitate on plant roots [113], thus preventing them from leaching into groundwater.

VI. Fast-Growing Biomass Crops in Sri Lanka

In this section, the literature related to selected biomass crops will be reviewed. Based on their prevalence in Sri Lanka and their capacity to thrive in a variety of environments, the plant species chosen for this study are Leucaena leucocephala (Lam.) de Wit (Fa-baceae) and Gliricidia sepium (Fa-baceae). [114], [115].

- Originally from Central America, South America, and Mexico, G. sepium was brought to Sri Lanka in 1889 [116], 117] as a shade tree for coffee and tea farms, where it eventually became naturalized. The rural people of Sri Lanka refer to the plant by the names "Albizia," "Maculatha," "Watahiria," and "Watamara." The drought tolerance of G. sepium allows it to thrive in a variety of soil types [118]. A tropical and subtropical agroforestry species, G. sepium, is commonly planted as living fences and shade trees [119]. G. sepium also has applications in wood thermoelectric power generation. Due to its applicability and potential uses, the researchers found that G. sepium was a valuable plant part in the agroforestry production systems in Sri Lanka [115]. G. sepium is a branched, quick-growing plant that can grow in a variety of environments. It has a high potential for dendro-thermal energy production, which is a sustainable, low-cost, and locally accessible way of using wood to generate heat in resource-limited agricultural systems. G. sepium has a quick sprouting capacity and good wood quality, which are desirable features for dendro-energy projects [120].
  Among the literature regarding the phytoaccumulation capability of G. sepium, Okon-Akan et al. 2016 found that this plant has the capability of absorbing Zinc, which reported around 108.59 mg/kg concentration of Zinc in its stem bark. This literature concluded that Gliricidia indicates a high potential for bioremediation projects in its native and introduced range [121].
- Leucaena leucocephala: A tree species from the family Fabaceae and subfamily Mimosoideae, L. leucocephala (Lam.) de Wit. can host many species that can grow vegetatively in very harsh environmental conditions [122]. Woody bioenergy plants, such as L. leucocephala, exhibit a strong propensity for developing deep root systems.

This property allows them to explore and immobilize heavy metals from the lower depths of polluted substrates. Large-scale use of these plants takes advantage of their dual benefit: deeper root penetration and high biomass yield. Consequently, this approach enhances the Phytoextraction of heavy metals, thereby facilitating the regeneration of polluted substrate [122]. L. leucocephala, otherwise known as 'Ipil Ipil', stands out because of its dense timber, rapid growth rate, and adaptability. The tree is economically significant as an energy source from biomass and a soil fertilizer while having environmental benefits. It has a robust root system that inhibits soil erosion, and current research shows potential thermal conversion to bioethanol substrates. L. leucocephala is a useful solution with economic advantages and ecological value [123]. Aside from its established uses for improving soil fertility and fodder production and providing timber and bioenergy, L. leucocephala has drawn significant attention owing to its potential in environmental remediation. A "miracle tree" because of its versatility [124], Because of its extensive root system and tolerance to a wide range of environments, L. leucocephala is an excellent candidate for phytoremediation in tropical and subtropical climates [125]. Such growing scientific interest signals that L. leucocephala possesses tremendous potential to help ensure agricultural and environmental sustainability.

L. leucocephala presents a valuable phytoremediation choice due to its rapid growth and immense biomass potential. Its high capacity for the generation of large quantities of seeds and harvestable phytomass in a short period aids in phytoextraction and facilitates faster recovery of contaminated sites.

Studies by Balasundaran & Ali 1987 even report that optimal conditions enable L. leucocephala to yield the highest recorded annual wood production [126]. This rapid expansion, coupled with a regeneration capacity of more than 50 t ha−1year−1, makes L. leucocephala a more viable phytoremediation option than other popular species. L. leucocephala outcompetes most rivals in short-term experiments and allows for harvest cycles ranging from 6 months to 10 years. Its excellent coppicing ability also ensures regeneration after wood harvests, without the need for costly replanting, a significant advantage in large-scale phytoremediation activities. These unique characteristics solidify L. leucocephala's position as a promising candidate for phytoremediation applications [122].

VII. Utilization of Phytoextraction Crops for Bioenergy

Energy crops are seeing a global boom of interest because they have the potential to be a clean, carbon-neutral, and green source of renewable energy. Their use is an area of interest with the potential to assist in meeting global energy demands in a more sustainable way. Basically, these crops sketch the vision of a future that is driven by renewable sources and could diminish the use of fossil fuels and the associated impact on the environment [127], [128].

Furthermore, considering the realistic yearly metal extraction potential per land area, Meers, Lamsal, et al., 2005 conclude that phytoextraction is best suited for moderately contaminated sites, not serving as a replacement for conventional methods on heavily polluted land [129]. A key stumbling block for phytoextraction, its slow remediation time, could be overcome if the harvested biomass becomes economically valuable. This opens the door to alternative phytoremediation approaches focused on gradual attenuation rather than rapid extraction. These slower-working schemes, relying on natural contaminant breakdown by plants, become more feasible with economically viable biomass utilization [130].

Cultivating specific energy crops on contaminated land offers a multifaceted solution. These crops not only remediate the contaminants through phytoremediation but also generate bioenergy. Additionally, they bring about indirect benefits such as improved soil quality, visually pleasing landscapes, and carbon sequestration. This creates a promising synergy between energy crop cultivation and phytoremediation of contaminated land, as highlighted by research [131], 132]. Furthermore, utilizing this neglected land provides multiple advantages. It alleviates pressure on limited agricultural land [133], [134], as contaminated sites would not compete with food production. It also brings an economic benefit by avoiding the high cost of acquiring productive agricultural land. Finally, re-using these barren or poorly vegetated sites for bioenergy crops helps prevent pollution from leaching or soil erosion, thereby protecting natural resources [135].

The global rise in contaminated land and increasing bioenergy demands necessitate the exploration of sustainable solutions. Phytoremediation, or the use of plants to clean up a polluted environment, combined with energy crops, offers a promising approach to achieve this goal. Several countries are actively developing the potential of energy crops for biodiesel while also determining their suitability for cleaning up contaminated land. This has led to a surge in research initiatives exploring the application of energy crop-based phytoremediation across the globe [136]-[138]. This risk-mitigation strategy for Phytoextraction is aimed at reducing risk and alternative land use instead of maximizing metal extraction efficiency, which has conventionally supported traditional research. This risk management-based emphasis and generation of alternative sources of income for farmers necessitate a new term to differentiate from traditional Phytoextraction. For this purpose, the authors propose "phytoattenuation" because this strategy is in line with the concept of natural attenuation for organic contaminants with an emphasis on gradual restoration instead of rapid removal. It also acknowledges the longer time period in-volved, unlike when using the "phytoextraction" term, which implies an obviously more active and faster extraction process [136].

VIII. Limitations and Challenges of Phytoremediation

While phytoremediation is cheap and effective for remediation of heavy metal-contaminated soil, there are several serious limitations to its long-term use and bulk production. One of these limitations is the fact that remediation using this technique is slow compared to physicochemical techniques such as excavation or soil washing. Phytoremediation requires several crop cycles and takes many years to reduce metal concentrations to a level of safety that may not accommodate time-sensitive projects [1]. Second, metal bioavailability in soil significantly affects phytoextraction efficiency. Most heavy metals are firmly bound in soil particles and thus less available for root uptake. Chelating agents such as EDTA can mobilize metals but also pose leaching risks and secondary groundwater contamination [108]. In addition, the choice of plant species is site-specific, and performance will differ with soil, pH, climate, and concentration of pollutants. While Gliricidia sepium and Leucaena leucocephala show promise in the tropics, their adaptability and pollutant-uptake capacity might not be universally applicable to all polluted environments. One of the primary issues is how contaminated biomass will be managed. Plants harvested for toxic metal accumulations must be disposed of or treated with care. Incineration is capable of recovering metals but might produce harmful emissions, whereas composting need not always be used for metal-laden biomass [139]. Lastly, phytoremediation is typically efficient in low to moderate levels of pollution. Plant development may be hindered in heavily polluted soils, and metal toxicity will prevent biomass yield and remediation [110], [140]. Without such limitations, integration with biomass valorization processes, e.g., bioenergy or phytomining, can render it more economic and sustainable.

IX. CONCLUSION

Gliricidia sepium and Leucaena leucocephala are two biomass crops that have the potential to be used in phytoremediation. They can offer promising, more sustainable remedial alternatives for soils contaminated by heavy metals, which are the most prevalent kind of pollution in places affected by leachates. It permits the safe phytoextraction of harmful metals while allowing contaminated biomass to be used productively for the production of bioenergy or streams of value-adding. The technique is low-cost and eco-friendly; however, to improve field usability, some issues, such as low remediation rates, biomass management, and metal bioavailability, need to be resolved. When paired with cyclical resource use, phytoremediation can significantly aid in the sustainable restoration of land and energy recovery in underdeveloped countries.

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