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Halophyte for Sustainable management of alkaline metal-contaminated soils: a review

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Abstract

In recent years, large swathes of farmland in arid and semi-arid regions have been affected by heavy metal pollution, which has raised widespread environmental concern. The accumulation of heavy metals in agricultural soils is an obstacle to achieving food safety and security globally. Bioremediation is a promising nature-based solution for addressing heavy metal pollution. Phytoremediation, defined as the use of plants to remove pollutants from the environment, is a low-cost, environmentally friendly, and effective method of decontamination of heavy metal-contaminated soil. Halophytes are capable of coping with many abiotic constraints that occur simultaneously in their natural environment. Halophytes, which are able to survive and reproduce in soils highly contaminated with heavy metals. In this review, we discuss current progress in the use of halophytes, mechanisms of their tolerance to heavy metal toxicity, and the potential for phytoremediation in heavy metal contaminated soils. This review is a try to gather the sparse information on phytoremediation research updates in the last decade to provide an outlook on the emerging green biotechnology for alkaline metal-contaminated soils rehabilitation.

Keywords: Alkaline soil; Heavy metal, Sustainable management, Halophyte, Phytoremediation, Tolerance mechanism.

Review article
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1. Introduction

Environmental pollution is a serious environmental concern all over the world with an ever-growing public outcry to ensure a safer and healthier environment. A variety of organic and inorganic pollutants have been reported to cause environmental pollution and severe health risks in living organisms [1]. Among them, heavy metals are highly notorious pollutants due to their high abundance and nonbiodegradable and persistent nature in the environment. Hence, they cause soil/water pollution and toxic, genotoxic, teratogenic and mutagenic effects in living beings [2]. They also cause endocrine disruption and neurological disorders even at low concentration [2]. Any naturally occurring metal/metalloid having an atomic number greater than 20 and elemental density greater than 5 g cm-3 is termed as heavy metal. They include copper (Cu), cadmium (Cd), chromium (Cr), cobalt (Co), zinc (Zn), iron (Fe), nickel (Ni), mercury (Hg), lead (Pb), arsenic (As), silver (Ag) and platinum group elements [3]. Among them, Cd, As, Hg, and Pb don't have any biological function in the body and thus, are non-essential elements. They can cause severe health hazards and are listed as priority pollutants by many environmental protection agencies worldwide [2]. Therefore, the removal of heavy metals from the contaminated matrix is an urgent need to safeguard the environment and human health. The buildup of toxic metals in various compartments of the environment is hazardous for biotic health including humans due to bioaccumulation and biomagnification of heavy metals in living organisms. Biomagnification refers to the greater tissue concentration of heavy metals [4] . The continuous rise in the levels of heavy metals in soil ecosystem is the major concern throughout the world [5,6]. Global environmental contamination is one of the most significant environmental challenges of our time that affects all components of the environment. The attention of researchers is focused primarily on hazardous substances (heavy metals), which are hardly degradable in nature and show high persistence and often exhibit toxic effects in the environment [7]. The pollution of the biosphere with toxic heavy metals is a widespread ecological problem resulting from anthropogenic activities like fossil fuel burning, ore mining and smelting, industrial and municipal waste disposal and agricultural activities [8].

Metal pollution is a long-term and high-scale environmental disturbance that can cause serious effects on soil health, biodiversity, and human communities. One of the alternatives to rehabilitate these areas is phytostabilization, a technique in which plant species are used to decrease the availability of potentially dangerous metals to the environment. Among heavy metals, Al (aluminium), Zn, Mn (manganese), Cr (chromium), Cu (copper), Cd (cadmium), Pb (lead) and Hg (mercury) are the common toxic metals [9]. In addition, some metalloids are also considered toxic such as As (arsenic) and Sb (antimony). Heavy metals pose significant inhibitory effects on aquatic and terrestrial ecosystems that result in increased physiological health risks [10]. Heavy metals have various ways of entrance in the plant body including contact with skin, food, air and water [11,12]. Heavy metals are the reasons of major health concerns in humans [13]. For instance, heavy metals may increase the onset of cognitive impairment, cardiovascular diseases, and chronic anemia [1] , cancer, damage kidneys, brain and nervous system [15]. In addition, teeth, bones and skin are also damaged by heavy metals [16]. Therefore, it is imperative to exclude the heavy metals from the environment so as to decrease the health risks.

Soil contamination with metals caused by human activities is a major environmental issue affecting environmental communities, human health, and economic activities worldwide [17]. Among the number of approaches to reduce the negative impacts of metal contamination, phytoremediation is recognized for being a cost-effective and environmentally friendly approach for in situ remediation of degraded soils. Since the main biological stresses posed by these degraded areas (drought, ionic stress, and low nutrient) coincide with some of those present in saline ecosystems, halophyte species have been proposed as a good alternative for phytostabilization in arid and semiarid ecosystems [18]. Halo flora could be exploited to grow them in soils challenged with heavy metals [19]. Halophytes have potential to be useful as 'green technology candidates' in phytoremediation efforts. It is cost effective because halophytes can grow in poor quality, low fertile soil and marginal land. The halophytes with exclusion or extraction ability can be utilized in phytostabilization purpose. Such halophytes, with high biomass and rapid growth will restrict the entry of toxic ions in root, will form a vegetation cover and maintain low level of toxic metals in soil. Halophytes like *Atriplex halimus, Atriplex nummularia, Mesembryanthemum crystallinum, Sesuvium portulacastrum, Tamarix smyrnensis, Salicornia* sp. have proved their potential in phytoremediation [18,20]. At the laboratory level, all of them have proved as better systems for phytoremediation and should be explored at field level. In addition, halophytes possess phytoextraction ability. Plants will accumulate toxic metals in aerial parts which can be harvested easily and the phyto-remediated soil will be devoid of or lessened with soil contaminants. Halophytes use the same set of morphological adaptations for both salt and metal ions. The excreted metal can be collected before it re-enters in to the soil and thereby reducing the metal load [19].

2. Sources of soil pollution

Agricultural soil is a non-renewable natural resource. Industrial and agricultural activity is detrimental to soil health and can distribute heavy metal into the soil environment, with harmful effects on human and ecosystem health. Heavy metals occur naturally in the soil environment from the pedogenetic processes of weathering of parent materials at levels that are regarded as trace (<1000 mg kg^{-1}) and rarely toxic [11,21]. Due to the disturbance and acceleration of nature's slowly occurring geochemical cycle of metals by man, most soils of rural and urban environments mayaccumulate one or more of the heavy metals above defined background values high enough to cause risks to human health, plants, animals, ecosystems, or other media [22]. The heavy metals essentially become contaminants in the soil environments because (i) their rates of generation via manmade cycles are more rapid relative to natural ones, (ii) they become transferred from mines to random environmental locations where higher potentials of direct exposure occur, (iii) the concentrations of the metals in discarded products are relatively high compared to those in the receiving environment, and (iv) the chemical form (species) in which a metal is found in the receiving environmental system may render it more bioavailable [22]. Heavy metals in the soil from anthropogenic sources tend to be more mobile, hence bioavailable than pedogenic, or lithogenic ones [23]. Metal-bearing solids at contaminated sites can originate from a wide variety of anthropogenic sources in the form of metal mine tailings, disposal of high metal wastes in improperly protected landfills, leaded gasoline and lead based paints, land application of fertilizer, animal manures, biosolids (sewage sludge), compost, pesticides, coal combustion residues, petrochemicals, and atmospheric deposition Singh, [24] are discussed hereunder.

3. Soil concentration ranges heavy metals

Pollutants and heavy metals are raising concerns throughout the world due to their negative effect on organisms, plants, and the ecosystem. Soil metal contamination derived from anthropogenic activities is a major environmental issue that affects ecological communities, human health, and economical activities worldwide [17]. Among the number of approaches to reduce the negative impacts of metal contamination, phytoremediation is recognized for being a cost-effective and environmentally friendly approach for in situ remediation of degraded soils. Soils may become contaminated by the accumulation of heavy metals and metalloids through emissions from the rapidly expanding industrial areas, mine tailings, disposal of high metal wastes, leaded gasoline and paints, land application of fertilizers, animal manures, sewage sludge, pesticides, wastewater irrigation, coal combustion residues, spillage of petrochemicals, and atmospheric deposition [24]. Heavy metals constitute an ill-defined group of inorganic chemical hazards, and those most commonly found at contaminated sites are Pb, Cr, As, Zn, Cd, Cu, Hg, and Ni [26].

Soils are the major sink for heavy metals released into the environment by aforementioned anthropogenic activities and unlike organic contaminants which are oxidized to carbon (IV) oxide by microbial action, most metals do not undergo microbial or chemical degradation [29] and their total concentration in soils persists for a long time after their introduction [30]. Changes in their chemical forms (speciation) and bioavailability are, however, possible. The presence of toxic metals in soil can severely inhibit the biodegradation of organic contaminants [31]. Heavy metal contamination of soil may pose risks and hazards to humans and the ecosystem through: direct ingestion or contact with contaminated soil, the food chain (soil-plant-human or soil-plant-animal-human), drinking of contaminated ground water, reduction in food quality (safety and marketability) via phytotoxicity, reduction in land usability for agricultural production causing food insecurity, and land tenure problems [32].

4. Techniques methods remediation metal-contaminated soils

Remediation techniques have been developed to rectify the heavy metal-contaminated sites, including surface capping, encapsulation, landfilling, soil flushing, soil washing, electrokinetic extraction, stabilization, solidification, vitrification, phytoremediation, and bioremediation. These remediation techniques employ containment, extraction/removal, and immobilization mechanisms to reduce the contamination effects through physical, chemical, biological, electrical, and thermal remedy processes [33]. These techniques demonstrate specific advantages, disadvantages, and applicability. In general, in-situ soil remediation is more cost-effective than ex-situ treatment, and contaminant removal/extraction is more favorable than immobilization and containment. Among the available soil remediation techniques, electrokinetic extraction, chemical stabilization, and phytoremediation are at the development stage [34].

Bioremediation tends to be more sustainable than traditional thermal or physico-chemical techniques. Bioremediation also brings other sustainability benefits, including decreased cost, increased worker safety and smaller life cycle environmental footprints compared with traditional remediation methods98, maximizing the economic, social and environmental benefits of soil remediation. These benefits have prompted the remediation industry to move towards such nature-based solutions. Phytoremediation is considerably investigated and progressively utilized in the field to remove the toxic metals and salt contamination from affected soil [36]. Amongst the phytoremediation techniques, phytoextraction has usually very efficiency to clean up of heavy metals from soil most probably due to its cost-effectiveness, visible benefits, and reasonable applicability [37]. Several halophytes were effectively used to get rid of toxic metals contamination from soil. The rate of translocation of metals/elements from root to shoot in halophytes mainly depending on the nature of halophyte species, targeted metals, and quality of the surrounding environment [38]. This is frequently documented as a most desirable phytoremediation method [39]. The effectiveness of this method significantly based on the type of plant species, availability and forms of metal of interest in the targeted soil [40] . These halophytes seem to be had reasonable capability to localize the targeted toxic metals and salts in their metabolically inactive cell and organs by the synthesis of compatible osmolytes, and strong antioxidant systems [39] . Therefore, phytoextraction by halophytes are signifcantly practicable for the detoxifcation of toxic metals from contaminated soil [41].

5. Use of Halophytes for phytoremediation as sustainable management

The engineered use of green plants to degrade/detoxify pollutants from the contaminated medium (soil) is technically described as phytoremediation. The term "phytoremediation: is made up of two words i.e. Greek head "phyto" (means plant) and Latin root "remedium" (means to correct or remove an evil). It can be applied for the eco-restoration of sites primarily contaminated with HMs and various recalcitrant organic pollutants [42]. Contamination of land with heavy metals poses severe environmental threats. Physical and chemical remediation techniques are generally used for remediating metals contaminated sites. These methods are cost-intensive and therefore, commercially non-viable, besides being disruptive in nature and causing deterioration of soil [43]. Alternatively, bio-remediation techniques are cost-effective and environment friendly. Plants are outstanding tracers of pollution because of their presence in almost every corner of the planet and they uptake organic and inorganic compounds in water, and soil. Phytoremediation could therefore be easily developed as an in-situ treatment for the removal of these contaminants together with the benefits of habitat rehabilitation and biomass generation that can be used as feedstock for the generation of renewable bioenergy [44]. Phytoremediation as a green biotechnology tool for emerging environmental pollution: a step forward towards sustainable rehabilitation of the environment. Plants have been utilized for the elimination of numerous pollutants from water and soil phase. Among the various phytoremediation techniques, hyperaccumulator plants are most commonly used for the remediation of the contaminated sites. Phytoremediation has been identified as an emerging, low-cost and eco-sustainable solution for HM pollution prevention and control. It is the most suitable alternative to conventional physicochemical remediation technologies, which are highly expensive, technically more suited to small areas, create secondary pollution and deteriorate soil fertility and thus, adversely affects agro-ecosystem [45].

Halophytes are classified as salt-tolerant plants as they have the ability to complete their life cycle under high salt conditions where halophytes cannot survive. Although halophytes represent only 1% of the world's flora, they are rich in diversity. They show diversity in habitats, response to abiotic stresses, and distribution among flowering plant taxa [47]. Flowers and Colmer [48] classified halophytes if the plant could complete its life cycle at 200 mmol NaCl, and on this basis 350 species were registered as halophytes, which are distributed in 20 orders and 256 families [47]. Several approaches have been used to remediate heavy metal-contaminated soils; however, the remediation effects were limited due to the complexity of the combined pollution, immature technology, and high costs [49]. Phytoremediation has been highlighted as an alternative technique to traditional methodologies as it provides a cost-effective, long-lasting, and aesthetic solution for remediation of contaminated sites. It was proposed that selecting target halophytes that can accumulate moderate amounts of heavy metals and produce high biomass yields may be a convenient and efficient means for phytoremediation heavy metal contaminated soils [50].

Halophytes are widely distributed in the coastal regions, marshy soils, mangroves swamps, estuaries, and saline semi deserts [51]. They can flourish well in soils ranging from normal to severely saline. Some halophytes can even grow well at salt concentrations higher than that of seawater (>500 mM [52]. Interestingly, dicot halophytes are more tolerant as compared to monocot species and exhibit optimal growth in 100–200 mM NaCl, whereas, monocotyledonous halophytes show optimal growth in 50–100 mM of NaCl [48]. The number of halophyte species is estimated to range from 2000 to 3000 [52] , and majority of them belong to angiosperms.

6. Mechanism of phytoremediation in halophytes

Halophytes show three biological detoxification mechanisms to combat the metal toxicity namely, metal ion exclusion, excretion and accumulation [53]. Exclusion is the process where metal ions are selectively excluded from roots and their entry in xylem stream is restricted [19]. In the excretion type of mechanism, plants possess special morphological features like glands, hairs, trichomes or bladders on their leaf or stem. The presence of excreted crystals of Cd and Pb on leaf surface confirmed the possible mechanism of metal excretion in this halophyte [54]. Metal excretion as the prime mechanism has also been noted in halophytes such as *Atriplex halimus*, *Atriplex marina*, *Armeria maritima*, and *Tamarix aphylla*. In the accumulation mechanism, some halophytes do not possess special morphological features and/or unable to exclude from root. They absorb toxic salt ions and rapidly translocate towards aerial parts like leaves. These ions are sequestered in to vacuoles to avoid accumulation in the cytoplasm [19]. Similar to salt ions, *Juncus acutus*, *Mesembryanthemum crystallinum*, *Salicornia maritime*, *Spartina alterniflora*, *Sesuvium portulacastrum* accumulate toxic metal ions in the aerial parts [55].

Halophytes have evolved a number of tolerance mechanisms against heavy metal ion toxicity, which include (a) avoidance or exclusion that minimizes the cellular accumulation of metals; (b) excretion of toxic ions through specialized structures and tolerance, which allow plants to survive; and (c) accumulating high concentrations of metals in vacuoles [19]. Based on the above mechanism, these plants are categorized into three groups: (a) metal excluders, (b) excretors, and (c) accumulators or hyperaccumulators [56]. Sustainment of biomass production and osmotic balance make halophytes as the excellent candidates for the sustainable remediation of HM contaminated sites [57]. Halophytic plant species exhibit a variety of HM tolerance mechanisms, like evasion or extrusion which limits the intracellular accrual of metals, release of toxic metal ions via specific structures like trichomes or glands and tolerance, which confers the ability to the plants to survive in toxic environment while storing increased content of metals [19,54]. Halophytic plants are divided in three groups based on their tolerance mechanisms against metal contamination, viz., metal excluding, excreting and accumulating ones [56]. Metal accumulators, also referred as hyperaccumulators, possess the capability to sequester and accumulate increased levels of metal ions in the aboveground tissues as an adaptation strategy to the toxic environment [58]. The mechanisms behind metal hyperaccumulation in the plant include metal ion chelation by ligands and/or sequestration of metal ions in the vacuolar or cell wall region.

Halophytic plants reveal their considerable HM tolerance potential and accumulation capacity in their tissues by triggering detoxifying/ sequestering mechanisms. Different accumulation ability indicates adaptive strategy of the plant for metal detoxification or tolerance [54]. It was speculated that non-selective salt resistance mechanisms are adapted by halophytes to accumulate hazardous ions in the sub-cellular compartments or salt glands or trichomes [59]. The most adapted detoxifying/sequestering mechanisms in halophytes are considered as HM complexation with ligands followed by sequestration from physiologically active cellular environment into less active sites of the cell [60]. They may also play important role as antioxidant molecules to prevent oxidative injuries induced by HM toxicities through complexation with cellular moieties or metabolic pathways [61]. It was reported that the level of several polyamines such as putrescine, spermidine, and spermine were elevated upon challenged with Cd in *Atriplex atacamensis Phil. and A. halimus* L. [62]. Phytochelatins were frequently implicated for detoxification due to their complexation mechanism with toxic metals [63] , hence can protect plants from HM toxicity, and maintain ion balance [64]. In addition to the physiological and biochemical mechanisms, studies are now exploring the metal accumulation and remediation potential of halophytes at molecular level [62]. Numerous halophytes show a high HM accumulation ability due to their efficiency to sequester toxic ions in trichomes or vacuoles, to execute adequate osmotic adjustment and to lessen the deleterious effect of oxidative stress [64].

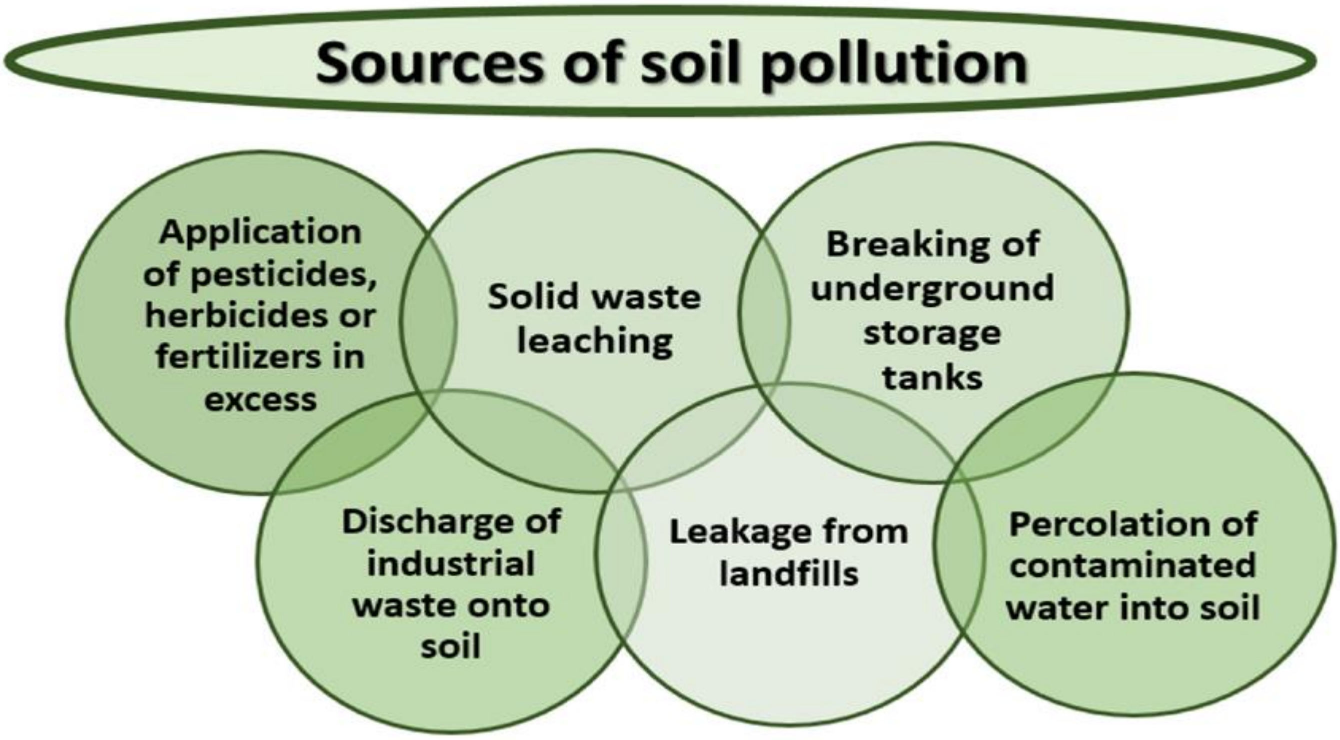

Figure 1. Some relevant sources of soil pollution (source [25])

Table 1. Soil concentation ranges and regulatory guidelines for some heavy metals (Soruce [15])

Metal	Soil concentation range* (mg kg^{-1})	Regulatory limits † (mg kg^{-1})
Pb	1.00 - 69000	600
Cu	0.10- 345	100
Cr	0.05 – 3950	100
Hg	< 0.01- 1800	270
Zn	150 – 5000	1500

*[27]; † Nonresidential direct contact soil clean-up criteria [28].

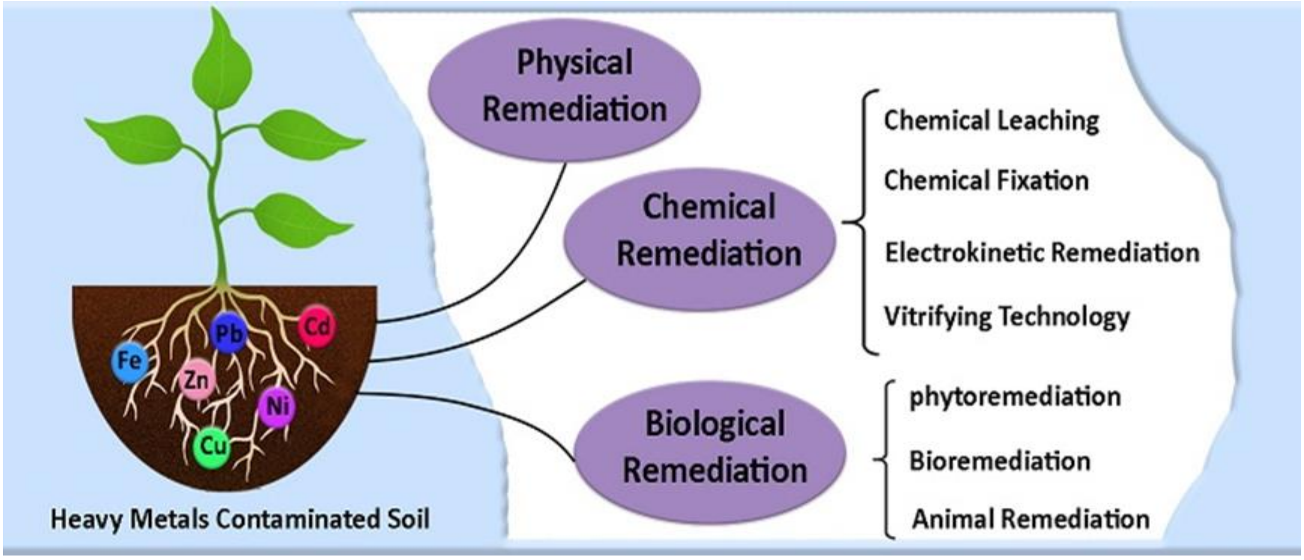

Figure 2. Techniques methods remediation metal-contaminated soils (source [35])

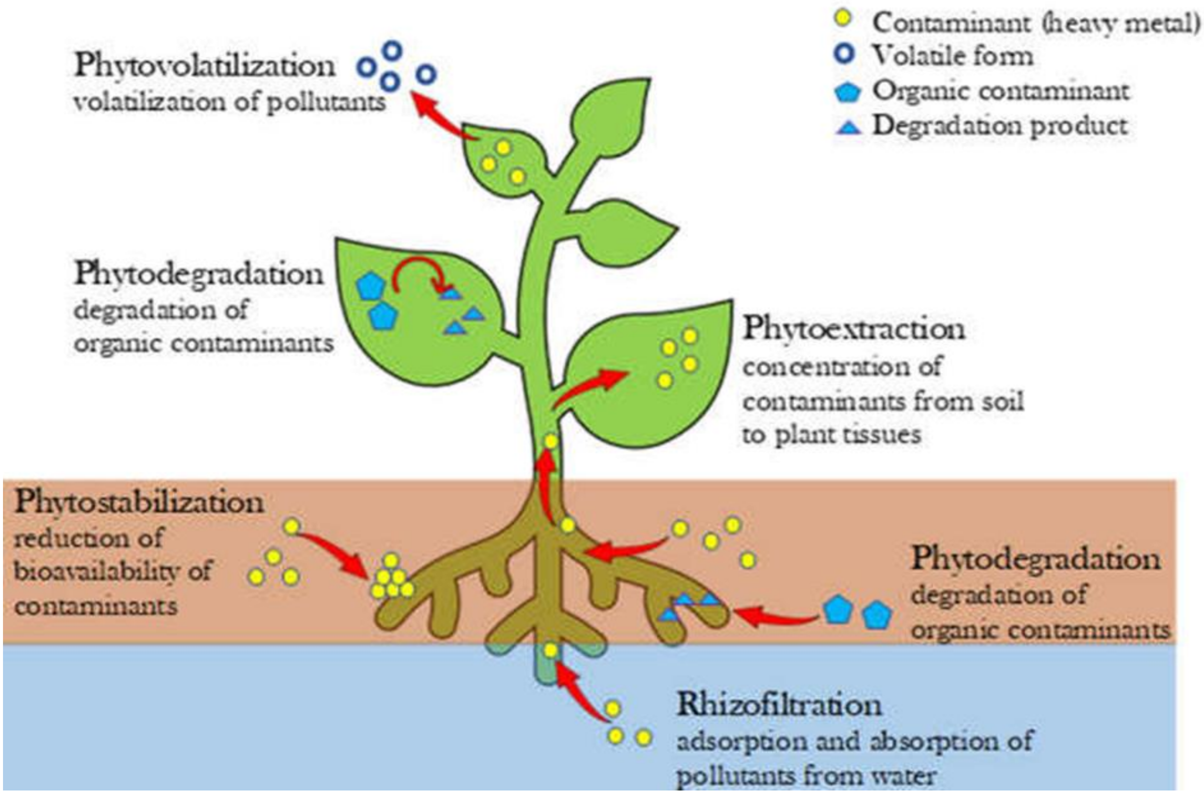

Figure 3. Schematic representation of different phytoremediation approaches by plants under study (source [46])

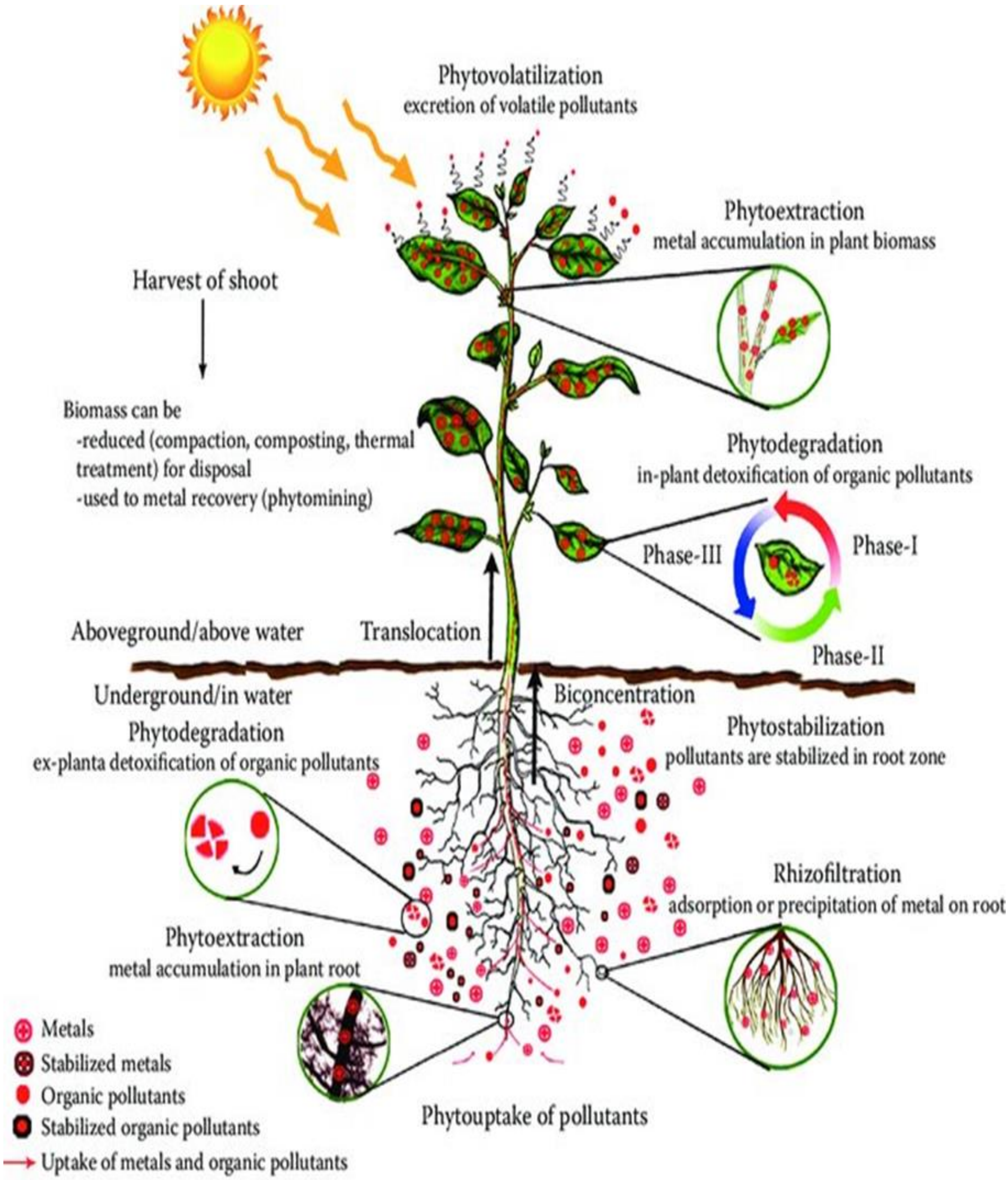

Figure 4. Schematic representation of various phytoremediation strategies

7. Future research perspectives

The high tolerance to soil contaminants, high nutritive value, and production of industrially important products makes halophytes a better system for utilization on non-fertile soils. Cultivation of halophytes offers sustainable solutions to degraded and infertile soils. Utilization of these species can be applied to reclaim dry lands around the coastal and degraded lands. The cultivation of halophytes in contaminated soil solves dual purpose. In the first step, halophytes will remove soil contaminants and make soil ready for cultivation of crops, and in second step, the harvested halophytes can be utilized as bioenergy source or production of value-added products. The ability of halophytes to combat metal ions has become successful in cleaning up the environment and restoring contaminated soil. Despite large-scale screening of halophyte species, extensive cultivation of halophytes is still to be achieved to realize their prospective use. More concerted efforts are needed to examine more halophytes to corroborate such an observation. More research should be directed at improving the growing conditions and tolerance of candidate metal halophytes at the field level.

8. Conclusions

Halophytes are of great importance for environmental management because of special morphological, anatomical, physiological, and biochemical features has offered them with great opportunities in sustainable management of heavily metalcontaminated environments. It's used in phytoextraction, phytostabilization, and phytoexcretion of heavy metals from the contaminated environments as compared to the non-halophytes. The metal phytoremediation potential of halophyte is considerably influenced by physico-chemical characteristics of soil, the selected plant species and most importantly, natural environmental conditions. Halophytes can grow on poor quality soil, allowing them to be used as plant media on soils of poor fertility resulting in lower operating costs. Choosing suitable plants to restore contaminated soil is a critical factor in phytoremediation, keeping in mind that the plant chosen should not transfer minerals to its aerial parts, and provide adequate vegetation cover that stabilizes low levels of minerals in the soil.

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