REVIEW ARTICLE

Phytoremediation Technology for Heavy Metal Removal from the Environment

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Abstract

Anthropogenic activities, industrialization, and urbanization have contributed extensively to the enhanced pollution levels in the environment. Along with soil and water pollution, air pollution is also escalating and contamination with heavy metals (HMs) is dangerous for the environment since it has negative impacts on people, animals, plants, and the ecosystem. HMs derive their origin from natural and anthropogenic sources. Commercial activities like processing of metals, mining, automobiles, geothermal energy plants, manufacturing industries, tanning, dyeing and plating are the sources of HM contamination. The non-biodegradable, permanent inorganic chemical components recognized as HMs are typically harmful at small doses even in humans. HM toxicity leads to carcinogenic effects, developmental and reproductive damage, cardiovascular ailments, haematological, respiratory and nervous system disorders, inflammation and gastrointestinal troubles etc. The absorption and accretion of these metals cause oxidative stress and molecular damage, cytotoxic and mutagenic effects, growth reduction and physiological disorder in plants. Therefore considering their toxic effects, various mechanical as well as physio-chemical technologies are employed for metal removal from the air, water and soil but these techniques have their own limitations and environmental consequences. Hence, phytoremediation is considered an innovative, potentially promising technology employing majorly green plants. The various phytoremediation techniques involve phytoextraction, phytostabilization, phytodegradation, phytotransformation, phytovolitization, and rhizofiltration. Employing these techniques, plants can remove contaminants through a variety of processes, including adsorption, absorption, transport and translocation, hyper-accumulation, transformation, and mineralization. While phytoremediation of air pollutants is still an emerging technology, assimilation properties of plants to convert a toxicant into non-toxic forms have been used extensively for phytoremediation of air. Plants like *Morus alba* and *Eucalyptus globulus* can efficiently remove metallic pollutants from air. Moreover, aquatic macrophytes like *Eichhornia crassipes, Spirodela polyrhiza*, *Pistia stratiotes, Azolla, Lemna minor,* and *Salvinia herzogii* are potentially used for cleanup of the HMs in water, while *Brassica juncea, Thlaspi caerulescens, Jatropha curcas, Pteris vittata*, *Vetiveria zizanioides, Gentiana pennelliana, Ambrossia artemisifolia* etc. display tremendous well known phytoremediation activity in soil. Phytoremediation is an innovative, aesthetically pleasing, non-intrusive, sustainable and cost-effective technology. Furthermore, due to the disadvantages like high maintenance cost, extensive labor requirement and risks involved in existing conventional technologies associated with pollution abatement, phytoremediation technique can act as a potential, cost-effective and efficient method for water, soil as well as air pollution control.

Keywords: Conventional technologies, Environmental pollution, Green plants, Heavy metal contamination, Phytoremediation, Sustainable

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Introduction

The world has been able to support substantially greater populations and higher living standards than at any other period in human history thanks to the enormous development in global production of commodities and services. However, natural resources have been depleted at an unprecedented rate to support this increase leading to environmental degradation contributing to environmental pollution. Pollution of soil, water, and air by anthropogenic activities is a noticeable feature of urban systems throughout the world, whose one of the types is heavy metal (HM) pollution. Since HMs are persistent, they pollute the air, water, and soil. (Rai, 2009).

The aerosols and various HM contaminants associated with particulate matter (PM) act as condensation nuclei for the deposition of the metals and aerosols. Most heavy metals (HM) found in air particulate matter come from burning petroleum and other fossil fuels. In localities with active mining and mine tailings, larger, coarser particles are sometimes linked to heavy metals like As, Cu, Cd, Cr, Hg, Pb and Zn (Gawronski *et al.*, 2017). Heavy-duty vehicle contamination primarily as fine particles interact with airborne particulates from industrial and urban processes to increase the background concentration of hazardous HMs (Xiao-Li *et al.*, 2006). However, Cd, Fe, Cr, Zn, Pb and Ni, released from different pollutant sources usually get absorbed in the PM_{10} respirable particulate matter. Furthermore, it has been concluded that industrial and commercial activities and geological composition are the chief sources of HM

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contamination in the air (Chaudhari *et al*., 2012). Water pollution from anthropogenic activities is a predominant issue in many countries of the world. It causes a decline in water quality and is a major cause of numerous diseases that are transmitted by water. The two different categories of water contamination sources are point and non-point sources. Considering the point source of toxic HMs like Mn, Co, Cr, Cu, Fe, Zn and other contaminants, industrial wastes are one of the key sources of water pollution. Domestic as well as industrial untreated wastewater contains cyanides, dyes, phenol, phosphorous, pesticides, suspended solids, toxic organic materials and HMs (Pakdel *et al*., 2018). Metal toxicity of ground and surface waters results in major environmental and health problem (Rai, 2009). Additionally, an elevated level of HMs in water disrupts aquatic ecology, distressing microphytes, macrophytes and fauna, including the fishes (Wijayawardena *et al*., 2016).

A global issue is heavy metal toxicity in soil, which lowers crop output and quality worldwide (Gill, 2014). Sources of metal pollution in soil are chiefly due to anthropogenic activities like industrial effluents, excessive use of agrochemicals, oil refineries, mining, electroplating, smelting processes, small-scale industries, military operations, and combustion of coal and brick kilns and even during nuclear winter (Eshleman *et al*., 1971). This has aided in the build-up of soil-borne unwanted metal concentrations, including Cd, Ni, Zn, Pb, Cu, and Cr (Singh *et al*., 2004). These HMs can seriously harm the health of humans through their entry into the food chain after being absorbed by the plants because they are mutagenic, and teratogenic, and can result in neurological disorders in people (Clemens and Ma, 2016; Tchounwou *et al*., 2012). HM toxicity in plants alters plants' biochemical, physiological, molecular, and metabolic processes (Kumar and Trivedi, 2019), which may result in senescence or cell death. While exceedingly higher HMs concentration may cause plant death also.

HMs, with the exception of alkali metals, are primarily composed of elements with atomic masses of 20 or more and specific gravities of five or higher (Rascio and Navari-Izzo, 2011). According to Park *et al.* (2012), transition metals, certain metalloids, lanthanides, and actinides may become harmful to living creatures even at low exposure levels. Though few HMs are essential trace elements, almost all are toxic to all forms of living organisms due to their tendency to form complex compounds within the cell (Martin, 2012). Furthermore, due to the high concentration of HMs, plants begin to mount up these metals, which hinders their ability to grow and develop. Additionally, the soil poisoned with HMs usually lacks the diversity of nutrients and microbes (Carlson *et al*., 1991).

Metal poisoning poses a major threat to human as well as plants health. Health risk assessment is a statistical method for determining the nature and possibility of cancer and non-cancer depending on current and lifetime exposure to any toxicants (Jiang *et al*., 2017). Three main routes are direct oral ingestion, particle inhalation through the nose and mouth, and dermal absorption through skin exposure, which can expose humans to metals (Miguel *et al*., 2007). Inadvertently ingesting soil fragments through hand-to-mouth actions, specifically up to six years, causes children to acquire a greater adsorption rate of HM sranging from 39 to 270 mg kg^{-1}, making children at most risk for exposure to HMs (Poggio *et al*., 2009). Studies have revealed that exposure to certain metals or metallic compounds over an extended period of time can cause chronic as well as acute illnesses in humans, including contact dermatitis, cancer, neurological diseases, cardiovascular issues, kidney and renal problems, damage to the lungs, and hair loss (Korashy *et al*., 2017).

Despite the need for natural resources for growth and development, the heavy metal pollution of the environment brought on by mining exploitation has resulted in significant environmental problems (Chopin and Alloway, 2007). There is a harmful effect of trace elements on the biochemistry of humans when consumed beyond bio-recommended limits. Mercury, arsenic, nickel, cadmium, and chromium are dangerous metals that can sicken people when detected in water sources at levels beyond acceptable limits (Ekpo *et al*., 2008). According to the worldwide census of trace element emissions (Nriagu and Pacyna, 1988), activities like mining and smelting discharge a considerable amount of lead and zinc into the natural environment entered. Trace elements are not easily decomposed by microorganisms in the soil, but they can get collected over time and be assimilated by the crops, reaching the human body through the food chain or direct interaction, which may lead to severe health problems (Qin *et al*., 2014). The contaminants such as Pb and Cd, are linked to human health issues such as elevated levels of lead in blood detected in children, osteomalacia, arthralgia, and excessive cadmium in urine which can harm the endocrine, circulatory, skeletal, neurological, enzymatic, and immunological systems if consumed in excess (Zhang *et al*., 2012). Copper though an essential element, in higher concentrations in drinking water can cause kidney damage or liver cirrhosis (Akpor *et al*., 2014). Long-term exposure to high levels of manganese has been scientifically associated with nervous system toxicity, which results in a condition that more frequently affects older people and has symptoms similar to Parkinson's disease. Zinc exposure can result in the development of asthma, sideroblastic anaemia, and digestive issues (Steenland and Boffetta, 2000).

Mining activities contaminate the roadside as well as adjoining agricultural fields by accumulating HM sin the nearby region through various processes such as shipping, smelting, ore extraction and refining, thus polluting the soil, water, and air (Das and Singh, 2011). Moreover, the fine particulates produced by mining activities could be dispersed into the environment by atmospheric and wind transportation (Csavina *et al*., 2012) and made available to humans via inhalation and skin contact. Excessive levels of HM sreleased from smelting and mining sites can have detrimental environmental effects, including soil and water phytotoxicity contamination and serious health risks (Pruvot *et al*., 2006). There is a risk of cancer in children and adults living/working in the Sukindamine, the country's largest chromite mine, which is heavily contaminated by nickel, chromium, lead and cadmium (Naz *et al*., 2018). Long-term exposure to hexavalent chromium cause stomach disturbance, diarrhea, ulcer, weakening of the immune system, tumor, and stomach and gastrointestinal cancer (Liu *et al*., 2013). The incidence of cancer is approximately nine times greater than average in the Dabaoshan mining area, and death rates can reach up to 56% for cancers such as oesophageal, liver, and other types of cancer (Liu *et al.*, 2005b). Among the most common health issues linked to lead/zinc mining include enhanced blood Pb levels in young children, kidney impairment, malacosteon, and complicated cancers. Bone damage, increased blood pressure, renal failure, diabetes, and cancer are caused by Cd exposure (Satarug *et al.* 2004), while anaemia, kidney disorders, neurological problems, and stomach-aches are the symptoms of lead poisoning (Silbergeld, 2003).

Consuming arsenic-contaminated water as a result of natural mineral deposits, arsenical pesticides, or inappropriately discarded arsenical compounds is a major environmental health issue worldwide, particularly in India, over the past twenty years. Arsenic poisoning has a wide array of clinical signs, and the right diagnosis is primarily dependent on knowledge of the condition (Saha *et al.*, 1999). Arsenic-contaminated drinking water uptake chronically is detrimental to almost all organs and body systems (Spallholz *et al.*, 2004; Khan *et al.*, 2007). It has been linked to cancer through gastrointestinal and respiratory exposure and is found throughout the body in several organs like skin, liver, lungs, and kidneys (Centeno *et al.*, 2006). Pigmentation and keratosis are the skin diseases primarily associated with chronic arsenic poisoning (Mazumder, 2008). Arsenic poisoning in early growth can lead to neurobehavioral abnormalities during puberty and neurobehavioral alterations in adulthood (Tsai *et al.*, 2003). The concerns to human health from using groundwater from the Subarnarekha River Basin as drinking water were discussed by Giri and Singh (2015). The biggest contributors to chronic cancer risks were As, Mn and Co, whereas the lowest were Cu, Cd, and Se for both adults and children.

The soils of hilly regions get polluted with HMs from pesticides and fertilizers, resulting in carcinogenic and non-carcinogenic human health concerns (Kaur *et al.*, 2018). Several documentation on the HM toxicity in humans has been recorded in the past three decades as a result of contamination in fish and related organisms (Krishna *et al.*, 2014). Regular ingestion of methyl-mercury tainted fish through the food chain has been linked to major health issues (Krishna *et al.*, 2014) and results in mercury poisoning in adults, which is marked by damage to certain visual cortical regions and neuronal loss in the cerebellar granule layer (Vettori *et al.*, 2003). Methyl mercury poisoning also leads to functionally weakened or deformed limbs, paralysis, sensitivity disorders, coma, and may even lead to fatality (Yorifuji *et al.*, 2013).

A significant factor in the human population's exposure to HMs is the consumption of plants cultivated in metal-affected areas as well as the absorption or inhalation of contaminated particles. Cadmium and lead levels in the diet were found to be higher than the recommended dietary allowance levels when rice and some vegetables were consumed in china (Zhuang *et al.*, 2009). It has been demonstrated that raising crops for human use on contaminated sites increases the uptake and accumulation of HMs in consumable plant components, endangering human health (Lim *et al.*, 2008) Table 1 shows the impact of heavy metals on human health.

Hence, considering the HMs toxicity, numerous techniques are used to treat heavy metal-contaminated soil, including physical or mechanical separation of the contaminant, acid leaching, soil washing, soil burning, electrochemical treatment, chemical treatment, solidification, electro-kinetics, pyro-metallurgical or thermal separation and biochemical processes, to prevent the accumulation and removal of these toxic HMs. One of the easiest techniques is to dig out the topmost layer of contaminated soil before dumping or capping it in a landfill (Cunningham *et al.*, 1995; Hasan *et al.*, 2019; Yan *et al.*, 2020). While during excavating, transporting, handling, and capping the pollutant, there is always a chance that it will leak out and contaminate the groundwater. Additionally, this approach is both cost ineffective and time taking (Parmar and Singh, 2015). The conventional technologies that can be used both *in situ* and *ex situ* for water and soil remediation include: (a) soil flushing (b) solidification/stabilization (c) electro kinetics (d) vitrification (e) pneumatic fracturing (f) chemical reduction/oxidation (g) excavation (h) and soil washing, retrieval, and off-site disposal. But these methods are prohibitively expensive, and the procedure frequently results in additional waste. Moreover, HM removal from wastewater is cumbersome since they exist in various chemical forms (Ali *et al.*, 2020). In addition, HM pollution poses a risk to the aquatic ecosystem in nations like India where rehabilitation costs are typically prohibitively high (Das *et al.*, 2014).

Plants are less harmful to the environment than the physical and chemical restoration techniques currently in use (Terry and Banuelos, 1999). Phytoremediation is a bioremediation technology that can be utilised alternatively to remove HMs from the environment. Therefore plants that are metal accumulating are deployed to eliminate the harmful metals, including radionuclides and organic contaminants, is a sustainable, economical, effective, environmentally and ecologically friendly "green" technique (Pilon-Smits and Freeman, 2006; Raskin *et al.*, 1997). In this method, plants extract, concentrate, and metabolize elements from the air, water, and soil. Additionally, phytoremediation is a relatively simple procedure because it doesn't require trained workers or specialised equipment (Ali *et al.*, 2020). For eliminating toxins from the surrounding environment, these remediation strategies may employ naturally occurring plants or ones that have undergone genetic engineering (Cunningham *et al.*, 1997). As a result, the current review provides an example of a novel and environmentally responsible phytoremediation technology focusing on HM contamination. Additionally, this compilation summarises the possible applications of many higher plants in the phytoremediation of air, water and soil.

Phytoremediation Technique And Its Types

The HM uptake in plants occurs chiefly through the roots, since the root system offers a large surface area for the absorption of essential nutrients and also the non-essential contaminants (Raskin and Ensley, 2000). HM ions' uptake occurs via the channel proteins, also designated as special transporters found in the root membranes. In the transport of HMs across the membranes, metal complexes are formed (Greipsson, 2011). The plasma membrane of the root cell harbours the specialized transporters, also known as channel proteins or H+-coupled carrier proteins, which are crucial for the uptake of heavy metal ions from the soil. They are able to move particular metals between cell membranes and mediate the influx-efflux of metals from roots to shoots (Ali *et al.*, 2013; Jacob *et al.*, 2018; Yan *et al.*, 2020). The heavy metal ions are often translocated to plant shoots through the primarily xylem vessels and deposited into the cellular vacuoles (Jabeen *et al.,* 2009). Phytoremediation is a revolutionary in-place remediation approach that is ecologically friendly, cost-effective, and non-destructive. It is based on the concept of "clearing nature" by harnessing the intrinsic capabilities of live plants (Etim, 2012). This environmentally beneficial method uses plants to degrade, stabilise, or mitigate soil, water, and air contaminants (Garbisu *et al.*, 2002; Macek *et al.*, 2000). Plants are considered a natural detoxifier and monitoring device for toxic pollutants (Upadhyay and Kobayashi, 2007). Some plants are known as "hyperaccumulators," and they can accumulate enormously high metal concentrations in their shoots (0.1 to 3% of their dry weight), in addition to accumulating metals in the plant roots and translocating them from the belowground parts to the aerial parts (Huang and Cunningham, 1996). To properly cleanse and repair ecosystems, a careful selection of species is essential, and the usage of plants is a universal prerequisite (Wei *et al.*, 2021). The main requirements are fast-growing plants with deep, extended roots, large biomass, simple harvesting, and the ability to accumulate hazardous metals in excess (Paz-alberto and Sigua, 2013). The plant must produce enough biomass since higher biomass lowers the overall concentration of metal in the plant tissue, allowing for significant overall metal accumulation. Plants that accumulate metal must be receptive to agricultural methods that permit the recurrent planting and harvesting of tissues rich in metal (Sumiahadi and Acar, 2018). The different types of phytoremediation processes are now discussed in detail.

The process through which HMs are absorbed by plant roots and transferred to an above-ground part of the plant, such as shoots, is known as phytoextraction, sometimes known as phytoaccumulation, and this procedure can efficiently remove metals such as Cu, Zn and Ni (Ali *et al.*, 2013; Ali *et al.*, 2020). Phytoextraction is based on a plant's intrinsic capability to absorb particular substances (HMs) from the environment and store them intracellularly till the plants can be harvested. It involves the alterations in enzyme kinetics of sulfur metabolism, intermediates formation moieties as the products of primary metabolism and expression of transporters or the metal ligands (Fasani *et al.*, 2017). Toxins are drawn from the soil or water into the roots of plants, where they eventually translocate, sequester and concentrate in shoots or other above-ground organs (Huang and Cunningham, 1996). To be taken up by the roots, the soil-bound metal shall initially be solubilized by the roots. This is accomplished by exudating metal-chelating compounds or metal reductases by roots, freeing the metal from its inorganic or organic soil components. Metal ions may gain entry inside the roots via intracellular or extracellular channels after getting solubilized and the metal ions chelation with phytochelatins and metallothioneins in cytosol takes place which is followed by their trafficking and storage into the vacuole by the vacuolar transporters (Zhao and Chengcai, 2011). Furthermore, these metal ions can get transported to the shoots or kept chelated in root vacuoles (Clemens, 2006).

In the photodegradation process, plants transform organic contaminants into a non-toxic form predominantly by microbial assistance. Phytodegradation is chiefly an enzymatic breakdown of pollutants which is applicable for water contaminant removal either from the groundwater or surface water, sediment sludges or from the soil substratum (Subrahmanyam and Prasad 2011). The process of pollutants being absorbed by the plants and their transformation into organic compounds that are either less harmful or non-toxic is known as phytotransformation. Excretion of various enzymes by the plants assist in the conversion of harmful metals into less toxic forms like the transformation of hexavalent chromium (more toxic) to trivalent chromium (less toxic) after the change of oxidation state (Wu *et al.,* 2011; Ali *et al.*, 2012).

A phenomenon known as phytostabilization occurs when plants release specific chemicals that combine with the toxicant to diminish its bioavailability and mobility in the environment. In other words, it implicates the plants' immobilisation or precipitation of contaminants from water or soil, thereby reducing their availability. In light of this, phytostabilization is simply a management strategy for immobilising or inactivating potentially hazardous compounds (Ali *et al.*, 2020). By absorbing and collecting pollutants in the soil through their roots, precipitating them in the root zone, adhering to the roots, and physically stabilising the soil, certain hyperaccumulating plants can immobilise toxins in the soil. Contaminants may get hidden in cell wall lignins, absorbed by soil humus through plant or microbial enzymes, or hidden by other processes that bind the substance to organic matter or sequester it in the soil (Prasad, 2003). It is useful for the treatment of As, Cd, Cr, Cu, Pb as well as Zn. Plants like *Phragmites australis* and *Typha domingensis* stimulate metal stabilization through their excluder tendency (Bonanno, 2013).

Using a process called phytovolitization, contaminants can be safely discharged into the atmosphere after being extracted from the soil and converted into gaseous form by the plants. More precisely, this technique makes use of plants which can evapotranspire pollutants through their stomata. Organic contaminants and heavy metals, such as Se, Hg, and As, can be detoxified using phytovolatilization (Mahar *et al.*, 2016). The benefit of Phytovolatilization is that the mercuric ions may get converted into its less toxic form i.e. gaseous elemental Hg (Ghosh and Singh, 2005). Plants like mustard and canola are beneficial for the phytovolatilization of selenium. It has been found that *Brassica juncea* and *Arabidopsis thaliana* can take up the HM and metalloids and change them into gaseous forms and their subsequent release into the atmosphere (Khalid *et al.*, 2017).

Pollutants from the aquatic environment are adsorbed or absorbed by plant roots and other components during phytofiltration. An analogous technology, rhizofiltration, is primarily used to eliminate heavy metals from the aquatic environment. Rhizofiltration is a technique which is employed to remediate wastewater, surface water, and extracted groundwater as well, having low amount of contaminants. It is chiefly the absorption or adsorption of contaminants in the solution around the root zone. Plants with deep fibrous root systems, whether terrestrial or aquatic, can be used in rhizofiltration since roots play an important role. Rhizofiltration is utilized for the removal of Cd, Cr, Cu, Pb, Ni and Zn which are predominantly retained within the roots (USEPA, 2000).

Phytoremediation of Air Pollutants

One of the major elements in establishing a plant's suitability for air pollution reduction is its capacity to absorb toxins from the environment and metabolise or detox them at the cellular level (Singh and Verma, 2007). Trees and herbaceous vegetation both work well to remove PM as well as associated heavy metal particles. It has been found that young twigs, leaves, and needles of the plants capture air pollutants (Irga *et al.*, 2015). *Amaranthus spinosus* L. and *Cephalandra india* have been known to fight air pollution (Mandal and Mukherji, 2001). Airborne heavy metal accumulation was tested on different tree species and high bioaccumulation capacity was found in selected trees which were suggested to be grown in the green and buffer zone in the urban areas (Alahabadi *et al.*, 2017). Metallurgy and mining produce a significant number of metal particles, including Cd that are released into the atmosphere. Some plants trap these Cd particles in their leaves by absorbing them from the air through foliar surface (Li *et al.*, 2023).

Gawronska and Bakera (2015) reported that plants can uptake indoor particulate matter. These PMs can be accumulated through dry deposition processes and the plants can accumulate both hydrophobic and hydrophilic PM in all of the size fractions. Outdoor plants can phytoremediate the aerosolised particulate matter (Saebo *et al.*, 2012). Due to HMs relationship with particulate matter (PMs), phytoremediation of PMs from ambient air also significantly contributes to the removal of those substances. Trees and herbaceous vegetation both work well to remove PM as well as associated heavy metal particles. With its hairy and grooved leaf surface, *Morus alba* may efficiently extract heavy metal particles from particulate debris. For instance, the leaves of *Morus alba* absorb the heavy metal ZN-65, which chiefly migrates to the lower stem and root from the atmosphere. As a result, trees are effective at protecting vulnerable metropolitan areas, phytoremediating the air pollution through filtration (Sharma *et al.*, 2020, Wei *et al.*, 2021). EL-Khatib *et al.* (2020) reported that *Eucalyptus globulus* is a good candidate to recover heavy metal from polluted air due to its capability to collect and endure the metal stress. As a result of 30-year monitoring of Ni^{2+} and Cu^{2+} concentrations in the organic horizon of Albic Rustic Podzols and the foliage of six plant species, a dynamic trend in the level of heavy metal accumulation in the components of forest ecosystems of the Kola Peninsula has been revealed against the backdrop of a five- to eight-fold reduction in pollutant emissions (Lyanguzova, 2017). Moreover, the exploitation of higher plants with microbes is possible for the airborne pollutants phytoremediation associated with particulate matter in indoor and outdoor environments (Irga *et al.*, 2015).

Phytoremediation Of Water Pollutants

Aquatic macrophytes have tremendous potential for heavy metal remediation. Aquatic plants in constructed wetlands are now widely applied throughout the world for waste water treatment (Girito *et al.*, 2017). Leaves are the primary organs for HM uptake in submerged aquatic plants, the HM transport method in floating plants can be passive, where the plant body comes into direct contact with the contaminant, or active, where the HMs are transported via the roots (Ali *et al.*, 2020). Free-floating plants like duckweed, water hyacinth and water lettuce are predominantly used for the HMs remediation from the waste water (Hua *et al.*, 2012; Singh *et al.*, 2012). When compared to other macrophytes, duckweed has been shown to be the best plant for phytoremediation (Ali *et al.*, 2020). Treatment wetlands located in tropical regions are dominated by water lettuce and water hyacinth vegetation (Rai, 2009). Diverse duck weed species, such as *Lemna minor*, *Lemna trisulca*, and *Lemna gibba*, have significantly increased the wastewater's ability to eliminate several HMs (Rahman and Hasegawa, 2011; Singh *et al.*, 2012; Zayed *et al.*, 1998). *Eichhornia crassipes* or the water hyacinth manifests significant removal efficiency for Cd, As, Cu, Mn, Fe, Pb, Cr, Hg, and Zn, as reported in different studies (Aurangzeb *et al.*, 2014; Fazal *et al.*, 2015; Mahalakshmi *et al.*, 2019). In Taiwan's Erh-Chung wetlands, the water hyacinth (*Eichhornia crassipes* Mart. Solms.) was tested for its capacity to absorb Cd, Ni, Pb, Cu and Zn (Liao and Chang, 2004). The remediation potential of *Eichhornia crassipes* and *Lolium perenne* in cleaning up contamination from the polluted rivers was checked by the construction of a floating bed on the Guxin River in Hangzhou. It was found that chemical oxygen demand, total particulate and NH_3-N of the study river were reduced by 20.0, 63.3 and 48.6%, respectively.

Azolla is a nitrogen-fixing, free-floating plant that has proven to be a promising option for recovering and removing HMs from damaged aquatic habitats (Arora *et al.*, 2006). The percentage reduction in metal concentration was approximately 25–67.90% at Belwadah (with *Lemna minor* and *Eichhornia crassipes*), 25–71.42% at G.B. Pant Sagar's Ash pond site (with *Azolla pinnata* and *Lemna minor*), and 25–77.14% at Dongia nala (with *Lemna minor, Azolla pinnata* and *Eichhornia crassipes*) (Rai, 2010). Das *et al.* (2014) investigated the cadmium phytoremediation capabilities of water lettuce, *Pistia stratiotes* L., and discovered that the plants could with stand high levels of Cd up to 20 mg L^{-1}. Moreover, Zayed *et al.*(1998) found that upon supplying with 10 mg Cd L^{-1} concentration, *Lemna minor* accumulated a large amount of Cd at a concentration of 13 g kg^{-1}. A combination of *Lemna minor* and *Azolla pinnata* efficiently removed the Zn and Pb from wastewater (Jain *et al.*, 1990). In contrast, *Wolffia globosa* was utilized in the elimination of Cr and Cd (Boonyapookana *et al.*, 2002). When arsenate was supplied to the experimental solutions, *Spirodela polyrhiza* absorbed arsenic by physicochemical adsorption and the phosphate absorption pathway, according to Rahman *et al.* (2007). Submerged hydrophytes such as *Ceratophyllum demersum*, *Potamogeton pectinatus* and *Vallisneria spiralis* are known to accumulate heavy metals; however, *Typha latifolia*, *Phragmites*, *Polygonum hydropiperoides*, and others are common emergent aquatic plants that can be used successfully for the phytoremediation of a variety of HMs (Kutty *et al.*, 2016; Rudin *et al.*, 2017; Sasmaz *et al.*, 2008).

Phytoremediation Of Soil Contaminants

Members of the genera *Thlapsi*, known to accumulate the metals Cd, Zn, and Pb, and *Alyssum*, known to accumulate Ni are among the earliest discovered species on land that are known to accumulate these metals. *Armeria maritima* (a Pb accumulator) and *Thlaspi caerulescens* (Zn accumulator), and two species of *Aeolanthus biformifolius* and *Haumaniastrum katangense* which are Cu and Co accumulators are specific instances of metal-accumulating plants (Prasad, 2002). Moreover, several other plants are reported as common pollutant accumulating plants

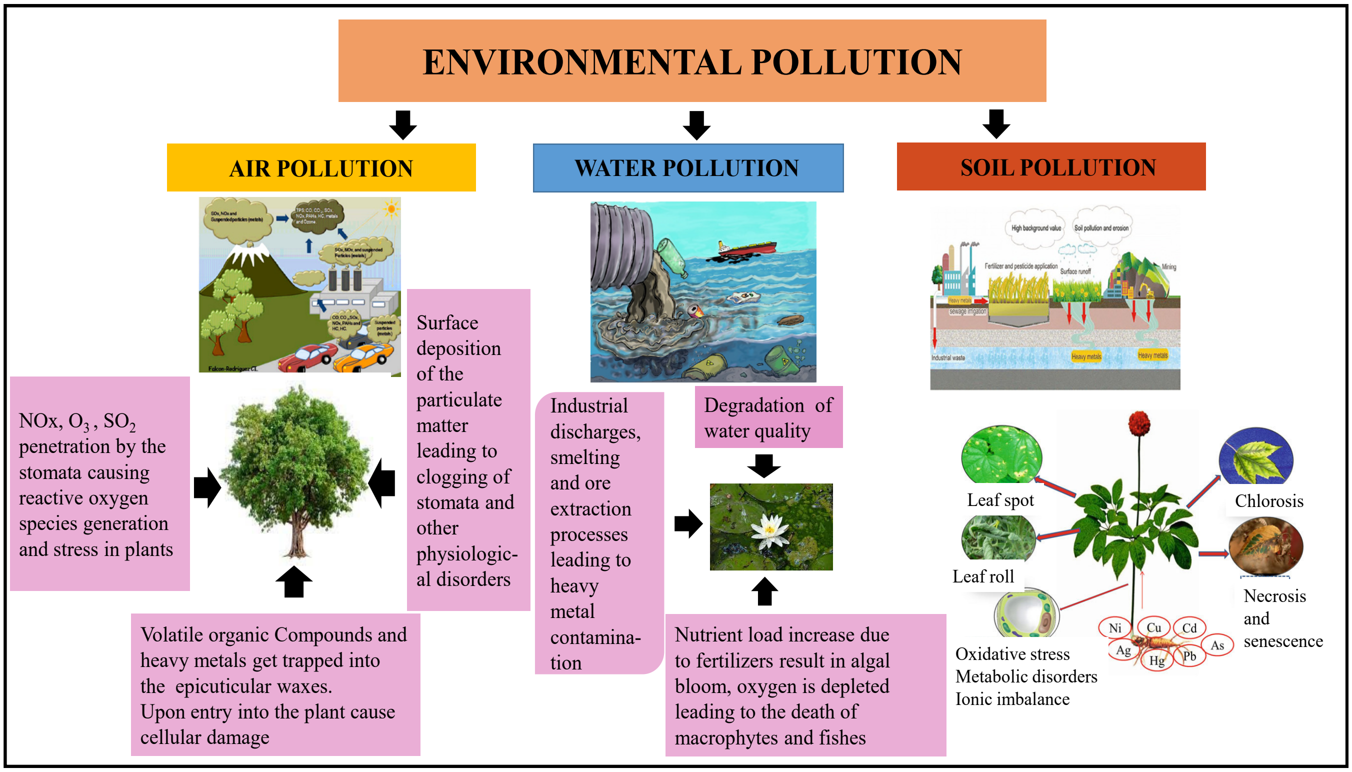

Fig. 1: Pollution in air, water and soil and its effects on plants and ecosystem

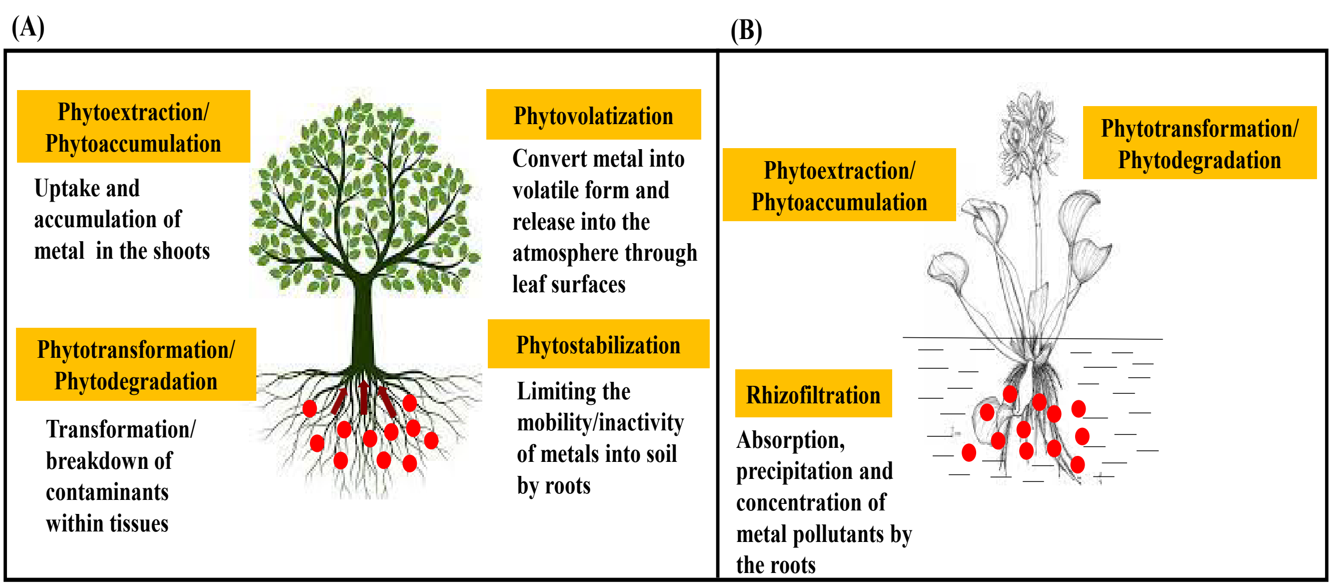

Fig. 2: Phytoremediation strategies employed for the removal of HMs from (A) soil and (B) aquatic environment.

like *Brassica juncea*, *brassica napus*, *Triticum aestivum*, *Zea mays*, *Helianthus annuus*, *Ambrossia artemisifolia*, *Pteris vittata*, *Vetiveria zizanioides* (Ma *et al.*, 2001). A list of plants that are being utilized for the removal of metals from soil has been given in Table 2. The phytoremediation capacity of *Jatropha curcas* of cadmium and lead polluted soil was investigated by Mangkoedihardjo (2008). Some species, like *Sedum alfredii*, can hyper accumulate Cd, Pb, and Zn and can even collect simultaneously two elements (Yang *et al.*, 2004, Yan *et al.*, 2020). Furthermore, *Jatropha curcas* and *Ricinus communis* are promising energy crops that have the potential to phytoremediate contaminated sites in addition to providing a variety of ecosystem services (Nsanganwimana *et al.*, 2014, Pandey *et al.*, 2015).

Due to their ability to hyperaccumulate a number of metal elements in their shoots, members of the Brassicaceae family are among the most significant groups of hyperaccumulators (Prasad and Freitas, 2003). The synthesis of biodiesel and phytoremediation using *Brassica napus* have both been documented in numerous researches. Additionally, *Brassica napus* is one of the most popular biodiesel sources due to its

Table 1: Impact of some heavy metals on human health

S.No.	*Heavy metals*	*Impact on human health*	*References*
1.	Arsenic	Heart attack, high blood pressure, black foot disease	Mahuepawar (2015)
2.	Arsenic	Developmental and reproductive damage, genetic toxicity, skin, lung, kidney and bladder disorders	Morais *et. al.,* (2012)
3.	Barium	Vomiting, diarrhea, muscle weakness, breathing difficulties, paralysis and numbness around the face	Martin and Griswold (2009)
4.	Cadmium	Bone diseases, kidney damage, prostate dysfunction and cancer	Adamis *et. al.,* (2003)
5.	Cadmium	Cartilage disease and bone fractures	Mishra *et al.,* (2019)
6.	Cadmium	Itai-itai disease	Mitra *et. al.*, (2022)
7.	Chromium	Stomach ulcers, nausea, irritation of the gastrointestinal tract, and in severe cases may cause death	Mishra and Bharagava (2016)
8.	Chromium	Carcinogenic effect	Coetzee *et. al.*, (2020)
9.	Copper	Chronic anaemia, high blood pressure	Mohod and Dhote, (2013)
10.	Lead	Intellectual abnormalities in children	Hou *et. al.*, (2013)
11.	Lead	Haematological damage and also damage to nervous connections especially in young children, brain disorders	Mohod and Dhote, (2013)
12.	Lead	Damages nervous system, kidney, immune system, liver, urinary system, and genetic expressions	Su (2014)
13.	Lead	Gastro-intestinal, neurological, renal, reproductive and cardiovascular problems	Mahuepawar (2015)
14.	Manganese	Psychologic and neurologic disorders	Azaman *et. al.*, (2015)
15.	Mercury	Congenital malformation and spontaneous abortion, gastrointestinal disorders (like corrosive esophagitis and hematochezia), damage to the brain and CNS, gingivitis	Sankhla *et. al.*, (2016)
16.	Mercury	Minamata disease	Mitra *et. al.*, (2022)
17.	Nickel	Tumours, fibrosis, lung inflammation and emphysema	Azaman *et. al.*, (2015)
18.	Nickel	Nasopharyngeal carcinoma and respiratory cancer	Mishra *et. al.*, (2019)
19.	Selenium	Vomiting, diarrhoea, nausea, coughing neurological abnormalities and bronchitis	Martin and Griswold (2009)
20.	Silver	Lung and throat irritation, inflammation and swelling, rashes and blue-gray discoloration of the skin	Martin and Griswold (2009)

Table 2: A list of plants that are being utilized for the removal of metals from soil

S. No.	*Plant*	*Pollutant*	*References*
1.	*Pteris vittata, Solanum nigrum, Bidens pilosa, Thalaspi caerulescens, Alyssum murale, Sedum alfredii*	Arsenic, Cadmium, Nickel and Zinc	Shah and Daverey (2020)
2.	*Acanthus ilicifolius*	Cadmium	Shackira and Puthur (2017)
3.	*Osmanthus fragrans, Cinnamomum camphora, Ligustrum vicaryi, Euonymus japonicus and Loropetalum chinense*	Cadmium	Zeng *et al.*, (2018)
4.	*Chromolaena odorata, Bidens pilosa and Praxelis clematidea*	Cadmium	Wei *et. al.*, (2018)
5.	*Vossia cuspidata*	Cadmium, Chromium, Zinc, andLead	Galal *et. al.*, (2017)
6.	*Halimione portulacoides*	Chromium	Ekta and Modi (2018)
7.	*Ipomoea alpina*	Copper	Cunningham and Ow (1996)
8.	*Calandula officinalis*	Copper	Goswami and Das (2016)
9.	*Thlaspi rotundifolium*	Lead	Reeves and Brooks (1983)
10.	*Arabidopsis thaliana*	Manganese	Delhaize *et. al.*, (1993)
11.	*Arabidopsis thaliana*	Mercuric ions	Rugh *et. al.*, (1996)
12.	*Pisum sativum*	Iron	Cunningham *et. al.*, (1994)
13.	*Astragalus racemosus*	Selenium	Sikdar and Kundu (2018)
14.	*Thlaspi caerulescens*	Zinc	Brown *et. al.*, (1994)

widespread production. Phytoremediation utilising *B. napus* is crucial for both the removal of HMs from the soil and the subsequent production of biodiesel because the plant's seeds contain 40–44% of its oil content (Laaniste *et al.*, 2004). Since mined soils are the main causes of air and water pollution, phytoremediation has been applied in mined soil restoration through the use of phytostabilization and phytoextraction techniques to stabilise as well as remove the toxic mine spoil (Wong, 2003). Phytoextraction has been shown to be an efficient method for removing heavy metals from polluted soil in high biomass-producing plants such *Helianthus annuus*, *Cannabis sativa*, *Nicotiana tabacum*, and *Zea mays* (Tlusto *et al.*, 2006; Herzig *et al.*, 2014; Yan *et al.*, 2020). Since damaged soils often contain high levels of numerous contaminant trace elements, drastic changes would be necessary for phytoremediation to become a practicable method, i.e., plants with large tolerance and accumulation rates for many metals. The main target metals for clean-up are arsenic, cadmium, lead, or mercury-polluted soil (Moffat, 1999). Rare reports of the use of decorative plants for phytoremediation exists despite the fact that they pose a lesser danger of HM build-up than crop plants (Khan *et al.*, 2021).

Despite having many benefits, phytoremediation technology has some drawbacks as well: (1) it is a labour-intensive process that may take multiple growth seasons to clean a site; (2) the build-up of organic or inorganic chemicals in plants may result in the creation of numerous harmful intermediates and (3) plants become contaminated with harmful HMs or chemicals following phytoremediation, which may endanger wildlife or taint the food chain. Consequently, the metabolic fate of contaminants in the plant system must be investigated to demonstrate phytoremediation's applicability (Morikawa and Erkin, 2003; Upadhyay and Kobayashi, 2007). Furthermore, challenges with biomass disposal and periodic growth of aquatic macrophytes are few of the impediments to transporting phytoremediation technology from lab to the field (Rai, 2009).

Biotechnology Application In Phytoremediation

The biotechnological application for generating transgenic plants is a cutting-edge technology for improving the efficacy of the phytoremediation process. This is due to the increased uptake, accumulation and metabolism of definite pollutants since specific genes in transgenic plants are introduced (Doty, 2008). In addition, genetic engineering techniques for phytoremediation can be deduced as a substitute source to improve the phytoremediation procedure through better plant potential like high yield even when they absorb HMs (Jeevanantham *et al.*, 2019). Arabidopsis and tobacco are the transgenic plants first used to effectively remove HMs like mercury and cadmium (Mishra *et al.*, 1989; Rugh *et al.*, 1996). Thus, introducing genes from diverse species into plants is expected to be required to develop a phytoremediation approach for particular trace elements (Kumar, 2021). According to Gasic and Korban (2007), the *Arabidopsis thaliana* phytochelatin synthase gene *AtPCS1* was overexpressed in Indian mustard, which improved its resistance to Arsenic and Cadmium metals. Although predicting how microbial genes will affect a complex multicellular creature like a plant is difficult, the effective introduction of a modified bacterial mercuric ion-reductase gene into the *Liriodendron tulipifera* and *Nicotiana tabacum* shows that bacterial genes transferred into plants may be useful for phytoremediation (Moffat,1999). Transgenic plants that overexpressed the ATP sulfurylase were found to be more tolerant to Cu, Cd, As, Zn and Hg compared to their wild type complements (Wangeline *et al.*, 2004). According to Rai (2009), it may be possible to genetically modify plants by over-expressing metal-binding peptides like phytochelatins (PCs) or glutathione (GSH). The production of chelators like GSH and PCs was increased as one of the methodology to enhance heavy metal and/or metalloid remediation (Tripathi *et al.*, 2007). The potential of genetically modified plants to absorb significant amounts of metal has resulted in effective gene-modification research in terrestrial plants; however, aquatic plant genetic engineering to boost metal absorption capacity is still in its early stages (Ali *et al.*, 2020). Therefore, utilizing already existing metal-tolerant plants and genetic engineering can speed up the process of translating phytoremediation technologies from the lab to the field.

Conclusion

Environmental heavy metal contamination is a result of anthropogenic activities like mining, metal processing, manufacturing industries, dyeing, tanning, and plating. Physical or mechanical separation like electrochemical treatment, soil washing, acid leaching, pyrometallurgical or thermal separation are all treatment approaches to remove metal load from the environment. However, these techniques are neither very cost-effective nor environment friendly. Nevertheless, phytoremediation is a long-term, cost-effective, and ecologically friendly "green" approach. While phytoremediation of air pollutants is still in its infancy, plants such as *Morus alba* and *Eucalyptus globulus* can efficiently remove metallic pollutants from air. Water contamination from anthropogenic activity is a major issue, and metals' toxicity in ground and surface water is a major environmental and health hazard. Aquatic macrophytes are employed for the phytoremediation and rhizofiltration to remove toxins from water. These macrophytes have potential for heavy metal/metalloids remediation, with free-floating plants such as *Lemna* spp., *Eichhornia crassipes*, and *Pistia stratiotes* being commonly used. Moreover, emergent aquatic plants and submerged hydrophytes can also be utilized. Plants have the capacity to absorb toxins from the environment and detox them at the cellular level, and can be used to remediate the metal-polluted soil. Metal-accumulating plants including *Brassica juncea*, *Helianthus annuus*, *Vetiveria zizanioides, Pteris vittata*, etc. can efficiently extract metals/metalloids from the soil. Transgenic plants can be used to improve phytoremediation by over-expressing metal-binding peptides and utilizing existing metal-tolerant plants. Hence the remediation through plants is an environmental friendly technique with a promising future and should be promoted in an era of global climate change.

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Author's contribution

Rana Eram: Material collection, validation, writing original draft and editing. Aditya Abha Singh: Conceptualization, supervision, material collection, validation, writing original draft, review and editing. Nikhita Bharti: writing review. Tanuja: Review and editing.

Conflict of interest

The authors declare no conflict of interest

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